Journal of Quantitative Spectroscopy & Radiative Transfer 186 (2017) 243–253

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

The Reference Forward Model (RFM)

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ARTICLE INFO

Article history:
Received 16 February 2016
Received in revised form
10 June 2016
Accepted 10 June 2016
Available online 23 June 2016

Keywords:
Radiative transfer model
Line-by-line model
Forward model

ABSTRACT

The Reference Forward Model (RFM) is a general purpose line-by-line radiative transfer model, currently supported by the UK National Centre for Earth Observation. This paper outlines the algorithms used by the RFM, focusing on standard calculations of terrestrial atmospheric infrared spectra followed by a brief summary of some additional capabilities and extensions to microwave wavelengths and extraterrestrial atmospheres.

At its most basic level — the 'line-by-line' component — it calculates molecular absorption cross-sections by applying the Voigt lineshape to all transitions up to $\pm 25\ \mathrm{cm}^{-1}$ from line-centre. Alternatively, absorptions can be directly interpolated from various forms of tabulated data.

These cross-sections are then used to construct infrared radiance or transmittance spectra for ray paths through homogeneous cells, plane-parallel or circular atmospheres.

At a higher level, the RFM can apply instrumental convolutions to simulate measurements from Fourier transform spectrometers. It can also calculate Jacobian spectra and so act as a stand-alone forward model within a retrieval scheme.

The RFM is designed for robustness, flexibility and ease-of-use (particularly by the non-expert), and no claims are made for superior accuracy, or indeed novelty, compared to other line-by-line codes. Its main limitations at present are a lack of scattering and simplified modelling of surface reflectance and line-mixing.

1. Introduction

The Reference Forward Model (RFM) was originally developed in the mid-1990s under an ESA contract to provide reference spectra for the MIPAS [12] limb-viewing infrared Fourier-transform spectrometer on the Envisat satellite. It started as a recoded version of GENLN2 [9] and, at its core, it still uses the GENLN2 approach to the line-by-line summation but its capabilities have gradually been extended to include a wide range of radiative transfer applications, from microwave to infrared wavelengths (see Table 1), and the ability to simulate satellite, aircraft/balloon or ground observations. Although the RFM does not include any scattering processes, it can still be used to compute molecular absorption at shorter wavelengths.

The RFM has featured in several model intercomparison exercises [14,33,31,4,27]. It has been used to provide the 'clear sky' component within scattering models [11,5], to generate monochromatic absorption coefficients for fast forward models [8,2,32] and as the actual forward model within retrieval schemes [15,35]. It has also been used to model atmospheres of other planets [20,19].

The code itself is designed for portability and robustness: written in (almost) standard Fortran77 and with input/output mostly via text files. It is also designed to be used as a 'black box' requiring the minimum of inputs and sensible defaults.

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http://dx.doi.org/10.1016/j.jqsrt.2016.06.018
0022-4073/

Table 1
Summary of RFM features.

Description	Details
General capabilities	
Satellite, aircraft/balloon, ground-based geometries	
Selection of specific isotopomers and vibration levels	
Homogeneous, plane-parallel or circular atmospheres	
Specific options	
Radiance, transmittance, etc. output spectra	Section 6.1
Aerosol extinction	Section 6.2
Molecular continua	Section 6.3
CO_2 line mixing	Section 6.4
CO_2 χ factor	Section 6.5
Collision Induced absorption	Section 6.6
Generate/use look-up tables of absorption cross-section	Section 6.7
Surface parameters	Section 6.8
Instrument line shape convolution	Section 6.9
Field-of-view convolution	Section 6.10
Jacobian (weighting function) spectra	Section 6.11
Horizontal atmospheric structure	Section 6.12
Non-LTE calculations	Section 6.13
Linear-in-tau layer emission	Section 6.14
Flux calculations and matrices	Section 6.15
Rayleigh extinction	Section 6.16
Specific applications	
Microwave spectra	Section 7.1
Extraterrestrial atmospheres	Section 7.2
Visible and ultraviolet spectra	Section 7.3

The aim of this paper is to outline some the basic algorithms used within the RFM at a level of detail allowing it to be compared with other models and to help in the interpretation of results. The source code is, in any case, available and clearly commented and more technical details are available on-line in the Software User's Manual which can be found on the RFM web-site [7].

The last major update of the RFM was v4.30 (September 2013), which made it compatible with the HITRAN 2012 database [25]. Subsequent versions (the latest is v4.34) have contained bug fixes and minor new features. The maintenance and development of the RFM are currently supported by the National Centre for Earth Observation. The code is free and can be obtained by contacting the author.

The main part of this paper describes the four basic structural components of the RFM which, in sequence, are

1. Defining the Calculation
2. Ray-tracing, including calculation of Curtis–Godson integrals
3. Calculation of absorption coefficients (including the line-by-line component)
4. Radiative transfer

These are followed by sections describing some of the optional features, and specific applications of the RFM.

2. Defining the calculation

The RFM is controlled by a text driver file in which the user specifies, as a minimum,

1. the type of output spectra required (e.g., radiance, transmittance)
2. the range and resolution of the output spectra
3. the list of absorbing species (or let the RFM select these itself)
4. the atmospheric profile
5. the viewing geometry
6. the sources of spectroscopic data.

Other inputs may also be required depending on the selected options. For example, an instrument line shape if convolved output spectra are required (Section 6.9).

The first three items are self-explanatory, the others are explained in more detail in the following.

2.1. Atmospheric profile

The RFM requires vertical profiles of temperature, pressure, and volume mixing ratios (VMRs) of all required absorbing molecules (also aerosol, Section 6.2) on a common set of (geometric) altitude levels. Strictly, these are profiles of 'mole fraction' rather than VMR, i.e., the ratio of the number of molecules of a particular species to the *total* number of air molecules but 'VMR' will be used here as a convenient abbreviation (the distinction is only important for species with relatively high concentrations). As an aside, no special distinction is made for water vapour: 'air' here is 'moist air' rather than 'dry air'. It is not necessary to specify *every* molecular component of the atmosphere; the complement of the mole fraction is assumed to be made up of non-absorbing molecules. The surface is assumed to be located at the lowest altitude level, not necessarily 0 km.

By default, a 1-D atmosphere is assumed, i.e., vertical structure only (see Section 6.12 for a 2-D atmosphere).

The user-defined altitude grid is also used for the internal representation of the atmosphere: n profile levels defining $n-1$ atmospheric layers, which in turn defines the physical thickness of the equivalent homogeneous path segments used for spectroscopic calculations and the radiative transfer. The layering can have a significant effect on the accuracy: particularly the assumption that the layer emits at a uniform temperature irrespective of its optical thickness (see Section 6.14). For a typical satellite application, 20–30 layers are usually adequate, with thickness varying from 1 km near the surface to 10 km or more in the mesosphere.

2.2. Viewing geometry

The definition of viewing geometry depends on which of three possible representations of the atmosphere are used. In order of increasing complexity these are:

1. Homogeneous
2. Planar
3. Circular

The homogeneous case, suitable for representing lab measurements or horizontal paths in the free atmosphere, is trivial and, apart from temperature, pressure and