Towards a Generic Radiative Transfer Model for the Earth's Surface-Atmosphere System: ESAS-Light

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WP1100: Literature survey Radiative transfer tools

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1 Introduction

The basic equation for solar radiative transfer is the radiative transfer equation (RTE) which has been formulated by Chandrasekhar (1960):

$$-\frac{\mathrm{d}\mathbf{I}(\theta,\phi)}{\kappa\rho\mathrm{d}s} = \mathbf{I}(\theta,\phi) - \frac{1}{4\pi}\int_0^{\pi}\int_0^{2\pi}\mathbf{P}(\theta,\phi,\theta',\phi')\sin\theta'\mathrm{d}\theta'\mathrm{d}\phi'. \quad (1)$$

Here $\mathbf{I}(\theta,\phi)$ is the Stokes vector depending on the propagation direction of the radiation given by the polar angle θ and the azimuth angle ϕ, κ is the extinction coefficient and ρ is the density of the medium. $\mathbf{P}$ is the scattering phase matrix. In the thermal wavelength region, the additional term αB accounting for thermal emission needs to be included. Here α is the absorption coefficient and B is the Planck function. Thermal emission is unpolarized.

It is not possible to solve the RTE analytically without approximations. The radiative transfer equation can be simplified by calculating only the first component of the Stokes vector, the intensity. There are several models using this simplified equation and they are termed scalar models. These models neglect polarization due to particle scattering or surface reflection. A further common approximation is to assume a plane-parallel atmosphere. That is, it is assumed that all profiles, i.e., profiles of gaseous atmospheric constituents and cloud profiles, are homogeneous in horizontal extent and that the atmosphere exhibits no curvature. Gaseous profiles usually do not change much on a small scale but cloud fields can by strongly inhomogeneous also in the horizontal directions. Especially in limb-sounding geometry, where the propagation path through clouds can be several hundred kilometers in horizontal direction, the plane-parallel atmosphere approximation is not applicable. However, for nadir-sounding geometry, plane-parallel models are very practical. Advantages of the plane-parallel approximation is that it is possible to find (with some additional approximations) analytical expressions for the solution of the RTE, for example the Eddington approximation which is also called the "two-stream-approximation". In principle it is possible to solve the polarized RTE in three-dimensional spherical geometry. Commonly used numerical methods are the the Monte Carlo method and discrete ordinate methods. Computation time and memory requirements of the numerical solutions depend very much on the considered geometry of the atmosphere. The fastest solutions can be obtained for one-dimensional plane-parallel models. Three-dimensional spherical models are very computer expensive, both in terms of time and memory needs.

In the following an overview of radiative transfer models for wavelength regions from the UV to the microwave is presented. There is a huge number of radiative transfer codes which have been developed since the 1950s, so that it is beyond the scope of this report to provide a complete list. However, this report should include most of the well-known and well-tested models and several other newly developed codes that are currently used in the remote sensing community. The models are sorted according to the following categories:

- Comprehensive radiative transfer packages: the models listed here are modular and can be used for various applications; they include exchangeable radiative transfer solvers that can be chosen depending on the application
- Radiative transfer solvers: Different methods to solve the radiative transfer problem, some of these solvers are included in the comprehensive radiative transfer packages

- Line-by-line models: These models perform radiative transfer calculation in a clear-sky atmosphere with very high spectral resolution
- Fast radiative transfer models: Inversion algorithms for remote sensing applications as well as numerical weather prediction (NWP) models require fast radiative transfer models. The focus of the models listed in this section is on speed optimization, rather than on accuracy.

Some of the models are included in more than one of the categories, for instance ARTS, which is a comprehensive model for the thermal region that includes a line-by-line module.

2 Comprehensive radiative transfer packages

2.1 libRadtran

The *libRadtran* software package (Mayer and Kylling, 2005) is a suite of tools for radiative transfer calculations in the Earth's atmosphere. It provides radiances, irradiances, actinic fluxes and heating rates in the solar and the terrestrial part of the spectrum. *libRadtran* has been used for a variety of purposes. *libRadtran* is open source software covered by the GNU General Public License (GPL). It is available from `http://www.libradtran.org`.

The design of *libRadtran* allows simple problems to be easily solved using defaults and included data, hence making it suitable for educational purposes. At the same time the flexibility in how and what input may be specified makes it a powerful and versatile tool for research tasks. *LibRadtran* has been validated in several model intercomparison campaigns, and by direct comparison with observations (Mayer et al., 1997; Van Weele et al., 2000; Hofzumahaus et al., 2002; Wendisch and Mayer, 2003; Cahalan et al., 2005; Kazantzidis et al., 2007).

The *libRadtran* model was originally designed to calculate spectral irradiance and actinic flux in the ultraviolet and visible parts of the spectrum (Kylling, 1992) (initially the package was called *uvspec* and the executable still carries this name). Over the years, *libRadtran* has undergone numerous extensions and improvements. Since about eight years, *libRadtran* includes the full solar and thermal spectrum, currently from 120 nm to 100 μm. *libRadtran* has been designed as a user-friendly tool which provides a variety of options to setup and modify an atmosphere with molecules, aerosol particles, water and ice clouds, and a surface as lower boundary. Probably the most unique feature of *libRadtran* is that it includes not only one but a selection of about ten different RT solvers, fully transparent to the user, including the widely-used DISORT code by Stamnes et al. (1988), a fast two-stream code (Kylling et al., 1995), a polarization-dependent code polRadtran (Evans and Stephens, 1991), and the fully three-dimensional Monte Carlo code for the physically correct tracing of photons in cloudy atmospheres, MYSTIC (Mayer, 1999, 2000; Emde and Mayer, 2007). As such, the *libRadtran* developers have not not developed everything themselves, but have also adopted available modules from other open source software packages, like DISORT and polradtran. The modular structure of *libRadtran* and the programming in standard C and Fortran77 is ideally suited for this approach.

The *libRadtran* model is structured into the following three essential parts: (1) An atmospheric

shell which converts atmospheric properties like ozone profile, surface pressure, or cloud microphysical parameters into optical properties required as input to (2) the radiative transfer equation solver which calculates radiances, irradiances, actinic fluxes and heating rates for the given optical properties; and (3) post-processing of the solver output including multiplication with the extraterrestrial solar irradiance correction of Earth-Sun distance, convolution with a optional instrument slit-function, or integration over wavelength depending on the choices of the user.

Included in *libRadtran* are also a number of tools for the calculation of air mass factors, photodissociation rates, solar angles, Mie scattering etc.

2.2 SCIATRAN

The SCIATRAN radiative transfer model (Rozanov et al., 2005) is suitable to simulate measurements of scattered solar radiation in the Earth's atmosphere in the ultraviolet, visible, and near-infrared (UV-Vis-NIR) spectral regions.

It includes any viewing geometry common for measurements of the scattered solar radiation within or above the atmosphere, e.g., limb, nadir, off-nadir, zenith, or off-axis as measured by satellite, air- and balloon-borne, or ground-based instruments.

SCIATRAN can be operated either in plane-parallel mode or in spherical mode. In the spherical mode the Earth's atmosphere is considered to be symmetrical with respect to the solar principal plane allowing the solar zenith angle dependent composition of the atmosphere to be accounted for.

The surface reflective properties can be described by either a constant or a wavelength dependent Lambertian albedo as well as by the bidirectional reflectance distribution function (BRDF).

The discrete-ordinates method is employed to solve the integro-differential radiative transfer equation in a plane-parallel atmosphere. To calculate the outgoing radiance at the top of the atmosphere either the finite difference scheme (Rozanov et al., 1997) or the finite element can be used alternatively to the discrete-ordinates method. An ordinary plane-parallel approach is inaccurate for shallow viewing angles and it is only valid for solar zenith angles less than 90°. This limitation is avoided employing the pseudo-spherical extension (differential-integral approach (Rozanov et al., 2001)), i.e., an integral radiative transfer equation is solved properly accounting for the single scattering in a spherical atmosphere and using an approximation for the multiple scattering part. Any viewing geometry and solar zenith angles up to 98° are supported. If required a subsequent iterative approach (Picard iteration, CDIPI) can be used to find a solution in fully spherical geometry.

SCIATRAN allows calculations of weighting functions by the quasi-analytical approach (Rozanov et al., 1998). SCIATRAN can also be used to calculate air mass factors for satellite, ground-based, and airborne measurements including off-axis geometry as well as height resolved radiation fluxes including actinic fluxes needed for photolysis rate calculations under both daylight and twilight conditions.

In the spherical mode, photochemically active species can be accounted for, i.e., radiative transfer calculations can be performed considering solar zenith angle dependent vertical distributions of atmospheric trace gases instead of using fixed vertical profiles in the entire atmosphere.

Inelastic rotational Raman scattering (Vountas et al., 1998) can be considerd at any supported viewing geometry.

In the plane-parallel mode clouds can be accounted for either using the internal cloud data base computed for various cloud droplet size distributions employing the Mie theory or supplying user-defined cloud optical parameters.

SCIATRAN has been validated in an extensive comparison of outgoing radiances in limb viewing geometry simulated by five different radiative transfer models including the approximative spherical CDI model and the fully spherical CDIPI model (Loughman et al., 2004). The weighting function calculations have been validated against the Monte Carlo Model MCC++ (Postylyakov, 2004).

SCIATRAN is available from `http://www.iup.uni-bremen.de/sciatran/`.

2.3 ARTS

The Atmospheric Radiative Transfer Simulator (ARTS) (Buehler et al., 2005) is a line-by-line model that includes cloud scattering and is mainly used in the sub-mm and microwave wavelength regions. The model can be employed to simulate measurements in up-, limb- and down-looking geometry. ARTS includes an option to simulate polarization. Cloud particles may be aspherical and horizontally oriented. Optical properties are in this case gererated using the T-matrix method. Two scattering algorithms are included, a 1D model based on discrete ordinates (Emde et al., 2004) and a 3D model based on the Monte Carlo method (Davis et al., 2005).

ARTS has been validated against several other radiative transfer codes (Melsheimer et al., 2005; Saunders et al., 2007; Mendrok, 2006).

ARTS is freely available and can be obtained from `http://www.sat.ltu.se/arts/`.

2.4 MODTRAN

The Moderate Resolution Transmittance (MODTRAN) Code calculates atmospheric transmittance and radiance for frequencies from 0 to 50,000 cm^{-1} at moderate spectral resolution, primarily 2 cm^{-1} (20 cm^{-1} in the UV). The original development of MODTRAN was driven by a need for higher spectral resolution and greater accuracy than that provided by the LOWTRAN series of band model algorithms. Except for its molecular band model parameterization, MODTRAN adopts all the LOWTRAN 7 capabilities, including spherical refractive geometry, solar and lunar source functions, and scattering (Rayleigh, Mie, single and multiple), and default profiles (gases, aerosols, clouds, fogs, and rain). MODTRAN is described in a variety of papers, e.g. (Acharya et al., 1999; Berk et al., 1999, 2005), see `http://www.kirtland.af.mil/library/factsheets/factsheet.asp?id=7915`. MODTRAN is commercially available for approximately 300 USD, and is widely used by the atmospheric community. A large number of validation papers is also listed at the mentioned web page.

Some specialities of MODTRAN: MODTRAN uses the DISORT solver. However, the MODTRAN single scattering radiances are computed separately from DISORT with inclusion of

spherical geometry effects; the plane-parallel DISORT single scattering contributions are subtracted from the DISORT radiances for generation of the total radiance values. The first versions of MODTRAN were optimized for narrow band radiance simulations in a clear atmosphere. The more recent versions of MODTRAN allow calculations in a cloudy atmosphere, see Roebeling (2008) for a comparison with SHDOM and DAK.

2.5 EarthCare Simulator

ECSIM, the EarthCare Simulator is a package designed specifically in order to simulate the ESA EarthCare satellite. It consists of several modules: An atmospheric scene creator, and, for each of the four instruments, a forward model program, an instrument model program, and a retrieval program. In the scope of this report we will not discuss the retrieval programs. A detailed description of all modules can be found at http://c3vp.org/ECARE/ECARE_sim.html.

The forward model for the high resolution spectral lidar (HRSL) is a Monte Carlo model that uses the method of local estimate as well as several variance reduction techniques in order to get fast convergence of the solution, i.e. the time-dependent return signal. The problem of randomly occuring spikes in the solution that occur in the presence of phase functions with a strong forward peak (e.g. for ice and water clouds) is solved by the approximation that the signal coming from photons that scatter n times before hitting the detector is dominated by photons that scatter forward $n-1$ times and backward once. Further, it assumes that the contribution to the n scatter signal is independent of the order in which forward and backward scatters occur. Then the n scatter signal can be simulated by only taking into account photon paths where the last scatter is the backward scatter (which is the only path that does not produce spikes) and then multiplying the result with the permutation factor 2^{n-1}. These approximations are good when the phase function is strongly peaked in forward and backward directions. The Monte Carlo model also takes into account polarization by simulating the Stokes vector of the photons. Finally, the frequency Dopper shift due to thermal molecular motion for Rayleigh scattering is taken into account approximately with help of Gaussian fits for the Rayleigh-Brillouin scattering line shape.

The HRSL instrument model program folds the resulting spectral profile with the transmission and reflection profiles of the Fabry-Perot etalon in order to separate the Mie and Rayleigh signals, respectively. It further estimates the noise contributions.

For the passive instruments two models are implemented, one for short-wave radiation and one for long-wave radiation. The short-wave radiation model is a simple Monte Carlo method similar to the one used for the HRSL. Here, the problem with the spikes must be treated differently: scatter events that produce spikes (signal contributions above a user defined threshold) are smoothed over the whole domain. The long-wave radiation model is a simple backward (inverse) Monte Carlo method.

The radar forward model assumes single scattering, which makes calculation of the signal simple. It further corrects the result for atmospheric attenuation, averaging over the beam footprint, noise effects from speckles and thermal motion, and the effect of range weighting due to the finite width of the transmitted pulse.

2.6 SHDOM

SHDOM (Evans, 1998) computes unpolarized monochromatic or spectral band radiative transfer in a one, two, or three-dimensional medium for either collimated solar and/or thermal emission sources of radiation. The properties of the medium can be specified completely generally, i.e. the extinction, single scattering albedo, Legendre coefficients of the scattering phase function, and temperature for the particular wavelength or spectral band may be specified at each input grid point. Radiances at any angle, hemispheric fluxes, net fluxes, mean radiances, and net flux convergence (related to heating rates) may be output anywhere in the domain. For highly peaked phase functions the delta-M method may be chosen, in which case the radiance is computed with an untruncated phase function single scattering correction. A correlated k-distribution approach is used for the integration over a spectral band. There may be uniform or spatially variable Lambertian reflection and emission from the ground surface. Several types of bidirectional reflection distribution functions (BRDF) for the surface are implemented, and more may be added easily. The horizontal boundaries may be either periodic or open. The method to solve the radiative transfer equation is described in more detail below in section3.1.3.

SHDOM is available from `http://nit.colorado.edu/shdom.html`.

2.7 SBDART

SBDART (Ricchiazzi et al., 1998), available at `http://www.icess.ucsb.edu/esrg/pauls_dir/`, is a FORTRAN computer code designed for the analysis of a wide variety of radiative transfer problems encountered in satellite remote sensing and atmospheric energy budget studies. The program is based on a collection of highly developed and reliable physical models, which have been developed by the atmospheric science community over the past few decades. The radiative transfer solver of SBDART is the well-known DISORT code (Stamnes et al., 1988, 2000).

SBDART contains an internal database of parameters for clouds composed of spherical water or ice droplets. This database was computed using a Mie scattering code and covers a range of particle size effective radius in the range 2 to 128μm.

In its standard mode of operation SBDART relies on low resolution band models developed for the LOWTRAN 7 atmospheric transmission code. These models provide the clear sky atmospheric transmisson from 0 to 50000 cm^{-1} and include the effects of all radiatively active molecular species found in the earth's atmosphere. The models were derived from detailed line-by-line calculations which were degraded to 20 cm^{-1} resolution for use in LOWTRAN. This translates to a wavelength resolution of about 5 nm in the visible and about 200 nm in the thermal infrared.

Since these band models represent rather large wavelength bins, the transmission functions do not necessarily follow Beers law; i.e., the fractional transmission through a slab of material depends not only on the slab thickness but also on the amount of material penetrated before entering the slab. In order to allow these transmission functions to be used with DISORT (which assumes Beers law behavior), the band models are approximated with a three term exponential fit (Wiscombe and Evans., 1977). A capability to read high resolution k-distribution optical

depths from a file was introduced in SBDART version 2.0. This mode of operation requires the use of the ancillary programs CKLW and CKSW.

Three extraterrestrial solar spectrum models are included. Six standard atmospheric profiles from the 5S model (precurser of 6S, section 5.1) are provided. Alternatively users may specify their own model atmosphere based on, for example, a series of radiosonde profiles.

SBDART can compute the radiative effects of several common boundary layer and upper atmosphere aerosol types. In the boundary layer, the user can select either rural, urban, or maritime aerosols. The aerosol models were derived from those provided in 5S and LOWTRAN 7.

SBDART contains six basic surface types (ocean water, lake water, vegetation, snow and sand) for which the spectral reflectivity is included. The spectral reflectivity of a large variety of surface conditions is well approximated by combinations of these basic types. For example, the fractions of vegetation, water and sand can be adjusted to generate a new spectral reflectivity representing new or old growth. Combining a small fraction of the spectral reflectivity of water with that of sand yields an overall spectral dependence close to wet soil.

2.8 STREAMER

STREAMER (Key and Schweiger, 1998) is a radiative transfer model that can be used for computing radiances (intensities) or irradiances (fluxes) for a wide variety of atmospheric and surface conditions.

Irradiances may be computed using two or more streams, either broadband or narrow band. For more than two streams the discrete ordinate solver DISORT is used. Radiances may be computed for any polar and azimuthal angle. Top-of-atmosphere albedos or brightness temperatures are output along with the radiances. Optionally STREAMER calculates upwelling, downwelling, shortwave, longwave, and net fluxes, the cloud radiative effect ("cloud forcing"), or heating rates.

The model database includes liquid and ice cloud optical properties, five aerosol optical models, and four aerosol vertical profiles. A variety of different ice particle shapes (column, aggregate, etc.) are available. Clouds may be specified as some combination of particle size, water content, optical and geometrical thicknesses. Optical properties and phase function may also be specified by the user.

Seven standard atmospheric profiles are included. Optionally the user may specify atmospheric profiles, or total column amounts of water vapor, ozone, and/or aerosols.

Various surface types are built in: open ocean (sea water), meltponds, bare ice, snow, vegetation (four types), and dry sand. Spectral albedo and bidirectional reflectance models (BRDF) are included, or BRDF data can be input.

STREAMER has an interactive (interpreted) mode and provides a web interface at `http://stratus.ssec.wisc.edu/streamer/`.

2.9 AER

The radiative transfer models developed at AER (Atmospheric Environmental Research) are being used extensively for a wide range of applications in the atmospheric sciences. The model is publicly available from the AER website: http://www.rtweb.aer.com. The models are used for remote sensing (e.g. TES, IASI), for the numerical weather prediction and for climate modelling. The following models are available: the line-by-line radiative transfer model (LBLRTM, see section 4.3); the line file creation program (LNFL); the longwave and shortwave rapid radiative transfer models, RRTM_LW and RRTM_SW; the monochromatic radiative transfer model MonoRTM; the MT_CKD continuum; and the Kurucz solar source function. LBLRTM and the associated line parameter database (e.g. HITRAN 2000 with 2001 updates (Rothman et al., 2003)) play a central role in the suite of models. The physics adopted for the rapid radiative transfer models are developed and evaluated using the well validated LBLRTM model.

3 Radiative transfer solvers

3.1 Discrete ordinate methods

3.1.1 DISORT

DISORT (Stamnes et al., 1988, 2000) is one of the mostly used solvers of the radiative transfer equation. It is mostly used for, but not restricted to, the Earth's atmosphere. It is based on the discrete ordinate method which allows accurate calculation of radiances, irradiances, and actinic fluxes. DISORT is a well-tested solver which forms the core of libRadtran, SBDART, STREAMER and MODTRAN. It is a radiative transfer code for vertically inhomogeneous, plane-parallel scattering media and may be applied from the UV to the microwave region of the electromagnetic spectrum. Bidirectional reflection and emission at the lower boundary is handled.

The discrete ordinate method was first described by Chandrasekhar (1960). However, the numerical scheme devised was numerically unstable and thus researchers made only little use of it until the eighties. After many years of development Stamnes et al. (1988) presented a numerically stable discrete ordinate algorithm. The azimuth dependence of the radiation field is treated by expanding the phase function in Legendre polynomials and the radiance in a Fourier cosine series which gives one independent equation for each Fourier component. The discrete ordinate approximation replaces the remaining integral over the polar angle by a Gaussian quadrature sum. This gives a set of coupled equations which are solved as a standard algebraic eigenvalue problem once the inhomogeneous atmosphere has been divided into a stack of homogeneous layers in which the single scattering albedo and the phase function are taken to be constant.

One advantage of the discrete ordinate method compared to the doubling and adding method, which has been popular for a long time, is that the computation time of individual layers does not depend on the optical depth of the scattering medium. Furthermore, by using the iteration-of-source-function method, radiances can be obtained at arbitrary angles and optical depths,

unrelated to the computational meshes of these quantities.

3.1.2 VDISORT

Weng (1992a,b) has extended the DISORT model to solve the polarized (vector) radiative transfer equation. The new model (VDISORT) can be applied in plane-parallel vertically inhomogeneous scattering media including spherical particles. The approach to the solve the vector equation is completely analogous to that for the scalar case.

Schulz et al. (1999) have tested VDISORT for both, Rayleigh and Mie scattering matrices. A few errors in the implementation of the model that had a serious impact on the model output were found and corrected. Furthermore the model has been extended to randomly oriented non-spherical particles. The phase matrix for randomly oriented non-spherical particles can not be decomposed in Legendre polynomials. Therefore in the improved version of VDISORT the scattering matrix is expanded in generalized spherical functions.

3.1.3 SHDOM

The Spherical Harmonics Discrete Ordinate Method (SHDOM) is applied for modeling radiative transfer in inhomogeneous three-dimensional scattering media. The algorithm is described by Evans (1998).

The spherical harmonics angular representation is used to reduce memory requirements and computational time for the calculation of the source function. If the scattering depends only on the scattering angle, which is the case for randomly oriented particles, the source function in spherical harmonics reduces to a multiplication. An adaptive spherical harmonic truncation is implemented, which can save computer memory for smooth source functions.

Discrete ordinates are used for integrating the source function. An adaptive grid approach for the spatial resolution depending on the change of the source function across a grid cell is implemented in order to increase the accuracy of the computations. Finer grid resolution is included only where it is needed.

The solution method of the radiative transfer equation is a Picard iteration. This scheme converges slowly for optically thick, conservative scattering media. To speed convergence a sequence acceleration method based on geometrical convergence is performed. Each iteration is done for one frequency at a time. For broadband calculations the correlated k- distribution approach is implemented. Instead of using 3D discrete ordinates one can also use the independent pixel (IP) mode. Here the 3D radiation field is calculated as separate columns in a 1D plane parallel model or as separate planes in a 2D model.

Evans (1998) validated the model for solar and thermal radiative transfer in three situations; for independent columns in a linearly increasing optical depth field, for a 3D Gaussian extinction field with a Mie phase function and for a 2D fractal extinction field. The model has been compared to doubling-adding (Evans and Stephens, 1991) and Monte Carlo (o'Brian, 1992) models. The model error decreases with increasing angular and spatial resolution.

3.1.4 SHARM

SHARM (Lyapustin, 2005) is a 1D monochromatic radiative transfer code designed to compute monochromatic radiance/flux in the shortwave spectral region over a Lambertian or anisotropic surface. The atmospheric properties can change arbitrarily in the vertical dimension. The algorithm uses the method of spherical harmonics. Two numerical "tricks" are implemented in Sharm-1D. The first one uses special symmetry properties of the matrix of the spherical harmonics system to reduce its size by a factor of two for the subsequent singular value decomposition. This method was originally suggested by Karp (1981). The second one is a "correction function" method of angular smoothing developed by Muldashev et al. (1999). An intercomparison among several 1D codes (Lyapustin, 2002) showed that in the special test cases SHARM-1D was as accurate as DISORT, yet faster in calculations including aerosol phase functions.

The code SHARM-3D (Lyapustin and Wang, 2005) has been developed for fast and accurate simulations of the monochromatic radiance at the top of the atmosphere over spatially variable surfaces with Lambertian or anisotropic reflectance. The atmosphere is assumed to be laterally uniform across the image and to consist of two layers with aerosols contained in the bottom layer. The SHARM-3D code performs simultaneous calculations for all specified incidence-view geometries and multiple wavelengths in one run. SHARM-3D includes a comprehensive precomputed lookup table of the threedimensional atmospheric optical transfer function for various atmospheric conditions. A linear kernel model of the land surface bidirectional reflectance factor (BRDF) is used. Water pixels are described using the BRDF model by Nakajima and Tanaka (1983).

The SHARM codes are available at `http://neptune.gsfc.nasa.gov/bsb/subpages/index.php?section=Projects&content=SHARM`.

3.1.5 COART

The Coupled Ocean-Atmosphere system Radiative Transfer (COART) is based on the discrete-ordinate method Coupled DIScrete Ordinate Radiative Transfer (CDISORT) code by Jin and Stamnes (1994). It solves the radiative transfer problem of a coupled system with a discontinuous interface of the radiative properties. The method is well suited for the coupled ocean-atmosphere system but can be extended to study radiative transfer within a media in which the index of refraction changes continuously throughout the medium.

The ocean-atmosphere system is described as two strata with different indices of refraction. The ocean and atmosphere are assumed to be vertically stratified and plane-parallel and can be divided into any required number of horizontal layers to account for the vertical inhomogeneity. The optical properties only depend of the vertical coordinate. The atmospheric absorption is based on the LOWTRAN 7 band model.

The coupled system is only necessary for solar radiation, whereas for thermal wavelengths the absorption by the ocean is so large that transport of the photons in the ocean is not necessary and the ocean surface can be modelled by its temperature.

The number of streams for the atmosphere and the ocean are different: the streams of the atmosphere are “refracted” into the ocean, i.e. the streams within the ocean for angles that correspond

to refraction at the interface are chosen such that they correspond to the streams of the atmosphere. By this method interpolation is not necessary when coupling the two systems. For the angles of total reflection within the ocean additional streams are introduced. The quadrature used to solve the equations is based on the method of Tanaka and Nakajima (1977).

The latest version (Jin et al., 2006) includes a rough ocean surface. It is decomposed into small planar facets the orientations of which follow a statistical distribution. The undulations of the surface are assumed to be larger than the wavelength of the light.

Further developments will include inelastic scattering effects and polarisation.

COART, including CDISORT, is still under development. The sources are not available yet, but an interface on the website `http://snowdog.larc.nasa.gov/jin/rtnote.html` permits to use it online by giving a set of input parameters.

3.2 Matrix operator methods

3.2.1 STAR

The System for Transfer of Atmospheric Radiation STAR (Ruggaber et al., 1994) was developed to model radiation quantities and photolysis frequencies in the troposphere. The model is based on the matrix operator code of Nakajima and Tanaka (1986). STAR was developed to calculate accurately and efficiently radiation quantities such as irradiance, radiance and actinic flux; all fluxes with their separation in direct / diffuse component and upwelling / downwelling. Additionally, integral quantities with respect to wavelength, such as erythemal dose and photolysis frequencies for 27 different species in the gaseous and aqueous phase; and integral quantities with respect to time, such as daily dose are computed. The calculations are carried out in the wavelength range from 280 nm to 700 nm, i.e. in the UV-B, the UV-A and the visible.

STAR uses variable data sets for the description of the atmosphere. The modular structure of the model allows to change of these data sets easily. A wide range of options for all relevant input data, as vertical profiles of ozone, nitrogen dioxide, sulfur dioxide, pressure, temperature, relative humidity, aerosol extinction, and liquid water content for homogeneous cloud layers, as well as solar zenith angle, ground albedo, and models for aerosol particles and cloud droplets is offered. The latter is based on the OPAC aerosol and cloud model (Hess et al., 1998). STAR took part at various model to model and model to measurement comparisons, documenting the high quality standard of the model.

The model was developed for all researchers dealing with the topic of UV radiation and its impact on humans, animals and plants and is freely availably for scientific use from `http://www.meteo.physik.uni-muenchen.de/strahlung/uvrad/Star/starprog.html`.

3.2.2 MOMO

The model MOMO (Fell and Fischer, 2001) is based on the matrix operator method to calculate radiative transfer in the combined atmosphere-ocean system. The main advantage of the matrix-

operator method concerns the simulation of light propagation in optically dense media. The code calculates azimuthally resolved radiances at a discrete number of incident and observation zenith angles at pre-defined depth levels. The implementation of the matrix-operator method mainly follows Plass et al. (1973), the analytical treatment of strongly peaked phase functions is based on the work of Potter (1970), the effects of refraction at the air/sea interface on the Gaussian quadrature scheme are treated as outlined in Kattawar et al. (1978).

Reflection at the rough sea surface is modelled according to the statistical description of the wave facet distribution derived by Cox and Munk (1954a), its incorporation into MOMO was inspired by Nakajima and Tanaka (1983). Transmission through the rough sea surface is treated using an approximation described in Fell and Fischer (2001). Atmospheric gas absorption, chlorophyll-α fluorescence (Fischer and Kronfeld, 1990) and Raman scattering are included. Polarisation as well as wind-direction dependent effects at the rough sea surface have been incorporated into experimental versions of the code.

3.2.3 MOM

The MOM model (Meerkötter et al., 1999) is based on the matrix-operator- method (MOM) developed by Plass et al. (1973). The solar and terrestrial versions of this code performed successfully in an intercomparison of radiation codes Ellingson and Fouquart (1991). Fischer and Grassl (1984) described the shortwave version. The longwave version has successfully been applied in a comparison of modeled and measured broadband fluxes from aircraft data (Saunders et al., 1992). In the solar spectral range, the radiative transfer code accounts for multiple scattering and absorption processes related to air molecules, aerosol/cloud particles, the absorbing gases, and the surface, in the longwave range additionally for the thermal emission of the relevant constituents. The solar spectral range, from 0.2–4 μm, is divided into 25 wavelength intervals, the terrestrial spectral range from 4–100 μm into 28 intervals. Average transmission functions accounting for gaseous absorption in the wavelength intervals are approximated by exponential sum fitting. The transmission functions result from line-by-line calculations based on the HITRAN-86 data base (Rothman et al., 1987). The spectral extraterrestrial sun in the solar range is extracted from data incorporated in the LOWTRAN-7 radiative transfer code. The spectral optical parameters of ice clouds and aerosol particles are represented in each wavelength interval by the phase function (solar range), the asymmetry factor (terrestrial range), the volume extinction coefficient, and the single scattering albedo. For spherical particles, the spectral optical parameters are computed using Mie-theory on the basis of given particle size distributions and spectral complex refractive indices. In case of cirrus clouds/contrails, the refractive indices for ice according to Warren (1984) have been used, the refractive indices of the different aerosol components stem from WMO (1986). The properties of hexagonally shaped particles are taken into account only for the solar region and computed assuming geometrical optics (Hess and Wiegner, 1994).

3.2.4 RTMOM

RTMOM (Govaerts, 2008) is a one-dimensional radiative transfer model that simulates radiation propagation in a plane-parallel atmosphere composed of horizontally homogeneous layers

bounded by an anisotropic scattering surface. These layers may contain aerosols and/or clouds, assuming elastic scattering. The atmosphere is composed of seven different absorbing gases, including, among other, water vapour, ozone and carbon dioxide. Gaseous absorption is calculated with the k-distribution method. The RTE is solved using the matrix operator method. The solar and thermal contributions of the radiative field are calculated from 0.25–15μm for spectral resolutions ranging from 0.001–0.010μm. RTMOM has been validated by comparison to various other models (libRadtran, 6S, FEM and MODTRAN). Results of this comparison are discussed in (Govaerts, 2006).

The model is freely available from `ftp://ftp.eumetsat.int/pub/MET/out/govaerts/RTMOM-BETA/index.htm`.

3.3 Monte Carlo Methods

3.3.1 MYSTIC

MYSTIC (Mayer, 1999, 2000; Emde and Mayer, 2007) is a Monte Carlo code which traces individual photons on their random paths through the atmosphere. Starting from the top of the atmosphere (for solar radiation), or being thermally emitted by the atmosphere or surface, the photon is followed until it hits the surface or leaves again at the top of the atmosphere (TOA). For solar radiation, the start position is a random location in the TOA plane, with the direction determined by the solar zenith and azimuth angles. Recently, MYSTIC has been extended by a backward photon tracing option which speeds up calculation of radiances and allows very fast calculations in the thermal spectral range. Furthermore it is possible to operate MYSTIC in fully spherical geometry. MYSTIC handles three-dimensional water and ice clouds in a one-dimensional background atmosphere of molecular scatterers and absorbers and aerosol particles. As a speciality, MYSTIC also allows to consider topography as well as inhomogeneous surface albedo and BRDF. MYSTIC is one of very few codes which solved all seven cases of the Intercomparison of 3D Radiation Codes (I3RC) - an ongoing international activity to compare 3D radiative transfer codes and to exchange ideas about model development, see section 3.3.5. In the I3RC, MYSTIC was within a small core group of models which generally agreed within 0.1 - 1%. More information and examples about mystic are available at `http://www.bmayer.de/mystic.html`.

3.3.2 MCARaTS

MCARaTS is an open-source scientific software to simulate the three-dimensional radiative transfer in atmospheric media with underlying surface (Iwabuchi, 2006). It uses the forward-propagating Monte Carlo photon-transport algorithm. The code can be optionally parallelized to run efficiently on parallel computers. The code can be applied to quantitative simulations of the solar and/or infrared energy budget of the earth and to quasi-observation of cloudy atmospheres with optical instruments. MCARTaTS may include a solar source and/or thermal emission from the atmosphere and surface, or a localized source (e.g. laser beam, isotropically emitting lamp, star in space, etc). Output quantities are radiative fluxes, heating rates, radiances and

air mass factors, camera-like images, local plane/spherical fluxes with pathlength distribution. MCARaTS is available from http://www.geocities.jp/null2unity/mcarats/.

3.3.3 MCC++

The model MCC++ (Postylyakov, 2004,?) employs the Monte Carlo method for polarized radiative transfer simulations in a spherically symmetric atmosphere. The model takes into account aerosol and molecular scattering, gas and aerosol absorption, and a Lambertian surface albedo.

MCC++ is linearized model, which allows the calculation of derivatives of all elements of the Stokes vector (Jacobians) with respect to the volume absorption coefficient simultaneously with the radiance calculation. MCC++ has been compared to several other spherical radiative transfer codes (Loughman et al., 2004).

3.3.4 GRIMALDI

GRIMALDI (Scheirer, 2002) is a small set of programs to calculate monochromatic or broad-band fluxes, radiances or photon path-length. GRIMALDI uses a line-by-line model to calculate gas-absorption coefficients and a Monte Carlo program to solve the radiative transfer problem. The model is freely available.

3.3.5 I3RC

The Intercomparison of 3D radiation codes I3RC (Cahalan et al., 2005) is an ongoing project initiated in the late 1990s. The objectives are to compare methods available for 3D atmospheric radiative transfer calculations, to provide benchmark results for testing and debugging 3D radiative transfer codes, to publish an open source toolkit (community 3D Monte Carlo code), and to help atmospheric science education by creating an educational web site on 3D radiative transfer. The webpage http://i3rc.gsfc.nasa.gov provides information about the project itself, about the Monte Carlo models that took part in the intercomparisons and an extensive list of publications related to 3D radiative transfer modelling. The current version of the community Monte Carlo code can be obtained (ordered) from the website.

3.4 Doubling and adding methods

3.4.1 PolRadTran

PolRadTran is a polarization-dependent one-dimensional plane-parallel solver by Evans and Stephens (1991). The solver may be applied to calculate the monochromatic radiance exiting a vertically inhomogeneous atmosphere containing randomly oriented particles. Thermal and solar sources are considered.

The radiation field is represented by a Fourier series in azimuth angles and the zenith angles are discretized using numerical quadrature. The number of quadrature angles and Fourier modes depends on the desired accuracy. Randomly oriented particles of all shapes having a plane of symmetry can be handled. The phase matrix defined in the so called scattering frame is used as model input. The scattering matrix depends only on the scattering angle, i.e., the angle between incoming and outgoing direction. The scattering matrix needs to be transformed to the phase matrix for the RT calculation, which is one of the major complications in the polarized model compared to scalar models.

The vector radiative transfer equation is integrated using the doubling and adding method. The key concept is the interaction principle which is also applied.

PolRadTran can be downloaded from `http://nit.colorado.edu/polrad.html`.

3.4.2 DAK

The basics of the radiative transfer model DAK (Doubling-Adding KNMI) are described in the publications by de Haan et al. (1987); Stammes et al. (1989). DAK is a 1D monochromatic plane-parallel radiative transfer model based on the matrix operator method. The model handles polarization.

The model is not available for the scientific community.

3.5 Successive Orders of Scattering

3.5.1 LOA radiative transfer code

The radiative transfer code developed at the Laboratoire d'Optique Atmospherique (LOA) of Lille University (Lenoble et al., 2007) includes a complete treatment of polarization due to aerosol scattering and the Earth's surface reflectance. It relies on the method of successive orders of scattering for a plane-parallel atmosphere. The objective of the code is the analysis of radiation measurements, understanding the contribution of aerosol scattering and absorption, and of the Earth's surface reflectance. The code allows the simultaneous introduction of several aerosol models with different characteristics and different profiles. It also offers the choice of different reflectance laws, for land and water surfaces. Several different versions of the codes are available for specific tasks.

3.5.2 6S radiative transfer code

The Second Simulation of a Satellite Signal in the Solar Spectrum (6S) is another basic RT code based on the method of successive orders of scattering. It is applied for the calculation of look-up tables to be used for remote sensing from satellite or airborne platforms. For more details see section 5.1.

3.6 Raman Scattering

Scattering of air molecules is usually treated as monochromatic, or elastic, dipole scattering by dielectric spheres. However, most air molecules are not perfect dielectric spheres and exhibit some degree of anisotropy which causes inelastic scattering. Thus, Rayleigh scattering has two components: the elastic Cabannes line and the inelastic rotational-vibrational Raman lines. According to van Deelen et al. (2005) about 96% of the light in a scattering event is scattered elastically, while the rest undergoes inelastic scattering. Raman scattering may take place with a change in the vibrational, rotational or electronic energy of a molecule. In the Earth's atmosphere only rotational Raman scattering is of importance. Rotational Raman scattering gives rice to filling in of Fraunhofer lines and absorption features of trace gases in the Earth's atmosphere. The effect is of importance for remote sensing applications.

The rotational Raman scattering (RRS) codes described below all treat Raman scattering to first order only. That is, RRS is treated as a perturbation to the elastic solution of the radiative transfer equation. van Deelen et al. (2005) have checked the validity of this approximation. For the conditions they investigated the error made neglecting multiple RRS is a maximum of 0.6% compared with a first order RRS approach. The magnitude of the error depends on the spectral resolution of the instrument, the presence of aerosols and clouds, the characteristics of the underlying surface and the viewing geometry.

3.6.1 Successive order of scattering

Joiner et al. (1995) developed a scalar successive order of scattering model including one order of RRS. They used the model to estimate the effect of RRS on Solar Backscatter Ultraviolet Radiometer (SBUV) measurements. The filling in predicted by the model was in good agreement with the observations.

3.6.2 Finite difference method

Rozanov et al. (1998) developed a first order RRS model based on a scalar finite difference solution of the RTE. The first order solution is obtained by dividing the problem into the radiative transfer equation for the elastic Rayleigh scattering atmosphere and an inelastic perturbation term. The solution is found by an iterative process. Rozanov et al. (1998) applied their model successfully to Global Ozone Monitoring Experiment (GOME) related measurements.

3.6.3 Vector radiative transfer

Landgraf et al. (2004) also treated RRS as a perturbation to the first order. However, they solved the vector RTE including RRS with the Gauss-Seidel iteration method. The effect of polarization on the Ring structures was found to generally be small and of minor importance.

4 Line-by-line models

Line-by-line models rely on spectroscopic databases (see section) 6) from which absorption coefficients can be calculated with high spectral resolution.

4.1 4A

The Automatized Atmospheric Absorption Atlas (4A) is a line-by-line and layer-by-layer method for determining atmospheric absorption in the thermal spectrum. The algorithm is described in Scott and Chedin (1981), and more up-to-date and precisely in Chaumat et al. (2006).

The code is based on a database called ATLAS, which contains monochromatic optical thicknesses as a function of temperature (12 bins), pressure (40 bins), wavelength (several thousand bins), and absorbing gas type, and is derived from the 2003 spectroscopy GEISA catalogue using STRANSAC.

The geometry is 1D spherical. For the surface emissivity the code provides 14 spectral classes, a user defined emissivity is possible.

The code takes into account χ-correction of Voigt profiles and effects of line coupling. It also estimates the solar contribution.

The output can be as a high spectral resolution profile, or convoluted with the slit function of an instrument. Further, the model can provide Jacobians needed for the retrieval of atmospheric parameters.

The spectral range is 600-3000 cm^{-1} and the spectral resolution is $5 \cdot 10^{-4}\mathrm{cm}^{-1}$.

The computational speed of the program is given to be 28 seconds for one spectral calculation with a Linux 3.4GHz processor, and 300 seconds for one spectral calculation plus 4 Jacobians.

The model is available at `http://ara.lmd.polytechnique.fr/htdocs-public/products/4A.html`.

4.2 ARTS

ARTS (see also section 2.3) is a line-by-line model which works with arbitrary wavelength grids, hence it can be used both for the simulation of high resolution sensors, and for the simulation of broad frequency ranges. The applicable spectral range is from the microwave up to the thermal infrared, but the model is currently only well validated below roughly 1 THz. In that frequency range, particular care has been taken to make the absorption calculation consistent with state of the art continuum models for water vapor and nitrogen, and with continuum and line mixing models for oxygen. Besides providing sets of spectra, ARTS can calculate Jacobians for a number of variables. Analytical expressions are used to calculate Jacobians for trace gas concentrations, continuum absorption, and ground emissivity. Perturbations are used to calculate Jacobians for pointing offsets and calibration offsets. For temperature Jacobians, the user can choose between an analytical method, which does not assume hydrostatic equilibrium, and

a perturbation method, which does assume hydrostatic equilibrium.

4.3 LBLRTM

LBLRTM is an accurate and efficient line-by-line radiative transfer model derived from the Fast Atmospheric Signature Code (FASCODE) (Clough et al., 1992). LBLRTM has been and continues to be extensively validated against atmospheric radiance spectra from the ultraviolet to the submillimeter (e.g. Turner et al. (2004)).

LBLRTM is freely available from http://rtweb.aer.com/.

4.4 KOPRA

The Karlsruhe Optimized and Precise Radiative transfer Algorithm KOPRA (Stiller, 2000) is a code for atmospheric radiative transfer modelling in the mid-infrared spectral range. KOPRA is a tool suitable for the analysis of numerous data in an automated retrieval set-up. It has been developed as self-standing algorithm including all relevant physics from the troposphere to the thermosphere as well as the instrument specific response function of the MIPAS/ENVISAT experiment besides other more standard ones. In KOPRA absorption coefficients are calculated on an optimized wavenumber grid. Line mixing, absorption and emission of heavy molecules and of continua caused by gaseous constituents and solid particles are included. Effects caused by non-local thermodynamic equilibrium (NLTE) can be considered. It includes several optimizations, for instance the modelling of the Voigt function by an accelerated Humlicek algorithm. A detailed model description can be found at http://www-imk.fzk.de/asf/ame/publications/kopra_docu/.

4.5 RFM

RFM (Reference Forward Model), available at http://www.atm.ox.ac.uk/RFM/ is a GENLN2-based line-by-line radiative transfer model. It can be operated in spherical or plane-parallel atmospheres. It includes field-of-view and instrument line shape convolutions, CO_2 line mixing and continua for H2O, O2, N2 and CO2. Non-LTE effects may be considered via user-supplied vibrational temperatures. RFM also computes Jacobians if required. The surface is implemented as a Lambertian reflector. Output quantities are spectra of radiance, transmittance, absorption, cooling rates, optical depth and/or brightness temperature.

4.6 MIRART

The Modular InfraRed Atmospheric Radiance and Transmission package MIRART (Schreier and Böttger, 2003) is a suite of programs for modeling atmospheric radiative transfer, typically by means of line-by-line calculations of absorption coefficients, and numerical solution of the integral radiative transfer equation and Beer's law. It is developed mainly for atmospheric

remote sensing applications. The code has been carefully tested in the framework of two extensive intercomparisons. Molecular weighting functions are implemented by means of automatic differentiation.

4.7 genln-2

GENLN2 (Edwards, 1992) is a general purpose line by line atmospheric transmittance and radiance model.It includes line-shape modelling and continuum absorption. GENLN-2 provides transmittances and radiances calculated for a clear-sky spherically symmetric atmosphere as outputs.

5 Fast radiative transfer models

5.1 6S and 6SV1

The Second Simulation of a Satellite Signal in the Solar Spectrum (6S) is a basic RT code used for the calculation of look-up tables to be used for remote sensing from satellite or airborne platforms. Its main use is to derive surface reflectances in clear sky conditions. The code is written in Fortran 77. The algorithm is described in Vermote et al. (1997), late improvements are described in Kotchenova et al. (2006).

6S is a 1D, non-spherical code, thus it cannot be used for limb observations. Clouds are not taken into account.

Molecular absorption is treated separately from scattering and reflection. Absorption is derived with an equivalent band model using the HITRAN database at 10 cm^{-1} resolution. The resulting transmissions (for each molecule separately) are multiplied to the result from the scattering computation. Due to the decoupling of scattering and absorption, the code can not be used in the presence of strong absorption bands.

Scattering and reflection are computed with help of the Successive Orders of Scattering (SOS) method. The model includes molecular Rayleigh scattering and Mie scattering by aerosols.

The surface reflection can be modelled by several schemes: Lambertian, BRDF, or Cox and Munk. The surrounding surface is given a different albedo than the spot being calculated, this is taken into account in the calculation. Surface elevation is implemented.

The aerosol models used are defined by the Commission (1983) or taken from King et al. (1984), Shettle (1984), and Remer et al. (1996). BRDF models implemented in the code are Hapke (1986), Pinty and Verstraete (1991), Iaquinta and Pinty (1994), Roujean et al. (1992), Minnaert (1941), Walthall et al. (1985), and Moral (1988).

The step size (resolution) used for spectral integration is 2.5nm.

Polarization has been implemented recently (6SV1, Kotchenova et al. (2006)). The effects of polarization are included through the calculation of the first three of the four components of the Stokes vector. The elliptical polarization, V, is set to zero. Also, it is assumed that surface

reflections are unpolarized.

The code has been thoroughly validated and compared with other models, see Kotchenova et al. (2006), Kotchenova and Vermote (2007), and Kotchenova et al. (2008).

The model can be obtained from the webpage http://6s.ltdri.org/.

5.2 RTTOV

RTTOV stands for **R**adiative **T**ransfer for **TOVS** (top operational vertical sounding) and is a very fast radiative transfer model for nadir looking/scanning passive infrared and microwave satellite radiometers, spectrometers and interferometers. It is a FORTRAN-90 code for simulating satellite radiances, designed to be incorporated within users' applications. It is delivered with readily calculated coefficient data sets for the channels/frequency regions of specific instruments/sensors.

The RTTOV approach is used operationally at several NWP centers for variational assimilation purposes. The present version is RTTOV 9_1, released in March 2008.

For all the satellite sensors supported (see listing below), given an atmospheric profile of temperature, water vapour and optionally other atmospheric constituents (see below) together with satellite zenith angle and surface temperature, pressure and optionally surface emissivity, RTTOV will compute the top of atmosphere radiances in each of the channels of the sensor being simulated. Users can choose the channels to be simulated.

It is not always necessary to store and access the full Jacobian matrix H and so the RTTOV package also has routines to only output the tangent linear values, i.e. the change in top of atmosphere radiances, for a given change in atmospheric profile about an initial atmospheric state. These routines are normally used as part of the variational assimilation of radiances.

Atmospheric profiles and other essential items: Temperature (mandatory), variable gas concentrations, cloud and surface properties (all referred to as the state vector, see above). The only mandatory variable gas is water vapour. Optionally ozone, carbon dioxide, nitrous oxide, methane and carbon monoxide can be variable with all other constituents assumed to be constant.

Satellite platforms presently supported: TIROS-N + NOAA.., DMSP, Meteosat, GOES, GMS, FY-2, TRMM, ERS, EOS, METOP, ENVISAT, MSG, FY-1, ADEOS, MTSAT, CORIOLIS

Instruments presently supported: HIRS, MSU, SSU, AMSU-A, AMSU-B, AVHRR, SSMI, VTPR, TMI, SSMIS, AIRS, HSB, MODIS, ATSR, AMSR, MVIRI, SEVIRI, GOES-Imager, GOES-Sounder, GMS/MTSAT imager, FY2-VISSR, FY1-MVISR, (CriS, VIIRS), WINDSAT, SSM/T-2, IASI

Information about RTTOV is available at the websites:

- www.metoffice.gov.uk/research/interproj/nwpsaf/rtm/rttov8_description.html
- www.metoffice.gov.uk/research/interproj/nwpsaf/rtm/rtm_rttov9.html

- Users guide: Saunders and Brunel (2005)

RTTOV fast RT model approach

RTTOV contains a fast model of the transmittances of the atmospheric gases that is generated from accurate line-by-line transmittances (GENLN2 / kCarta / LBLRTM, or Liebe-89 MPM, resp.) for a set of diverse atmospheric profiles (43L TIGR profile dataset / t101L 52 profile ERA-40 dataset) over wave-number range of the specific channels/instruments in question. The monochromatic transmittances are convolved with the appropriate spectral response functions and are used to compute channel-specific regression coefficients by use of a selected set of predictors. These regression coefficients can then be used by a fast transmittance model to compute transmittances given any other input profile. This parameterization of the transmittances makes the model computationally efficient and in principle should not add significantly to the errors generated by uncertainties in the spectroscopic data used by the line-by-line model.

So, it is important to state that the primary goal of RTTOV is very fast computing RT for pre-calculated fixed channels of instruments, but with atmospheric profiles and additionals (surface and cloud items, zenith angles etc.) relatively free in choice.

6 Spectroscopic databases

The most common and complete spectroscopic databases are HITRAN (Rothman et al., 2005) and GEISA. Both are freely available and can be obtained from the respective web-pages:

- http://cfa-www.harvard.edu/HITRAN/
- http://ara.lmd.polytechnique.fr/htdocs-public/products/GEISA/HTML-GEISA/index.html

Both databases are very extensive. They include line parameters of about 40 molecules and about 100 isotopes. The HITRAN community is very active, there is the biennial HITRAN database conference plus several meetings every year connected to HITRAN. Both of the databases are regularly updated.

6.1 HITRAN

HITRAN is an acronym for high-resolution transmission molecular absorption database. HITRAN is a compilation of spectroscopic parameters that is used to predict and simulate the transmission and emission of light in the atmosphere. The database is a long-running project started by the Air Force Cambridge Research Laboratories (AFCRL) in the late 1960's in response to the need for detailed knowledge of the infrared properties of the atmosphere. The HITRAN compilation, and its analogous database HITEMP (high-temperature spectroscopic absorption parameters), are now being developed at the Atomic and Molecular Physics Division, Harvard-Smithsonian Center for Astrophysics. In addition to the Mega-line HITRAN2004

database, HITRAN includes data of aerosol indices of refraction, UV line-by-line and absorption cross-section parameters, and more extensive IR absorption cross-sections.

6.2 GEISA

GEISA (Gestion et Etude des Informations Spectroscopiques Atmosphériques: Management and Study of Spectroscopic Information) is a computer-accessible spectroscopic database, designed to facilitate accurate forward radiative transfer calculations using a line-by-line and layer-by-layer approach. It was started over three decades at Laboratoire de Météorologie Dynamique (LMD/IPSL) in France. GEISA is maintained by the ARA group at LMD (Ecole Polytechnique) for its scientific part and by the ETHER group (CNRS Centre National de la Recherche Scientifique-France) at IPSL (Institut Pierre Simon Laplace) for its technical part. Currently, GEISA is involved in activities related to the assessment of the capabilities of IASI (Infrared Atmospheric Sounding Interferometer on board of the METOP European satellite) through the GEISA/IASI database derived from GEISA. GEISA also includes an aerosol database providing refractive indices of various aerosol types and the corresponding optical properties.

7 Cloud optical properties

7.1 Water clouds

7.1.1 Mie calculations

Water droplets in clouds are in good approximation of spherical shape. Hence detailed optical properties (including the phase matrix required for polarized simulations) can be calculated using the well-known Mie-Theory. The complex refractive index of water is required as input. Among many freely available Mie codes, the one by Wiscombe (1980) is fast, reliable and well tested. A list of codes to calculate electromagnetic scattering by particles has been compiled by Flateau and is available at `http://atol.ucsd.edu/scatlib/`.

7.2 Ice clouds

7.2.1 Parameterization for climate models

The parameterization of the optical properties of ice crystals by Ebert and Curry (1992) is widly used in global climate models. Five spectral intervals in the shortwave and five intervals in the infrared are employed, with the ice cloud optical properties parameterized in terms of ice water path and the effective radius of the ice crystal size distribution. The parameterization thus allows the flexibility of varying the ice water path and effective radius independently of each other.

The parameterizations by Fu (1996); Fu et al. (1998) have also been developed for climate models. The scattering phase functions are parameterized as Henyey-Greenstein phase func-

tions. The parameterizations are based on 28 ice crystal size distributions from in situ aircraft observations in both tropical and midlatitude regions. For the single scattering calculations, a composite scheme has been developed for randomly oriented hexagonal ice crystals by comparing results from Mie theory, anomalous diffraction theory, the geometric optics method, and the finite-difference time domain technique. The range for the effective radius is from 9 – 65 μm.

These parameterizations are accurate only for the calculation of radiative fluxes, not for radiances since they do not include scattering phase functions. Also the spectral resolution is very coarse.

7.2.2 Parameterization for remote sensing applications

The parameterization by Key et al. (2002) provides the shortwave bulk optical properties of seven ice particle shapes, or "habits", which are parameterized as a function of the effective radius and ice water content by integrating the scattering properties over 30 in situ size distributions. Accurate light scattering calculations are the basis for the parameterization (Yang et al., 2000). The particle habits are solid and hollow hexagonal columns, hexagonal plates, two- and three-dimensional bullet rosettes, aggregates of columns, and dendrites. Parameterizations of the volume extinction coefficient, single-scattering albedo, and the asymmetry parameter are presented for 6, 24, and 56 band shortwave schemes from 0.2 to 5.0 mm. Applications to downwelling flux and upwelling radiance calculations indicate that differences in fluxes for various habits can be more than 15%, and differences in retrievals of cloud optical depth from satellite visible reflectances can be more than 50%.

Baran et al. (2003) provides a consistent set of single-scattering properties for radiative transfer calculations and remote sensing of cirrus clouds. The single-scattering properties consist of the extinction coefficient, single-scattering albedo and phase function. A randomly oriented randomized hexagonal ice aggregate is assumed to derive the extinction coefficient and single-scattering albedo. The phase function is an extension of the Henyey-Greenstein model called the "analytic" phase function, which is generated from the asymmetry parameter at non-absorbing and absorbing wavelengths.

The parameterizations by Key et al. (2002) and Baran et al. (2003) can be used to calculate radiances because they use the double-Henyey- Greenstein and the "analytic" phase functions respectively, which better represent both forward and backward peaks. They do of course not include specific features like the halo.

7.2.3 Ice Cloud Bulk Scattering Models by Baum

The newest, most complete parameterization for ice clouds has been developed by Baum et al. (2005a,b, 2007). It is available from the website `http://www.ssec.wisc.edu/~baum/Cirrus/IceCloudModels.html`.

Based on recent research, the ice cloud bulk scattering models have been developed and are being explored for application to global cloud retrievals from satellite data.

The models are based on a large set of particle size distributions (more than 1100) to account

for the range of crystal sizes and habits found in polar, midlatitude, and tropical ice clouds. The models include a particle shape mixture which depends on the effective radius of the size distribution. The considered habits are the same as included in the parameterization by Key et al. (2002) and include droxtrals in addition. The models include besides extinction, single scattering albedo and asymmetry parameter the complete phase function (rather than only the Heney-Greenstein approximation), so that these models provide the best currently available input to calculate radiances accurately.

8 Aerosol optical properties

As mentioned in section 6, HITRAN and GEISA provide databases for aerosols. Both include refractive indices of various aerosol type. GEISA provides in addition optical properties databases (OPAC, GADS and LITMS).

8.1 OPAC

OPAC (Hess et al., 1998) is a software package which contains the optical properties in the solar and terrestrial spectral range of atmospheric particles, i.e. water droplets, aerosol and ice crystals.

Aerosol in the atmosphere is assumed to be a mixture of different components. This mixture can be achieved with data given by the user or by the use of typical mixtures, called aerosol types, which are provided in OPAC. Multiplying the stored data with realistic number densities, either user-defined of pre-defined in OPAC, gives absolute optical properties. Moreover, the height distribution of the particles can be varied. For those aerosol components, which are assumed to change their size with relative humidity, values for humidity classes are given. The data are provided for 61 wavelengths between 0.3 μm and 40 μm and for 8 relative humidities.

8.2 GADS

The Global Aerosol Data Set (GADS) (Koepke et al., 1997) is a completely revised version of the aerosol climatology by D'Almeida et al. (1991).

Aerosols are modeled as 10 components which are described by respective size distributions and spectral refractive indices. From these data the optical properties are calculated with Mie-theory at wavelengths between 0.25 μm and 40 μm and for 8 values of relative humidity.

The properties of the aerosol components themselves are available in the software package OPAC. For the entire globe, on a grid of 5 degrees longitude and latitude, with 7 differentiating height profiles, and both for summer and winter, the aerosol at the gridpoints is composed of these aerosol components.

The GADS data set consists of aerosol properties averaged in space and time and therefore is mainly determined for use in climate modelling.

8.3 The Amsterdam Light Scattering Database

In recent years a considerable amount of experimental single scattering matrices as functions of the scattering angle have been obtained with the light scattering facility in Amsterdam, for samples of randomly oriented small mineral particles in air (aerosol particles) with broad ranges of sizes and shapes. From these data, it has become clear that particle shape is highly important in determining the overall light scattering behavior of these samples.

The database (Volten et al., 2001) contains the following data for several samples of mineral aerosol particles in random orientation:

- Tables of scattering matrix elements as functions of the scattering angle from at most 3 to 174 degrees at two wavelengths, 441.6 nm and 632.8 nm.
- Tables of size distributions as measured with a laser diffraction method.
- Scanning Electron Microscope (SEM) images of the particles that are indicative of their shape characteristics.
- Information about the origin, color, composition and/or the complex refractive index of the samples, when available.

Information on the accuracy of the data is provided, whenever possible.

8.4 IOPA

The report by Santer et al. (2007) summarizes an ESA study about aerosol optical properties. Look-up tables of aerosol optical properties (including phase functions) have been generated based on (polarized) sky radiance measurements from the surface by the CIMEL instrument. These lookup-tables will be used to retrieve aerosol optical properties from MERIS measurements.

9 Surface properties (BRDF and spectral albedo)

9.1 MODIS surface products

From MODIS measurements spectral albedo as well as BRDFs are derived. The global data products are described at `http://edcdaac.usgs.gov/modis/mod43c1v4.asp`. The 1-km global albedo is computed by integrating the Bi-directional Reflectance Distribution Function (BRDF), which describes the characteristic anisotropy of the land surface. The MODIS BRDF parameters (MOD43B1) are the best fit model weights determined by inverting the multi-date, multi-angular, cloud-free, atmospherically corrected surface reflectance observations acquired by MODIS over a 16-day period.

The data is available at the NASA Earth Observing System Data Gateway (`http://delenn.gsfc.nasa.gov/~imswww/pub/imswelcome`).

9.2 Global land cover maps

The U.S. Geological Survey (USGS), the University of Nebraska-Lincoln (UNL), and the European Commission's Joint Research Centre (JRC) have generated a 1-km resolution global land cover characteristics data base for use in a wide range of environmental research and modeling applications. The global land cover characteristics database was developed on a continent-by-continent basis. All continental databases are based on 1-km Advanced Very High Resolution Radiometer (AVHRR) data. There are seven global data sets, each representing a different landscape based on a particular classification legend.

Two versions of the Global Land Cover Chacteristics database are available. The first version (Version 1.2) was released to the public in November, 1997. A revised version (Version 2.0) includes updates and addititional classifications for vegetation surfaces has..

The databases are available from the website http://edcsns17.cr.usgs.gov/glcc/.

9.3 POSTEL - Land Surface Thematic Center

POSTEL is a thematic center to describe the soil and vegetation from Earth Observation satellite data, at regional and global scales. It is supported by several French national public institutions.

The role of POSTEL is to transform images acquired by remote sensing Earth observation satellites in spatialized data describing soil and vegetation properties. This data includes for example the land cover classification, the spectral surface albedo, the surface temperature, and the bidirectional reflection functions (BRDF). The data is free of charge for scientific use and can be obtained at http://postel.mediasfrance.org/en/BIOGEOPHYSICAL-PRODUCTS/.

The space-borne POLDER-1/ADEOS-1 instrument (operated from November 1996 to June 1997) has provided the first opportunity to sample the BRDF of every point on Earth for viewing angles up to 60°-70°, and for the full azimuth range, at a spatial resolution of about 6km, when the atmospheric conditions are favorable (Hautecœur and Leroy, 1998). From April to October 2003, the land surface BRDF was sampled by the POLDER-2/ADEOS-2 sensor. From March 2005, the POLDER-3 sensor onboard the PARASOL microsatellite measures the bidirectional reflectance of the continental ecosystems. The BRDF data measured from all POLDER instruments are available from the website http://postel.mediasfrance.org/en/BIOGEOPHYSICAL-PRODUCTS/BRDF/. There are three databases for the three instruments, the database for POLDER-3 includes BRDFs for a full year.

9.4 UW-Madison Baseline Fit Emissivity Database

This global database includes infrared land surface emissivities. It is derived using input from the Moderate Resolution Imaging Spectroradiometer (MODIS) operational land surface emissivity product (MOD11). The baseline fit method, based on a conceptual model developed from laboratory measurements of surface emissivity, is applied to fill in the spectral gaps between the six emissivity wavelengths available in MOD11. The six available MOD11 wavelengths

span only three spectral regions (3.8-4, 8.6, and 11-12 microns), while the retrievals of atmospheric temperature and moisture from satellite IR sounder radiances require surface emissivity at higher spectral resolution.

The data can be obtained from http://cimss.ssec.wisc.edu/iremis/ after registration.

9.5 BRDF parameterizations for land surfaces

Rather simple parameterizations of BRDF's for land surfaces have been derived by Rahman et al. (1993) and Wanner et al. (1997). The latter is used for the BRDF retrieval from MODIS data. It is derived using the kernel-driven semi-empirical Ambrals BRDF model, utilizing five variants of kernel functions characterizing isotropic, volume and surface scattering.

9.6 BRDF parameterizations for the ocean surface

Almost a half century ago, Cox and Munk (1954a,b) derived the probability distribution of surface slope from aerial photographs of the sun's glitter on the sea surface. Their relationship between variance of the surface slope and wind speed has been widely used to model the optical properties of the sea surface. Their results were deduced from a very limited number of photographs taken under selected conditions. The BRDF derived by Cox and Munk permits an excellent fit of POLDER observations (Bréon and Henriot, 2006). Based on Cox and Munk (1954a,b), Nakajima and Tanaka (1983) derived a BRDF parameterization that is now widely used in the radiative transfer community. Ebuchi and Kizu (2002) derived the probability distribution of the sea surface slope using sun glitter images derived from the visible wavelength radiometer on the Geostationary Meteorological Satellite (GMS) and surface vector winds observed by spaceborne scatterometers. The surface slope shows a narrower distribution and much less directivity relative to the wind direction than that reported by Cox and Munk.

9.7 RAdiation transfer Model Intercomparison (RAMI)

BRDFs can be simulated using radiative transfer models. Such models are compared in the RAMI intercomparison experiments (http://rami-benchmark.jrc.it/). The goal RAMI is to provide a basis for comparing a large variety of computer codes that model the radiation fields typically encountered in remote sensing. Of particular interest are the radiance distributions of solar radiation reflected from vegetation canopies, as well as the corresponding inverse problem of deriving biogeophysical canopy parameters from remotely sensed radiances.

10 Extraterrestrial solar irradiance

10.1 Solar spectrum spectrum by Kurucz

The Kurucz solar source function Kurucz and Bell. (1995) is widely used in radiative transfer modelling. It is based on theoretical radiative transfer calculations for the solar atmosphere. The solar source function is available is at a high spectral resolution (i.e. for monochromatic calculations) and at 1 cm^{-1} resolution.

10.2 Solar spectrum spectrum by Thuillier

A recent publication by Thuillier et al. (2003) describes the solar spectral irradiance from 200 to 2400 nm as measured by the SOLSPEC spectrometers from the ATLAS and the EURECA missions. The publication provides references to extraterrestrial solar irradiance data. It uses the Kurucz and Bell. (1995) spectrum for comparison. The spectra agree within the expected measurement accuracy.

In the UV wavelength range the ATLAS-3 solar spectrum has been established (Mayer et al., 1997). Homogenized spectra have been compiled by Bernhard et al. (2004) for the UV/Vis wavelength ranges and by Gueymard (2003) for the UV/Vis/NIR/TIR wavelength ranges.

10.3 Air Mass Zero solar spectral irradiance

In 2000, the American Society for Testing and Materials developed a reference spectrum (ASTM E-490) for use by the aerospace community. That ASTM E490 Air Mass Zero solar spectral irradiance is based on data from satellites, space shuttle missions, high-altitude aircraft, rocket soundings, ground-based solar telescopes, and modeled spectral irradiance. The integrated spectral irradiance has been made to conform to the value of the solar constant accepted by the space community; which is 1366.1 W/m2.

In the 0.1195 to 0.41 μm range, the values are averages of two different instruments on the Upper Atmosphere Research Satellite (UARS), the Solar Ultraviolet Spectral Irradiance Monitor (SUSIM) and the SOLar STellar Irradiance Comparison Experiment (SOLSTICE), reported by Woods et al. (1996). These data were obtained in April 1993 during a period of moderate solar activity, and were scaled by a factor of 0.96843 to match the Neckel and Labs (1984) data over the 0.33 to 0.41 μm range. In the 0.41 to 0.825 μm range, the values are from the McMath Solar Telescope at Kitt Peak, Arizona, as reported by (Neckel and Labs, 1984). In the 0.825 to 4.0 μm range, the values are from the high-resolution solar atlas computed by Kurucz (1993). These data were smoothed to 2-and 20-nm wavelength resolution and scaled by a factor of 1.00085 to match the Neckel and Labs data at 0.825 μm. In the 4.0 to 1000μm range, the values are from the logarithmic irradiance versus wavelength fits reported by (Smith and Gottlieb, 1974). These data were scaled by a factor of 0.99437 to match the Kurucz data at 4.0 μm. The composite spectral irradiance data were then scaled by a factor of 0.99745 to force the integrated total irradiance equal to the solar constant.

This and other extraterrestrial solar spectra can be ordered from the website http://rredc.nrel.gov/solar/spectra/am0/.

10.4 BASS2000 data archive

BASS2000 (Base de donnees Solaire Sol 2000) archives and distributes French groundbased solar observations provided by various instruments: the THEMIS telescop, the RadioHéliographe and Réseau Décamétrique of Nancay, the SpectroHéliographe of Meudon, the Coronographe of Pic du Mid. Data is available for scientific use from the website http://bass2000.obspm.fr/solar_spect.php.

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