Generic Radiative Transfer Model for the Earth’s Surface-Atmosphere System – ESAS-Light II: Towards a community tool

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Final report

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0 Introduction

Radiative transfer modeling plays a key role for remote sensing because it is central for the development and testing of inversion algorithms as well as for the design of new remote sensing instruments: Remote sensing of planetary atmospheres and surfaces uses radiation covering a wide range of wavelengths, coming either from the sun or from the atmosphere (passive remote sensing), or from an artificial radiation source (active remote sensing). Radiation is affected by interaction with the atmosphere and surface – the observed radiation therefore contains information about the atmosphere and surface which can be retrieved.

The libRadtran software package (Mayer and Kylling, 2005) is freely available at www.libradtran.org and covers the complete solar and thermal spectral range, concentrating but not necessarily restricting itself on the Earth’s specific requirements. One of the most relevant features of libRadtran is that it includes a selection of about ten different RT solvers, including the widely-used DISORT code by Stamnes et al. (1988), a fast two-stream code (Kylling et al., 1995), a polarization-dependent code (Evans and Stephens, 1991), and the fully three-dimensional Monte Carlo code for the physically correct tracing of photons in cloudy atmospheres, MYSTIC (Mayer, 2009; Mayer et al., 2010; Emde and Mayer, 2007; Emde et al., 2010a; Buras and Mayer, 2011; Emde et al., 2011).

In a preceding ESA study (ESASLight I, Emde et al. (2010b)) the libRadtran package was improved and extended based on the outcome of an initial phase of user requirement consolidation. In particular the following major points were addressed: The MYSTIC solver was extended by a module to take into account polarization (Emde et al., 2010a) and inelastic rotational Raman scattering was added by developing a new solver based on the discrete ordinate method (Kylling et al., 2010). Furthermore the handling of clouds, especially ice clouds with very strong forward scattering, has been improved. The simulation of aerosol was made more flexible, i.e. it is now possible for the user to define his own mixtures of basic aerosol types. Another major part of the ESASLight I study was to develop a prototype version of a graphical user interface (GUI). At the end of ESASLightI, several points for further improvements of libRadtran have been identified, most of them have been addressed in ESASLight II.

Of particular importance was the development of a new molecular absorption parameterization for the full spectral range from the UV to the TIR as an alternative to the already existing correlated-k distributions and the LOWTRAN band model. Such a parameterization has been newly developed. It is very flexible: it includes band models at different spectral resolutions and optimized parameters for various satellite instruments. In particular the simulation of satellite instruments is now very efficient and at the same time very accurate. Since the spectral response functions for a large number of currently operating and future remote sensing instruments are now included in libRadtran it is also very simple to setup the simulations.

The radiative transfer solvers for polarization and Raman scattering have been optimized with respect to computational speed.

The GUI has been improved, in particular it is now organized in a logical way, e.g. cloud properties may only be specified if a cloud is defined in the simulation. In order to achieve this improvement, the option names of libRadtran have been revised, which allows to sort them in a logical way. After the renaming, the documentation of libRadtran has been revised.
Finally a radiative transfer benchmark dataset has been established which may be used by other radiative transfer modelling groups to validate their codes.

1 Task 1 - New input options

1.1 Absorption parameterization

Accurate modeling of spectrally-integrated radiative quantities requires the radiative transfer problem to be solved at a very large number of wavelengths if the wavelength range is affected by molecular absorption lines. Different parameterizations have been developed that increase the computational speed of such modeling problems. The correlated-k approach is the most prominent general approach; the basic idea of the correlated-k approach is to sort the wavelength grid according to the molecular absorption coefficients such that radiances on the reordered wavelength grid are smooth and monotonic, so that the spectral integration requires much less wavelength grid points. The optimum ordering depends on pressure, temperature, and gas concentration. For example, the correlated-k parameterizations from Kato (Kato et al., 1999) and Fu (Fu and Liou, 1992) for wide spectral bands, and the parameterization from Kratz (Kratz, 1995) for AVHRR channels are available in the libRadtran radiative transfer package. A different approach is taken by LOWTRAN which uses a low-resolution band model for the molecular absorption; the molecular transmittance is approximated by exponential functions (Kneizys et al., 1996). LOWTRAN is included in libRadtran, where it is frequently used for pseudospectral calculations in spectral regions affected by molecular absorption, for example for calculating channel-integrated radiances of different satellite channels. However, recent comparisons of measured longwave downward fluxes in the atmospheric window around $\lambda=10\mu m$ with LOWTRAN calculations revealed some discrepancies, whereas line-by-line calculations using HITRAN2004 data showed much better agreement with the measurements (Wacker et al., 2009).

During the ESASLight II study we aimed at extending libRadtran by a parameterization which provides a higher accuracy and higher computational speed than LOWTRAN. To achieve this goal we selected an approach which is based on the methods presented by Buehler et al. (2010) and Buehler et al. (2011). A detailed description of our implementation, which we name “REP-WVL”, will be presented by Gasteiger et al. (2014). We summarize the methodology and the application of REPWVL in the following.

1.1.1 Methodology

The basic idea of the approach is that a spectrally-integrated radiative quantity $I_{\text{int}}$ can be approximated by weighted means of monochromatic radiative quantities $I(\lambda)$ at only a few so-
1.1 ABSORPTION PARAMETERIZATION

called “representative wavelengths” $\lambda_{\text{rep}}$:

$$I_{\text{int}} = \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} I(\lambda) R(\lambda) d\lambda \approx I_{\text{int,para}} = \Delta \lambda \sum_{i_{\text{rep}}=1}^{n_{\text{rep}}} I(\lambda_{i_{\text{rep}}}) w_{i_{\text{rep}}},$$

(1)

with

$$\Delta \lambda = \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} R(\lambda) d\lambda$$

$R(\lambda)$ is the spectral weighting function of the parameterized band or instrument channel from $\lambda_{\text{min}}$ to $\lambda_{\text{max}}$. $w_{i_{\text{rep}}}$ are the weights of the representative wavelengths $\lambda_{i_{\text{rep}}}$. We adopted this approach for the radiative transfer in Earth’s atmosphere with solar and terrestrial radiation source for spectral bands and for various satellite channels. We selected three different band widths for the band parameterizations: A coarse case with band widths of 15 cm$^{-1}$, a medium case with 5 cm$^{-1}$, and a fine case with 1 cm$^{-1}$. For solar radiation source we consider the range from $\lambda=395$nm to $\lambda=5 \mu$m, whereas we consider the range from $\lambda=2.5 \mu$m to $\lambda=100 \mu$m for terrestrial radiation source. The solar fine resolution band parameterization, for example, contains 23320 bands. Each of the bands, which are defined by $R(\lambda)=1$ within the band limits ($\lambda_{\text{min}}, \lambda_{\text{max}}$), is parameterized by a set of representative wavelengths $\lambda_{i_{\text{rep}}}$ with corresponding weights $w_{i_{\text{rep}}}$, as given by Eq. 1.

The representative wavelengths and weights for each band and channel have been selected using an optimization method which minimizes the deviation of the parameterization from the accurate spectrally-integrated radiances for a set of atmospheric states (“training data set”). This training data set needs to cover the variability of the Earth’s atmosphere because our aim was the generation of a parameterization that is applicable to any realistic terrestrial atmosphere. As a starting point, we selected the dataset of Garand et al. (2001): This data set consists of 42 molecular atmospheres, which are defined by profiles of temperature, pressure, and volume mixing ratios of various gases. An investigation of the variability between the 42 atmospheres revealed that the volume mixing ratio profiles of some gases do not provide the desired variability. To increase the variability of our data set we have created for each of the 42 atmospheres a second molecular atmosphere where we scaled the concentration of two randomly selected gases. Then we added cloud and aerosol layers to these 84 molecular atmospheres: For each molecular atmosphere, one clear sky case, 5 aerosol cases, 2 water cloud cases, and 2 ice cloud cases were considered. Thus, our training data set consists of 840 different atmospheres. The microphysical properties and the heights of the aerosol and cloud layers were randomly chosen from a wide parameter range.

After defining the atmospheric training data set, line-by-line calculations from $\lambda=395$nm to $\lambda=100$ $\mu$m with a frequency step of 250 MHz (at about 3 million wavelengths) were performed for the 840 atmospheres. The spectral molecular absorption coefficients for the 84 molecular atmospheres were calculated using the ARTS radiative transfer model (Eriksson et al., 2011), whereby line parameters of the HITRAN 2004 spectroscopic database (Rothman et al., 2005) and the MT_CKD continuum model, version 1.0 (Clough et al., 2005) were used by ARTS. Using the molecular absorption profiles from ARTS, the DISORT radiative transfer solver (Buras and Mayer, 2011) implemented in the libRadtran software package (Mayer and Kylling, 2005) was utilized to calculate line-by-line radiances of the 840 atmospheres at their top. The calculations were performed for solar radiation source, using the Kurucz (1992) solar spectrum, from
\[ \Delta_{\text{para}} = \sqrt{\frac{1}{N_{\text{rad}}} \sum_{i_{\text{rad}}=1}^{N_{\text{rad}}} \left( \frac{I_{\text{int},i_{\text{rad}}} - I_{\text{int},i_{\text{rad}}}^{\text{true}}}{I_{\text{int},i_{\text{rad}}}^{\text{true}}} \right)^2 } \]

over all \( N_{\text{rad}} \) spectral radiances is below 1%. The optimum weights \( w_{i_{\text{rep}}} \) for a given wavelength combination are always determined using a non-negative least squares routine. At each \( n_{\text{rep}} \), depending on the number of possible wavelength combinations, a systematic search or simulated annealing is applied for finding the optimum or a near-optimum wavelength combination. We briefly summarize the simulated annealing approach, which is described by Buehler et al. (2010) in detail: Simulated annealing starts with a random set of \( n_{\text{rep}} \) wavelengths (‘initial state’ \( S_0 \)) and an ‘initial temperature’ (\( T_0 \)). The algorithm iteratively replaces one randomly chosen wavelength by another random wavelength (‘new state’ \( S' \), with \( S \) being the previous state). The probability of acceptance of \( S' \) decreases with increasing \( \Delta_{\text{para}}(S') - \Delta_{\text{para}}(S) \) and decreasing temperature \( T \) if \( \Delta_{\text{para}}(S') \geq \Delta_{\text{para}}(S) \); the new state \( S' \) is always accepted if \( \Delta_{\text{para}}(S') < \Delta_{\text{para}}(S) \). The initial temperature \( T_0 \) is high so that the algorithm does not get stuck in local minima too quickly. The temperature \( T \) is gradually reduced during the annealing procedure so that the set of wavelengths gets more and more forced towards low \( \Delta_{\text{para}} \). We increased the temperature reduction factor (compared to Buehler et al. (2010)) from 0.9 to 0.99 for our calculations, in order to reduce the likelihood that the simulated annealing procedure gets stuck too early in a local minimum of \( \Delta_{\text{para}} \).

For being applicable to radiative transfer problems, the parameterization requires information on the absorption cross sections \( C_{\text{abs}} \) of the molecules at the representative wavelengths. Therefore, we supplemented the parameterization with lookup tables of \( C_{\text{abs}} \) on a grid of pressures.
temperatures, and gas concentrations. The lookup table approach is described by Buehler et al. (2011), whereby we used an optimized grid of pressures, temperatures, and gas concentrations. We provide one lookup table for each species, and within the tables only wavelengths with absorption are considered in order to save disk space.

1.1.2 Band parameterization

The black curve in Figure 2 shows average relative errors $\Delta_{\text{para}}$ of the thermal coarse resolution band parameterization in percent as function of wavelength (band). The horizontal axis is linear in terms of $1/\lambda$ so that all $15\text{cm}^{-1}$ wide bands are equidistant. As mentioned above, $\Delta_{\text{para}} < 1\%$ was allowed during the parameterization creation. $\Delta_{\text{para}}$ is typically only slightly smaller than 1% for thermal bands. The figure also shows (in red) the number of representative wavelengths $n_{\text{rep}}$ for each band. Its maximum value is 9 with an average of 3.88 $n_{\text{rep}}$ per band.

The band parameterizations are invoked by the uvspec input option `mol_abs_param repwvl`. By default, the coarse band resolution is used. The specific band resolutions (here: fine) may be selected by `mol_abs_param repwvl fine`. The wavelength range may be reduced with the `wavelength` option.

Figure 3 shows deviations of brightness temperatures between different methods (representative wavelength parameterization (REPWVL), exact line-by-line calculations (LBL), LOWTRAN parameterization) for the thermal coarse resolution bands applied to the US standard atmosphere which was not part of the training data set. The LBL calculations shown here have been performed with a spectral resolution of 180 per cm$^{-1}$ and the LOWTRAN calculations with 10 per cm$^{-1}$. Note that the values shown in green have been scaled by a factor of 0.1. The red curve illustrates that the error of REPWVL for thermal bands reaches maximum values of about 1K for a few bands, but is generally on the order of 0.1K. The comparison with the green line reveals that the error of LOWTRAN is on average about one order of magnitude larger than the error of REPWVL.

Figure 2: Average relative error $\Delta_{\text{para}}$ of bands (black) for training data set and number of representative wavelengths $n_{\text{rep}}$ per band (red) for thermal coarse resolution band parameterization.
Figure 3: Deviations of brightness temperatures of upward fluxes at top of US standard atmosphere between the different approaches; ground albedo is set to 0.0.

Table 1: Number of representative wavelengths $n_{rep}$ for MSG3 channels.

<table>
<thead>
<tr>
<th>source</th>
<th>solar</th>
<th>thermal</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_{center} [\mu m]$</td>
<td>0.6</td>
<td>1.6</td>
</tr>
<tr>
<td>$n_{rep}$</td>
<td>2</td>
<td>5</td>
</tr>
</tbody>
</table>

1.1.3 Satellite channel parameterization

Table 1 shows, as an example for the satellite channel parameterizations, the number of representative wavelengths $n_{rep}$ required for the channels of the Spinning enhanced visible and infrared imager on a Meteosat Second Generation (MSG) satellite. The maximum $n_{rep}=11$ is required for the channel centered at $\lambda = 3.9 \mu m$ when considering solar radiation, but most $n_{rep}$ are in the range from 2 to 5. The average value of $n_{rep}$ over all satellite channel parameterizations (see list in Sect. 1.2) is only 2.3. The low number of radiative transfer calculations required to simulate satellite channel radiances results in a very low computational time for the REPWVL channel parameterizations.

For example, a uvspec simulation of top of atmosphere radiances of the 3.9 $\mu m$ channel using the REPWVL parameterization, the DISORT solver, and thermal radiation source takes 0.105 seconds on a PC, whereas it takes 9.1 seconds on the same PC if LOWTRAN with a spectral resolution of 5cm$^{-1}$ is used instead (both computation times are for complete uvspec runs, including initialization etc.). A further benefit of the REPWVL parameterization is that
1.2 Predefined setups for remote sensing instruments

Simulations of satellite radiometer measurements require knowledge about the spectral response functions of the radiometer channels. During ESASLight II response functions of more than 370 satellite channels have been collected and converted to a format readable by libRadtran. ADEOS-POLDER, ALOS-AVNIR, ALOS-PRISM, EARTHCARE-BBR, EARTHCARE-MSI, ENVISAT-AATSR, ENVISAT-MERIS, ERS-ATSR, LANDSAT-MSS, LANDSAT-TM, LANDSAT-ETM, MSG-SEVIRI, PARASOL, PROBA-CHRIS, SENTINEL-OLCI, SENTINEL-SLSTR, SEOSAT, SPOT-HRV, SPOT-HRVR, SPOT-VEGETATION, and SPOT-HRG channels have been added to libRadtran together with REPWVL parameterizations specifically optimized for these channels. As shown in Sect. 1.1, the channel parameterizations are activated quite easily and require very little computational time because on average only 2.3 monochromatic calculations are required for modeling channel integrals.

<table>
<thead>
<tr>
<th>channel</th>
<th>REPWVL - LBL</th>
<th>REPWVL - LOWTRAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>msg3_seviri_ch039</td>
<td>0.12K (0.48K)</td>
<td>0.52K (2.09K)</td>
</tr>
<tr>
<td>msg3_seviri_ch062</td>
<td>0.24K (0.74K)</td>
<td>0.62K (0.97K)</td>
</tr>
<tr>
<td>msg3_seviri_ch073</td>
<td>0.17K (0.42K)</td>
<td>1.92K (3.12K)</td>
</tr>
<tr>
<td>msg3_seviri_ch087</td>
<td>0.16K (0.61K)</td>
<td>0.41K (1.58K)</td>
</tr>
<tr>
<td>msg3_seviri_ch097</td>
<td>0.33K (1.04K)</td>
<td>2.26K (8.31K)</td>
</tr>
<tr>
<td>msg3_seviri_ch108</td>
<td>0.12K (0.29K)</td>
<td>0.40K (1.11K)</td>
</tr>
<tr>
<td>msg3_seviri_ch120</td>
<td>0.13K (0.53K)</td>
<td>0.49K (1.45K)</td>
</tr>
<tr>
<td>msg3_seviri_ch134</td>
<td>0.41K (1.37K)</td>
<td>3.90K (6.16K)</td>
</tr>
</tbody>
</table>

Table 2: Root mean squared deviations (maximum) for brightness temperatures of radiances within thermal satellite channels, averaged over different viewing angles and atmospheres; the ground albedo is set to 0.0.

It is easily activated by a single uvspec input option (e.g. mol_abs_param repwvl_channel msg3_seviri_ch039), whereas a combination of four input options (mol_abs_param lowtran, wavelength_grid_file, wavelength, filter_function_file) is required to use LOWTRAN for channel simulations.

Tab. 2 shows mean and maximum deviations of brightness temperatures of radiances modeled for the MSG3 channels. The deviations between the different methods are given in this table. The deviations were averaged over 12 atmospheres (6 standard atmospheres from Anderson et al. (1986) and 6 atmospheres from Chevallier et al. (2006)) and 10 viewing directions for each atmosphere. The maximum deviations are given in parentheses. The mean deviations of REPWVL from exact LBL are in the range from 0.12K to 0.41K, depending on the channel, with a maximum deviation of 1.37K found for the 13.4\(\mu\)m channel. The deviations from LOWTRAN are always larger (by up to a factor of 11) than the deviations from LBL, which shows that the newly implemented REPWVL parameterization approach provides a higher accuracy than LOWTRAN.
### Table 3: Space-borne measurements of spectral solar irradiance on a broad spectral range. Resolution and accuracy refer to $\lambda = 500$ nm.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Mission</th>
<th>Operation</th>
<th>Range</th>
<th>Resolution / Accuracy</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCIAMACHY</td>
<td>ENVISAT</td>
<td>2002-</td>
<td>240-2380 nm</td>
<td>0.5 nm / 2-3% (with gaps in the IR)</td>
<td>Skupin et al. (2005)</td>
</tr>
<tr>
<td>SIM</td>
<td>SORCE</td>
<td>2003-</td>
<td>200-2400 nm</td>
<td>10 nm / 2% (8% in IR)</td>
<td>Harder et al. (2010)</td>
</tr>
<tr>
<td>SOLSPEC</td>
<td>SOLAR/ISS</td>
<td>2008-</td>
<td>165-3080 nm</td>
<td>1-2 nm / 1%</td>
<td>Thuillier et al. (2009)</td>
</tr>
</tbody>
</table>

#### 1.3 Extraterrestrial solar irradiance data

Sunlight provides the power for many processes on the Earth and in its atmosphere. As the molecular absorption varies significantly with wavelength, exact knowledge on the spectral distribution of the sunlight reaching the Earth’s atmosphere at its top (’extraterrestrial irradiance’) is indispensable for exact simulations of the radiative transfer of sunlight through the atmosphere. In this context, it must be emphasized that the extraterrestrial irradiance is not constant with time; it varies for example with the solar activity cycle ($\approx 11$ years). A literature review on measured and modelled extraterrestrial irradiance data was performed during ESASLight II in order to find the best spectrum for inclusion in *libRadtran*.

Table 3 gives an overview of space-borne measurements of spectral solar irradiance that have been performed covering the range from ultraviolet to infrared. First space-borne measurements on a broad spectral range were performed using the SOLSPEC instrument during the ATLAS and EURECA missions (Thuillier et al., 2003); these spectra are already included in *libRadtran*. The spectra from these measurements are now generally accepted as the de-facto standard spectra with an uncertainty of about 3.5% to 4% (Harder et al., 2010). The SCIAMACHY spectrometer onboard the ENVISAT satellite measures spectra with a higher spectral resolution than SOLSPEC, however, with some spectral gaps in the infrared. Comparison of the spectra from SCIAMACHY and SOLSPEC showed agreement of channel-mean irradiances better than 5% (Skupin et al., 2005). The Spectral Irradiance Monitor (SIM) onboard the SORCE satellite was developed to provide high measurement precision and the ability to perform physically-based degradation corrections (Harder et al., 2010). The spectral resolution of SIM is lower than the spectral resolution of SCIAMACHY and SOLSPEC. The agreement of spectra from SIM and SOLSPEC in the range from the ultraviolet to the near-infrared is on the order of 2%; for $\lambda > 1350$ nm, however, the agreement is only about 8% because of less certain calibration of SIM at these wavelengths (Harder et al., 2010). The SOLSPEC instrument installed on the SOLAR payload, integrated on the International Space Station (ISS), is improved compared to...
### Table 4: Various extraterrestrial solar irradiance spectra, excluding those listed in Table 3. Resolution refers to $\lambda = 500$ nm.

<table>
<thead>
<tr>
<th>Name</th>
<th>Range</th>
<th>Resolution</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chance</td>
<td>200-1001 nm</td>
<td>0.04 nm</td>
<td>Chance and Kurucz (2010)</td>
</tr>
<tr>
<td>Kurucz</td>
<td>200-200000 nm</td>
<td>0.001 nm</td>
<td>Kurucz (1992)</td>
</tr>
<tr>
<td>Fontenla</td>
<td>0.12-100000 nm</td>
<td>0.0025 nm</td>
<td>Fontenla et al. (2011)</td>
</tr>
</tbody>
</table>

the original SOLSPEC instrument used during the ATLAS and EURECA missions, taking into account the lessons learnt from these missions (Thuillier et al., 2009); the data however is not available yet.

Table 4 provides an overview of various other solar spectra. The Chance extraterrestrial spectrum has been determined from ground- as well as balloon-based grating spectrometer measurements with a spectral resolution better than the space-borne measurements (see Tab. 3 for comparison). In general, however, measurements can not resolve the full spectral variability of the solar irradiance. To overcome this limitation models for the solar irradiance have been developed and validated by comparison with measurements. The spectrum from Kurucz (1992) uses a model of the solar atmosphere which considers, for example, turbulence and the rotation of the Sun, which are relevant for Doppler shifts of spectral lines. Line data of the atomic and molecular absorption/emission lines are utilized for the calculation of the spectrum. The spectral resolution of the Kurucz model is very high with 0.001 nm in the visible. This spectrum was already available in libRadtran with spectral resolutions of 0.1 nm and 1 nm. The full-resolution Kurucz spectrum has been added to libRadtran during ESASLight II. The spectrum by Fontenla et al. (2011) uses a semi-empirical physical model of the Sun and considers the variability of the spectrum with the solar cycle. However, the variability of the these extraterrestrial spectra due to the solar cycle is much smaller than the deviations from measured spectra.

The literature review is presented in more detail in Gasteiger et al. (2011). It is concluded that the full-resolution Kurucz solar spectrum best suits the requirements for high accuracy radiative transfer simulations and thus has been included in libRadtran. This spectrum is used as the extraterrestrial source in the representative wavelength parameterization (Sect. 1.1).
2 Task 2 - Improvement of RT solvers

2.1 Efficient radiative transfer solver including polarization

In the first ESAS-Light study it turned out that the accuracy of the polradtran solver is not sufficient, especially in case of strongly peaked phase functions. Polarization has been accurately included into the Monte Carlo solver MYSTIC. Monte Carlo methods are normally used for simulations in complex 3D geometries like inhomogeneous clouds or topography which is almost impossible using other methodologies for solving the radiative transfer equation. The drawback is usually that it is computationally expensive. By comparing computational times of MYSTIC and polradtran, we found that MYSTIC is even more efficient, especially when a new method called “Absorption Lines Importance Sampling” (ALIS, Emde et al., 2011) is applied.

The original implementation of ALIS was not flexible and not fully documented. For example it was only possible to use the method when a file including the molecular absorption optical thicknesses was provided. Moreover it was only applicable for narrow spectral ranges, because optical properties of clouds and aerosols were assumed to be constant. Also it did not work in combination with post-processing options, i.e. it could only output the normalized radiances and the user has to apply e.g. a filter function himself. During the project, the spectral dependence of aerosol and cloud optical properties has been included in ALIS, the only remaining assumption is that the scattering phase function is constant over the assumed spectral interval.

ALIS now works with all absorption parameterizations in libRadtran, in particular also with the new parameterization based on representative wavelengths (see Task 1). All post-processing options like calibration or filter functions can now be used in combination with ALIS.

As an example Fig 2.1 shows polarized simulations of calibrated radiances using ALIS in the O$_2$A band for clearsky (red), with aerosol (green) and with cloud (blue).

The original ALIS method has been developed for the solar spectral range. It has been extended to the thermal range and comparisons with DISORT have shown a very good agreement. Vector calculations in the thermal region have shown, that polarization is negligible here, at least when only randomly oriented particles are considered.

MYSTIC in 1D is very efficient, especially for the computation of high-spectral-resolution polarized radiance spectra as measured e.g. by SCIAMACHY. It has been shown in Task 6 (Emde et al., 2013) that, when only one measurement geometry is required it runs even faster than the SCIATRAN model. For one O$_2$A spectrum at one geometry SCIATRAN requires 29min 28s whereas MYSTIC requires 5min 50s with $1 \cdot 10^6$ photons corresponding to an accuracy better than 1%. If one is interested in differential optical thickness one can safely run less photons, because the statistical noise results in a bias which is subtracted by the polynomial fit. In this case $1 \cdot 10^5$ are sufficient and a spectrum can be calculated within less than one minute. If one wants to calculate several observation geometries, SCIATRAN may become faster, because it can calculate all geometries in parallel. The times given here correspond to calculations on a single processor (Intel Xeon 1.4 GHz).
Figure 4: Polarized radiance simulations of O$_2$A spectra using MYSTIC for clearsky (red), aerosol (green) and cloud (blue).
2.2 Speeding up the Raman scattering solver

For calculations including rotational Raman scattering the following discrete ordinate version of the radiative transfer equation is solved:

\[
\sum_{j=-1}^{j\neq 0} \frac{\omega_{d}^E}{2} \sum_{j=-1}^{j\neq 0} c_j \Pi_{d}^E(\tau_{\lambda_j}, \mu_i, \mu_j) I^m(\tau_{\lambda}, \mu_j) = I^m(\tau_{\lambda}, \mu_i) - \frac{\omega_{d}^E}{2} (2 - \delta_{0,m}) \Pi_{b}^E(\tau_{\lambda}, \mu_i, \mu_0) e^{-T(\tau_{\lambda})}
\]

\[
Q^m(\tau_{\lambda}, \mu_i) = \sum_{s=1}^{NS} \frac{\omega_{s}^E(\tau_{\lambda_s}) I^0_{\lambda_s}}{4\pi} (2 - \delta_{0,m}) \Pi_{b}^E(\tau_{\lambda_s}, \mu_i, \mu_0) e^{-T(\tau_{\lambda_s})} - \frac{\omega_{s}^E(\tau_{\lambda_s}) I^0_{\lambda_s}}{4\pi} (2 - \delta_{0,m}) \Pi_{b}^E(\tau_{\lambda_s}, \mu_i, \mu_0) e^{-T(\tau_{\lambda_s})}
\]

For derivation of Eq. 3 and definitions of symbols please see Kylling (2012b).

To account for single rotational Raman scattering at a given wavelength, radiation from \(NS = 233\) other wavelengths must be considered in the Earth’s atmosphere. That implies solving the radiative transfer equation 233 times in order to get the contribution from these 233 wavelengths. This “brute-force” approach is accurate, but computationally expensive. To speed up the calculations, the elastic radiation field (radiances at a given number of streams in all atmospheric layers) is calculated for a given (user-defined) wavelength grid. When calculating the source term in Eq. 4 the radiation field is interpolated to the wavelength of the individual Raman lines. The wavelength grid the radiation field is calculated on must be sufficiently fine to include all variations in scattering and absorption cross sections. As the wavelength grid is user defined the user may tune the wavelength grid to the specific applications and required accuracy.

The reduction in computing time will depend on the wavelength region being simulated. For a single wavelength around 400 nm and a wavelength grid with 0.05 nm resolution a factor 2 decrease in computation time is achieved. However, if a spectrum between 340-400 nm is simulated the computer time decrease by about a factor of 15-20.

The speeded-up Raman solver has been used to investigate the influence of rotational Raman scattering for the Carbon Monitoring Satellite (CarbonSat), Fluorescence Imaging Spectrometer (FLORIS, FLEX mission), Medium Resolution Imaging Spectrometer (MERIS) and the Ocean Land Colour Instrument (OLCI). Results for all sensor are presented by Kylling (2012a). Below
results for CarbonSat and FLORIS are summarized.

### 2.2.1 CarbonSat

The primary mission objective of CarbonSat is the “quantification and monitoring of CO$_2$ and CH$_4$ sources and sinks at the regional scale for i) a better understanding of the processes that control the Carbon Cycle dynamics and ii) an independent estimate of local greenhouse gas emissions (fossil fuel, geological CO$_2$ and CH$_4$, etc.) in the context of international treaties” (Buchwitz et al., 2010). To measure CO$_2$ and CH$_4$ knowledge about the O$_2$ column is required. This may be obtained by measuring in the strongly absorbing O$_2$-A band. At high spectral resolution, rotational Raman scattering effects may be present. These effects are quantified for CarbonSat below.

Buchwitz et al. (2010) presents O$_2$-A band simulations for worst, nominal and best atmospheric cases (their Table 6 and repeated in Table 5). For these cases top of the atmosphere (TOA) nadir radiances are simulated. The worst case is reproduced with the libRadtran/uvspec radiative transfer model in the upper plot of Fig. 5. It is noted that the nadir radiances presented by Buchwitz et al. (2010) in their Figs. 20, 25 and 29 have been scaled by $1/\cos(sza)$. Thus, the absolute values presented here and by Buchwitz et al. (2010) differs by factors of 1.0, 0.64 and 0.26 for the best, nominal and worst cases respectively. It is noted that the ambient atmosphere is not defined in Buchwitz et al. (2010). Here the US-standard atmosphere is used (Anderson et al., 1986). The O$_2$ absorption line structure was calculated by the ARTS-model (Eriksson et al., 2011). In addition to O$_2$-absorption, the H$_2$O continuum was included.

The uvspec simulations were made with a spectral resolution of 0.01 nm. The extra-terrestrial solar spectrum was taken from the revised high-resolution Kurucz solar spectrum (Kurucz, 1992; Fontenla et al., 1999) using the “Solar source function” of Clough et al. (2005). Following Chance and Spurr (1997) the spectrum was resampled at even 0.01 nm increments using a triangular filter with full-width at half-maximum (FWHM) of 0.01 nm. Depending on the case, RRS filling-in is in the order of 1-4 % and of largest magnitude within the O$_2$-A band, see lower plot, Fig. 5.

### 2.2.2 FLORIS/FLEX

The FLEX mission is devoted to monitor the photosynthetic activity of the terrestrial vegetation layer (Drusch and FLEX team, 2011). The natural fluorescence signal is weak compared to the reflected solar radiation. However, by measuring at wavelengths where the solar spectrum
is attenuated, for example the O$_2$-A and B bands, information about natural fluorescence may be retrieved (Ganter et al., 2010). The influence of fluorescence magnitude, surface pressure, aerosol optical depth, aerosol layer height and aerosol type on the TOA radiance, has been investigated by Ganter et al. (2010) for the O$_2$-A and B bands. Here, the effect of RRS is investigated for a case corresponding to the aerosol free case studied by Ganter et al. (2010). Aerosols generally will decrease the filling-in effect due to RRS.

The TOA nadir radiance in the spectral region covering the O$_2$-A and B bands, is shown in Fig. 6 at high spectral resolution, 0.01 nm (blue line), for a cloudless sky together with a 0.3 nm resolution (red line) calculation representative for the FLORIS instrument. The simulations included fluorescence as shown by the red line. The surface albedo is shown by the green line. The albedo and fluorescence spectra were taken from data generated by the FLUSS project, see also Miller et al. (2005), with the following parameters: Chlorophyll a and b 40; Stoichiometry 1; Fluorescence 0.02; Relative azimuth angle 40; Viewing zenith angle 41.4; Leaf area index 3; Soil-type code 2; Solar zenith angle 30.

The US-standard atmosphere model was adopted (Anderson et al., 1986). The ARTS-model
2.2 SPEEDING UP THE RAMAN SCATTERING SOLVER

Figure 6: The TOA nadir radiance at high, 0.01 nm (blue line), and coarser, 0.3 nm (magenta line), spectral resolution. The fluorescence spectrum, multiplied by a factor of 100, is shown in red while the surface albedo used for the simulation is shown by the green line. The solar zenith angle is $30^\circ$.

by Eriksson et al. (2011) was used to calculate high-resolution absorption optical depth profiles including $O_2$, $H_2O$, $CO_2$, $O_3$, CO and $CH_4$. Most of the absorption line structures are due to $H_2O$ except for the $O_2$-A and B bands.

Simulations were made with and without RRS and with and without fluorescence. The resulting spectra in the $O_2$-A and B bands are shown in upper plots of Figs. 7 and 8 respectively. The corresponding filling-in is shown in the lower plots. The fluorescence signal (Upper plots Figs. 7 and 8) is stronger in the $O_2$-B band than in the $O_2$-A band, see also Figs 2 and 3 in Guanter et al. (2010). The effect due to changes in fluorescence magnitude, surface pressure, aerosol optical depth, aerosol layer height and aerosol type as reported by Guanter et al. (2010), is about an order of magnitude larger than the filling-in caused by RRS.

The effect of RRS has also been calculated for MERIS and OLCI. Generally the effect of RRS decreases with decreasing spectral resolution. Also, the presence of clouds and aerosol decrease the impact of RRS. The importance of RRS will depend on the retrieval procedure adopted for the quantity to be measured. Retrieval procedures that utilize the full spectral resolution of CarbonSat and FLEX/FLORIS will most likely benefit from including RRS. Radiative transfer models may calculate the impact of RRS for these instruments. Thus, corrections for RRS may readily be included in the retrieval and potentially reduce the uncertainty in the retrieved quantity. It is noted that for high-resolution CarbonSat measurements over the ocean, vibrational Raman scattering may have an additional filling-in effect.
Figure 7: Upper plot: The TOA radiance in the O$_2$-A band at various spectral resolutions with and without fluorescence. Lower plot: The filling-in due to RRS at various spectral resolutions with and without fluorescence.
2.2 Speeding up the Raman scattering solver

Figure 8: Upper plot: The TOA radiance in the O$_2$-B band at various spectral resolutions with and without fluorescence. Lower plot: The filling-in due to RRS at various spectral resolutions with and without fluorescence.
3 Task 3 - Improvement of user friendliness

3.1 General improvements

The main objective of this task was to clean up the source code in \textit{libRadtran}, which has been growing significantly during the last years. Although much of this, such as commenting the source code and introducing a compliant programming style, is only of importance for code developers, the restructuring also led to significant improvements for the users:

First, the internal cloud structure was generalized. Hitherto, the user could only define a molecular atmosphere, one-dimensional aerosol profiles, and at most two types of three-dimensional atmospheric constituents such as clouds or aerosols. With the generalization, it has now become possible to add an arbitrary number of three-dimensional constituents, e.g. a 3D distribution for each size bin of an aerosol type. To this end, the new options \texttt{profile\_file} and \texttt{profile\_properties} were implemented, which are used in analogy to \texttt{wc\_file} and \texttt{wc\_properties}.

Second, the memory consumption of \textsc{uvspec} has been streamlined by deallocating unused memory and by allocating only variables which are needed for the current simulation. This reduces memory requirements by up to a factor of 3.

Third, and most important, the naming of the input options has been completely restructured: The number of options had lately increased to more than 300, but without any logic behind the naming of the options. By introducing a consistent nomenclature and deleting obsolete and redundant option names, we could reduce the number to less than 150. The new names are also largely self-explanatory. This improvement was also performed to facilitate implementation into the GUI (see below).

In order to guarantee backward compatibility, a script was written which translates old-style input files to the new nomenclature. The execution of the script is simply done by writing \texttt{python src\_py/translate.py oldinputfile.inp > newinputfile.inp}.

The second objective of this task was to investigate on alternative solutions to simplify the installation procedure of \textit{libRadtran}. A simple solution which was realized during the project is to provide a compiled version of \textit{libRadtran} within a virtual machine. The user only has to install the VirtualBox software (available at VirtualBox.org) on his or her computer and load the virtual machine into it. The \textit{libRadtran} version contained in the virtual machine is fully functional. Merely for large scale simulations with computation times on the scale of days or more and if large memory footprints (>2GB) are needed for the simulations do we recommend to install \textit{libRadtran} on a real machine as usual. The virtual machine is available on the ESASLight II wiki download page.

3.2 Graphical User Interface (GUI)

During the ESASLight I study a first version of a Graphical User Interface (GUI) was developed for the \textsc{uvspec} tool. Several possible improvements to the GUI were identified during ESASLight I and have been included during EASLight II. These include:
3.2 Graphical User Interface (GUI)

- Improved formatting of the help functionality for the options.
- Conditional selection of input options.
- Improved plotting capabilities by using matplotlib (matplotlib.org). Furthermore, plotting of input options has been included.
- Sample input files for various satellite instruments have been added as examples to the GUI.
- A feature has been included to allow users to add their own examples.
- The capability to run all solvers has been added. In addition an ongoing run may be interrupted by a “cancel” button.

A screenshot of the GUI for a FLEX/FLORIS simulation, including plots of input and output data, is given in Fig. 9. In order to incorporate the new input structure of uvspec, the GUI was redesigned both internally and visually. The structure of the input options are now directly reflected in the various input option groups of the GUI.

In addition to the improvements identified during ESASLight I, the following changes have been made to the GUI:

- The invocation of the GUI does no longer depend on location. Thus, it is no longer necessary to go to the GUI folder to start the GUI.
• Activated options are now printed in bold letters and documentation is available when clicking on the option name.

• The “General” page of the GUI has been updated.

• The examples in the GUI have been sorted such that they will appear in the same order on any machine.

### 4 Task 4 - Outreach and Training

A workshop at ESTEC will take place on 30/31 October 2013. On the first day there will be presentations about *libRadtran* in general and the ESASLight projects. Also basic instructions on the usage of *libRadtran* will be given. On the second day the users will get practical tasks to be solved using libradtran. The tasks focus on satellite applications. On the afternoon users may alternatively work on their specific applications together with a *libRadtran* developer.
5  Task 5 - RT reference dataset

Radiative transfer simulations are required for all different kinds of remote sensing techniques, e.g. atmospheric, land, and ocean remote sensing. In the scientific community a large number of radiative transfer models have been developed, most of them for specific applications. Radiative transfer models are required as forward models for inversion algorithms, which requires that the models are very efficient with respect to computational time. To fulfill this requirement various approximations are made in order to simplify the radiative transfer problem. The consequence is that at ESA different tools are used for different space missions in order to generate L2 products. Even for the same mission where the L1 data is exactly the same the L2 data products can be based on different radiative transfer models which makes it difficult to compare the L2 products.

In this task a reference dataset for radiative transfer simulations has been generated that should serve as a benchmark against which radiative transfer models used to generate L2 products can be compared. Various simulation setups have been defined with focus on applications for satellite remote sensing. The cases are of different complexity, e.g. with and without polarization.

<table>
<thead>
<tr>
<th>Parameters for calculations, all combinations with and without polarization</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Viewing angle range</strong></td>
</tr>
<tr>
<td><strong>Solar zenith angles</strong></td>
</tr>
<tr>
<td><strong>Solar azimuth angles</strong></td>
</tr>
<tr>
<td><strong>Surface albedos</strong></td>
</tr>
<tr>
<td><strong>Monochromatic cases, wavelengths</strong></td>
</tr>
<tr>
<td><strong>Case A</strong></td>
</tr>
<tr>
<td><strong>Case B</strong></td>
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<tr>
<td><strong>Case C</strong></td>
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<tr>
<td><strong>High spectral resolution, O$_2$A-band</strong></td>
</tr>
</tbody>
</table>

Table 6: Test cases for solar spectral region.

For validation the radiative transfer calculations in the solar spectral region (UV/Vis/NIR) have been compared to the SCIATRAN model (Rozanov et al., 2005) which is used at the University of Bremen as the forward model for retrievals of trace gases, aerosols, and cloud properties from SCIAMACHY measurements. The test cases for the solar spectral region are summarized in table 6. An excellent agreement between the models was found, the agreement between DISORT and SCIATRAN for calculations including Rayleigh scattering and absorption is better than 0.01%. For polarized calculations the Monte Carlo solver MYSTIC has been compared against SCIATRAN. Here the difference between the models was within the noise of the Monte Carlo simulations. Fig. 10 shows an example case, where polarized high spectral resolution measurements in the O2A band are simulated. The relative difference between the models is here well below 1%. The SCIATRAN results are provided as benchmark data, because the
radiative transfer solver is analytical and the results can be reproduced exactly.

Figure 10: \( \text{O}_2 \)A spectra calculated with MYSTIC (‘-’) and SCIATRAN (‘–’) for a viewing angle of 60° and a relative azimuth angle of 150°. Colors correspond to different solar zenith angles.
Figure 11: Relative difference between MYSTIC and SCIATRAN for the spectra shown in Fig. 10.
### Line-by-line calculations in three spectral bands

| Case A | 6190–6210 nm, strong water vapor absorption |
| Case B | 9995–10005 nm, window region, many narrow absorption lines |
| Case C | 10795–10805 nm, window region, few absorption lines |
| General: | surface emissivities 1.0, 0.8, and 0.5 |
| | viewing angles from nadir to limb in 1° steps |

Table 7: Test cases for thermal spectral region.

Results for the thermal spectral region have been compared to the radiative transfer models KOPRA (Stiller, 2000) and to ARTS (Buehler et al., 2005; Eriksson et al., 2011). The KOPRA model is the forward model used mainly for trace gas retrievals from MIPAS at the Karlsruhe Institute of Technology. ARTS is used as forward model for trace gas retrievals from measurements in the microwave/sub-mm and in the infrared spectral regions (e.g. AMSU-B, ODIN, HIRS) and is mainly developed at the Luleå Technical University in Kiruna and at the Chalmers Institute of Technology in Gothenburg. The test cases for the thermal range are listed in table 7. The model intercomparison has shown that there are large uncertainties due to vertical interpolation schemes of the model and due to different water vapor continuum models, especially in spectral regions where water vapor absorption is high. An example case is shown in Fig. 12, where nadir spectra for a region with high water vapor absorption are calculated. The surface has no impact on the radiances since it is not seen due to the high absorption in the lower model levels. The difference between DISORT and ARTS is only due to a different vertical interpolation scheme, since both models use the same absorption optical thickness as input for the radiative transfer simulation. KOPRA uses a different water vapor continuum model, therefore the difference between KOPRA and DISORT is larger. The non-negligible differences between the radiative transfer models can be well explained and is difficult to decide which setup is the best result to be provided as benchmark. Therefore we provide the data of all three models.

In order to make the reference dataset useful for the scientific community a webpage has been created (http://www.meteo.physik.uni-muenchen.de/~esaslight2/doku.php?id=task5:task5). The webpage includes detailed information about the simulation setups and the benchmark results as well as plots showing the results of the model intercomparisons.
Figure 12: The top panel shows nadir spectra calculated with DISORT ('-'), ARTS ('--'), and KOPRA ('-'). The middle and bottom panels show relative differences with respect to DISORT.
6 Task 6 - Conclusions and recommendations

The long term objective of the ESASLight project is to give actors in the field of remote sensing of planetary environments full access to a user friendly, open source, well documented and free of charge radiative transfer toolbox. With the libRadtran toolbox this objective is already met, but of course such a toolbox is never complete. New measurement techniques require new forward modelling capabilities. Ideas of what could be implemented in a future ESASLight study are listed in the recommendation report (Gasteiger et al., 2013). In the following, some of the ideas are summarized.

A great improvement regarding the modeling of radiative transfer through ice clouds would be to include oriented ice crystals. So far, libRadtran can only handle randomly oriented particles, which means that several halo features, e.g. the sun dogs, can not be simulated. This also has an impact on radiance measurements from satellite, especially when they are polarization dependent. Also the modeling of aerosols could greatly be improved by including more aspherical aerosol types, which are much more realistic than spherical particles.

MYSTIC is a fully 3D radiative transfer code, however so far it only takes 3D cloud fields as input. For molecules and aerosols horizontally homogeneous profiles are assumed. In particular when larger areas are simulated, e.g. MSG-SEVIRI images, this is not realistic, because e.g. the water vapor field is very inhomogenous as one can see in the satellite images. So it would be desirable to include 3D fields of molecules and aerosols in MYSTIC.

Raman scattering could also be simulated more realistically if included in MYSTIC, because one could study 3D effects on rotational Raman scattering and also it would be possible to consider multiple Raman scattering.

Currently polarized ground reflection is only implemented for the ocean surface. Bidirectional reflectance matrix parameterizations for various land surfaces should be included in libRadtran in the near future.

libRadtran has been designed as a modular toolbox and hopefully many extensions will be included in the future. In order to make sure that the introduction of a new option has no side effects it is important to have a verification tool that is always used when new code is added to the package. For this reason it is absolutely necessary to develop an extensive testsuite.

7 Summary

The overarching objective of ESASLight II was to provide a radiative transfer toolbox for the Earth observation remote sensing community which can be used for forward simulations of the Earth surface-atmosphere system. In order to meet this objective the functionalities of the libRadtran toolbox have been extended and improved.

A new molecular absorption parameterization for the full spectral range from the UV to the TIR has been developed and implemented in libRadtran. It is based on the most recent absorption coefficients and replaces the LOWTRAN band model which dates back to the 1970s. The parameterization uses simulated annealing to find representative wavelengths for a given spectral
A weighted mean of the radiances at these wavelengths yields the integrated radiance. Using this approach band models at different resolution have been developed. In order to simulate remote sensing instruments it is even more efficient to find the representative wavelengths for the individual channels. This has been done for various remote sensing instruments. The new parameterization is efficient and at the same time very accurate, this has been shown in an extensive validation, where we compared against detailed line-by-line calculations.

In order to simplify the setup of simulations for remote sensing instruments, we collected spectral response functions of more than 370 satellite channels and converted them to a format readable by *libRadtran*. For all these channels the new absorption parameterization is available.

A literature review about extraterrestrial solar spectra has been conducted. The conclusion was that the full resolution spectrum by Kurucz is the best for high accuracy radiative transfer simulations, therefore it has been included in *libRadtran*.

During the ESASLight I study it turned out that the 1D solver polradtran is not accurate for simulations including aerosols and clouds. Therefore another fast solver for polarized radiative transfer simulations was requested. We found that for polarized calculations MYSTIC is a very efficient solver, especially when the “Absorption Lines Importance Sampling” method, which has been fully implemented within the project, is applied. This method allows to calculate all required wavelengths in parallel, thus it is extremely efficient for high spectral resolution computations. We have shown that it is even faster than 1D discrete ordinate solvers, thus we concluded, that we do not need another 1D solver including polarization.

The efficiency of Raman scattering solver has been improved. For a single rotational Raman scattering at a given wavelength, 233 other wavelengths must be calculated in order to get the contribution from these wavelengths. In order to speed up the calculations, radiative transfer simulations are done on a specified wavelengths grid and in order to get the contributions, the radiation field is interpolated. The speeded-up Raman solver has been used to investigate the influence of rotational Raman scattering for various satellite missions (CarbonSat, FLORIS/FLEX, OLCI).

During the project the *libRadtran* code has been restructured and cleaned up. This led to significant improvements for the user, e.g. the memory consumption of uvspec could be reduced by a factor of 3. The naming of input options has been completely restructured in a logical way, so that the number of options could be reduced from more than 300 to about 150. This restructuring also made it possible to include a logical structure into the GUI, i.e. the selection of input options is now conditional. Besides many small improvements, several new examples and plotting facilities have been added to the GUI.

A reference dataset for radiative transfer simulations has been generated that should serve as a benchmark against which radiative transfer models can be compared. Various simulation setups have been defined with focus on applications for satellite remote sensing. The cases are of different complexity, e.g. with and without polarization. Model intercomparisons between *libRadtran*, SCIATRAN, ARTS and KOPRA were performed to establish benchmark results for the solar and the thermal spectral region. The benchmark data is published on the project website http://www.meteo.physik.uni-muenchen.de/~esaslight2/doku.php?id=task5:task5.
All material of the ESASLight-II study including progress reports, presentations, minutes etc. can be obtained from the project website http://www.meteo.physik.uni-muenchen.de/~esaslight2.

The development of libRadtran is an ongoing project which will continue after the end of the ESASLight studies. New active and passive observation methods continuously raise new demands to radiative transfer models and new processes and features will be included. ESASLight I and II have given this development a great push, by funding a number of very relevant additions and improvements which would not have been possible without the support by ESA.

We hope to be able to address the most urgent new requirements in the near future, possibly supported by an extension of the ESAS-Light studies.
References


