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

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Needs for current and future forward modelling capabilities for remote sensing

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1 Introduction

The objective of this review is to understand what are the current and future needs for the users of the libRradtran toolbox, ESA in the first step and the remote sensing community in the second step. To define the requirements, the objectives of current and future ESA missions are summarized and discussed with focus on the required forward modelling capabilities. On the basis of the remote sensing instruments and the quantities that they measure, a description of appropriate radiative transfer methodologies is provided. Radiative transfer models are the forward models in the inversion algorithms, that are applied to analyse the satellite measurements. Following this review a list of requirements for libRadtran toolbox will be derived.

2 ENVISAT

The website `http://envisat.esa.int/` provides detailed information about all ENVISAT instruments. Product handbooks as well as other documents can be downloaded.

2.1 Advanced Synthetic Aperture Radar ASAR

ASAR measures ocean currents and topography, landscape topography as well as snow and ice.

The Advanced Synthetic Aperture Radar (ASAR), operating at C-band, ensures continuity with the image mode (SAR) and the wave mode of the ERS-1/2 AMI. It features enhanced capability in terms of coverage, range of incidence angles, polarisation, and modes of operation. This enhanced capability is provided by significant differences in the instrument design: a full active array antenna equipped with distributed transmit/receive modules which provides distinct transmit and receive beams, a digital waveform generation for pulse "chirp" generation, a block adaptive quantisation scheme, and a ScanSAR mode of operation by beam scanning in elevation.

The ASAR measurement principle as well as data products and algorithms are described in the ASAR Product Handbook. There is also a website: `http://envisat.esa.int/instruments/asar/`. The retrieval algorithms are based on the Doppler shift of the Radar pulse and do not require a radiative transfer model.

2.2 Medium resolution imaging spectometer MERIS

MERIS measures ocean colour and biology, vegetation and atmospheric quantities (clouds and aerosol properties).

MERIS is a programmable, medium-spectral resolution, imaging spectrometer operating in the solar reflective spectral range. Fifteen spectral bands can be selected by ground command.

The instrument scans the Earth's surface by the so called "push-broom" method. Linear CCD arrays provide spatial sampling in the across-track direction, while the satellite's motion provides scanning in the along-track direction.

The cloud albedo and the cloud optical thickness are estimated from measurements of the MERIS channel centred at 753.75nm (Fischer et al., 2000). The retrieval algorithm requires a radiative transfer model that calculates solar radiances. Inferring the optical properties from measured satellite radiances is an inverse problem, which is tackled by a polynomial approach where the cloud albedo and optical thickness are related to a polynomial function of the radiance to be measured.

There is no simple relationship nor analytical formulation of the coherence between the radiances at top of atmosphere and cloud top pressure. Therefore radiative transfer simulations are used to establish an appropriate algorithm to retrieve cloud top pressure. A polynomial approach using measurements in the oxygen-A band has been proposed by Fischer and Grassl (1991).

The water vapour retrieval algorithms dedicated for MERIS are described in Fischer and Bennartz (1997). The general approach is to relate the columnar water vapour content to the ratio of MERIS channels 14 and 15, located at 890 nm and 900 nm, respectively. The regression coefficients are derived by inverting results a radiative transfer model.

The retrieval of surface properties is described in Gobron et al. (2004). It uses 3 MERIS channels (442, 681, and 865 nm). The algorithm requires a radiative transfer model that includes BRDFs of the various different surface types.

Over water, the first step of the MERIS processing is to perform an atmospheric correction. This atmospheric correction is based on look-up-tables generated using a forward model of the water-atmosphere system. In a second step, there are two algorithms to retrieve water constituents: the simple one is empirical and the second one is based on forward radiative transfer modelling in water.

Other documents describe the retrieval methods for the following quantities, not all of them can be addressed in detail in this report: Turbid water flag, gelbstoff water flag, pigment index retrieval, vegetation index, pigment index, sun glint flag, cloud reflectance, photosynthetically available radiation and the terrestial chlorophyllindex. Most of the algorithms require forward radiative transfer modelling for the MERIS channels.

2.3 Advanced Along-Track Scanning Radiometer AATSR

The prime scientific objective of the Advanced Along Track Scanning Radiometer (AATSR) is to establish continuity of the ATSR-1 and ATSR-2 data sets of precise sea surface temperature (SST), thereby ensuring the production of a unique 10 year near-continuous data set at the levels of accuracy required (0.3 K or better) for climate research and for the community of operational as well as scientific users who have been developed through the ERS-1 and ERS-2 missions. Land surface temperature is also derived from AATSR.

AATSR data have a resolution of 1 km at nadir, and are derived from measurements of reflected and emitted radiation taken at the following wavelengths: 0.55 μm, 0.66 μm, 0.87 μm, 1.6 μm, 3.7 μm, 11 μm and 12 μm.

From the calibrated top of the atmosphere Brightness Temperatures available from these bands, SST is calculated using the 11 and 12 μm channels during the day and the 11, 12 and 3.7 μm channels at night. SST and top of atmosphere brightness temperatures are related linearly via a set of coefficients that are computed via forward radiative transfer calculations.

AATSR also includes three visible/near infrared channels centered at 0.55, 0.67 and 0.87μm. These were first introduced on ATSR-2 and have extended the instrument's capabilities over land, particularly for the study of vegetation. Much of the time, the basic calibrated top of the atmosphere reflectance measurements from the AATSR visible and near infrared channels are used for studies of vegetation quantity and quality.

The algorithm to retrieve land surface temperature (Prata, 2002) is based on a regression scheme where the coefficients are determined using a radiative transfer model that simulates the AATSR measurements. Hence the required model must be able to simulate solar and thermal radiances. Surface temperature retrievals do not require accurate BRDFs.

Currently AATSR does not retrieve cloud and atmospheric parameters on a routine basis. However, the different AATSR channels can be used directly to provide information on the basic location, extent and structure of clouds. Two fields in the Level 2 product have also been reserved for Cloud Top Temperature (CTT) and Cloud Top Height (CTH), should suitable retrieval algorithms become available in the future. These algorithms require a radiative transfer code that handles multiple scattering in clouds.

2.4 Radar Altimeter 2 (RA-2)

Radar Altimeter 2 (RA-2) is an instrument for determining the two-way delay of the radar echo from the Earth's surface to a very high precision: less than a nanosecond. It also measures the power and the shape of the reflected radar pulses.

It is a nadir-looking pulse-limited radar altimeter based on the heritage of ERS-1 RA functioning at the main nominal frequency of 13.575 GHz (Ku Band), which has been selected as a good compromise between the affordable antenna dimension that provides the necessary gain and the relatively low attenuation which experience the signals propagating through the troposphere.

The altitude retrieval is based on the time delay of the radar echo. No radiative transfer modelling is required here.

2.5 Microwave Radiometer MWR

The main objective of the microwave radiometer (MWR) is the measurement of the integrated atmospheric water vapour column and cloud liquid water content, as correction terms for the radar altimeter signal. In addition, MWR measurement data are useful for the determination of surface emissivity and soil moisture over land, for surface energy budget investigations to support atmospheric studies, and for ice characterization.

MWR is a dual-channel nadir-pointing Dicke-type radiometer, operating at frequencies of 23.8 GHz and 36.5 GHz.

A microwave radiative transfer model is required to retrieve the water vapor column and the liquid water content.

2.6 Global Ozone Monitoring by Occultation of Stars GOMOS

The key objective of the GOMOS mission is the long-term monitoring of the global vertical ozone distribution from the upper troposphere to the upper mesosphere on a global coverage, with a high vertical resolution, and with a very high and a long-term stable accuracy. Other objectives of the mission include the stratospheric gas-phase chemistry and mesospheric ozone and clouds.

GOMOS is a medium resolution spectrometer measuring in the ultraviolet, the visible and in the infrared and using the stellar occultation technique. In spectral bands between 250 nm to 675 nm, 756 nm to 773 nm, and 926 nm to 952 nm.

The retrieval of GOMOS measurements requires a forward model, that includes extraterrestrial stellar fluxes as radiation source. The occultation measurement geometry requires a spherical model atmosphere including refraction.

2.7 Michelson Interferometer for Passive Atmospheric Sounding MIPAS

The Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) is a Fourier transform spectrometer for the measurement of high-resolution gaseous emission spectra at the Earth’s limb. It operates in the near to mid infrared where many of the atmospheric trace-gases playing a major role in atmospheric chemistry have important emission features.

In particular, MIPAS provides global observations of NOy compounds and of all important greenhouse gases. Moreover, it allows the sensing of various species in the upper troposphere and in the mesosphere. Such measurements are relevant for studies of tropospheric chemistry, tropospheric/stratospheric exchange processes, and the Earth s global energy budgets.

Retrieval algorithms for high spectral resolution measurements to obtain trace gas concentrations are based on the optimal estimation method (Rodgers, 2000; Fischer et al., 2008). This method requires a fast forward radiative transfer model that calculates Jacobians. The high spectral resolution requires a line-by-line model for the IR wavelength region. In order to simulate the limb observation geometry a spherical model atmosphere including refraction is needed. Clouds are mostly be treated as blackbody emission.

2.8 Scanning Imaging Absorption Spectrometer for Atmospheric CHartographY SCIAMACHY

SCIAMACHY is an imaging spectrometer whose primary mission objective is to perform global measurements of trace gases in the troposphere and in the stratosphere. The solar radiation transmitted, backscattered and reflected from the atmosphere is recorded at relatively high resolution (0.2 nm to 0.5 nm) over the range from 240 nm to 1700 nm, and in selected regions between 2000 nm and 2400 nm. The high resolution and the wide wavelength range make it possible to detect many different trace gases despite low concentrations (The mixing ratios of most constituents are of the order of 10^{-6} or less). The large wavelength range is also ideally suited for the detection of clouds and aerosols. SCIAMACHY has three different viewing geometries: nadir, limb, and sun/moon occultations which yield total column values as well as distribution profiles in the stratosphere and (in some cases) the troposphere for trace gases and aerosols.

The retrieval is based on the optimal estimation method (Rodgers, 2000). A list of publications related to SCIAMACHY retrievals is available at `http://www.iup.physik.uni-bremen.de/sciamachy/`. There is also a book about SCIAMACHY that includes a chapter about the applied retrieval methods (Gottwald et al., 2006).

A forward model for the UV/VIS wavelength range is required. Due to different observation geometries, it should be possible to select different model geometries (plane-parallel for nadir observation and spherical for limb and occultation). For limb and especially occultation measurements the forward model needs to handle refraction. Raman scattering and polarisation should also be considered. For occultation measurements the concentration change of photochemically active trace gases along the instrument's line of sight needs to be taken into account. Cloud, Rayleigh and aerosol scattering is important in the UV/Vis wavelength range. Lunar occultation may also be measured. For this case the reflected light from the moon should be considered in the radiative transfer model as radiation source.

2.9 Doppler Orbitography and Radio-positioning Integrated by Satellite DORIS

The Doppler Orbitography and Radio-positioning Integrated by Satellite instrument is a microwave tracking system that can be utilized to determine the precise location of the ENVISAT satellite.

DORIS operates by measuring the Doppler frequency shift of a radio signal transmitted from ground stations and received on-board the satellite. The reference frequency for the measurement is generated by identical ultra-stable oscillators on the ground and on-board the spacecraft.

DORIS retrieval algorithms are based on the Doppler shift of the radio signal. They do not require radiative transfer modelling.

2.10 Laser Retro-Reflector LRR

The Laser Retro-Reflector (LRR) is mounted on the Earth-facing panel of Envisat close to the RA-2 antenna to support satellite ranging for precise orbit determination and RA-2 range measurement calibration. Laser tracking provides the distance between the spacecraft and the station and is assimilated in precise orbit determination. It will be used extensively during the commissioning phase and regularly during the mission to verify the stability of the positioning system.

No atmospheric parameters are retrieved from LRR and no radiative transfer model is required.

3 MetOp

The Meteorological Operational satellite programme (MetOp) is a new European undertaking providing weather data services that will be used to monitor climate and improve weather forecasts. The MetOp programme's series of three satellites has been jointly established by ESA and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), forming the space segment of EUMETSAT's Polar System (EPS). The webpage `http://www.esa.int/esaLP/LPmetop.html` provides much information about MetOp.

3.1 Infrared Atmospheric Sounding Interferometer (IASI)

IASI is one of the most advanced onboard instruments measuring infrared radiation emitted from the surface of the Earth to derive data of unprecedented accuracy and resolution on humidity and atmospheric temperature profiles in the troposphere and lower stratosphere, as well as some of the chemical components playing a key role in climate monitoring, global change and atmospheric chemistry.

IASI is a Fourier Transform Spectrometer based on a Michelson Interferometer coupled to an integrated imaging system that observes and measures infrared radiation emitted from the Earth. The optical interferometry process offers fine spectral samplings of the atmosphere in the infrared band between wavelengths of 3.4 and 15.5 microns. This enables the instrument to establish temperature and water vapour profiles in the troposphere and the lower stratosphere, as well as measure quantities of ozone, carbon monoxide, methane and other compounds, all of which play major roles in atmospheric processes such as the greenhouse effect.

The retrieval of temperature and trace gases will be based on the optimal estimation method (e.g., Carissimo et al. (2005)). Efficient high spectral resolution radiative transfer modelling in the infrared spectral region is needed for this purpose. Pre-calculated lookup-tables of absorption coefficients instead of accurate line-by-line models can be used to handle the very large number of channels. Various models are available, see for instance Saunders et al. (2007).

3.2 Advanced Microwave Sounding Unit (AMSU-A1/2)

These two instruments are cross-track scanning radiometers with a total of 15 channels. In conjunction with HIRS they measure atmospheric temperature and moisture profiles in the troposphere and stratosphere and provide measurements on precipitation, snow cover, sea-ice concentration and soil moisture.

Retrievals of water vapor from AMSU instruments are often based on regression methods (Houshangpour et al., 2005; Buehler and John, 2005), where the coefficients are determined using radiative transfer simulations. A radiative transfer model for the microwave spectral region is required for this purpose. Clouds are transparent in AMSU-A channels, therefore cloud scattering can be neglected. Precipitation consists of much larger particles which scatter microwave radiation. Therefore scattering in precipitation needs to be considered.

3.3 The Microwave Humidity Sounder (MHS)

MHS acquires measurements at various altitudes of atmospheric humidity, including rain, snow, hail and sleet, and temperature by measuring microwave radiation emitted from the surface of the Earth.

MHS has channels in the 89-190 GHz range. Channels at 157 GHz and 183 GHz provide atmospheric humidity data. The 89 GHz channel provides information on surface temperature and emissivity (in conjunction with AMSU-A data) and detects low altitude cloud and precipitation.

As for AMSU-A a microwave radiative transfer model is required to analyze the measurements. Since MHS has channels at larger frequencies (up to 190 GHz), clouds have a larger impact (Sreerekha et al., 2008), so that besides precipitation cloud scattering needs to be taken into account.

3.4 High resolution Infrared Radiometer Sounder (HIRS)

The instrument covers 20 spectral bands from the visible into the longwave infrared. In conjunction with AMSU-A1/2 it measures atmospheric temperature and moisture profiles in the troposphere and stratosphere. Its data is further used to determine the surface albedo, ocean surface temperature, the total atmospheric ozone levels, precipitable water, and the cloud height and coverage.

Full exploitation of HIRS measurements requires a radiative transfer model to calculate radiances for the IR and VIS wavelength regions.

3.5 The Global Navigation Satellite System Receiver for Atmospheric Sounding (GRAS)

GRAS is a Global Positioning Satellite (GPS) receiver that operates as an atmospheric-sounding instrument, providing a minimum of 500 atmospheric profiles per day through a process of GPS radio occultation. GRAS will supply atmospheric soundings of the temperature and humidity of the Earth's atmosphere.

GRAS uses radio occultation to measure vertical profiles of atmospheric temperature and humidity by tracking signals received from a constellation of GPS navigation satellites while they are setting or rising behind the Earth's atmosphere. Radio occultation is based on the fact that when radio waves pass through the atmosphere, either during a rise event or during a set event as seen by the receiver, they are refracted along the atmospheric path. The degree of refraction depends on gradients of air density, which in turn depend on temperature and water vapour. Therefore, measurement of the refracted angle contains information about these atmospheric variables.

The transfer of radiowave needs to be simulated for GRAS retrievals (von Engeln and Nedoluha, 2005).

3.6 Advanced Scatterometer (ASCAT)

ASCAT, an enhanced follow-on instrument to the highly successful scatterometers flown on ESA's ERS-1 and ERS-2 satellites, measures wind speed and direction over the ocean. Its six antennas allow for simultaneous coverage of two swaths on either side of the satellite ground track, providing twice the information of the earlier instruments. ASCAT also contributes to activities in areas as diverse as land and sea ice monitoring, soil moisture, snow properties and soil thawing.

ASCAT uses radar to measure the electromagnetic backscatter from the wind-roughened ocean surface, from which data on wind speed and direction can be derived. The measuring principle relies on the fact that winds over the sea cause small-scale disturbances of the sea surface, which modify its radar backscattering characteristics in a particular way. These backscattering properties are well known and are dependent on both the wind speed over the sea and the direction of the wind with respect to the point from which the sea surface is observed.

3.7 Global Ozone Monitoring Experiment-2 (GOME-2)

GOME-2 is a spectrometer that collects light arriving from the Sun-illuminated Earth's atmosphere or a direct view to the Sun and decomposes it into its spectral components. The recorded spectra are used to derive a detailed picture of the atmospheric content and profile of ozone, nitrogen dioxide, water vapour, oxygen, bromine oxide and other gases. GOME-2 covers the 240-790 nm wavelength regions, i.e. wavelengths covering ultraviolet and visible light.

A radiative transfer model for the UV/VIS spectral range is required. For accurate retrievals Raman scattering should be taken into account (e.g., Hoogen et al. (1999); Vountas et al. (1998)).

4 Meteosat

4.1 Meteosat Second Generation

MSG (Schmetz et al., 2002) is a two-satellite operational service, like the previous Meteosat system, with one operational satellite and one satellite available in orbit as a spare. The first satellite, Meteosat-8, was launched on 28 August 2002 and became operational in January 2004. 21 December 2005 Meteosat-9 was launched and the two remaining MSG satellites, Meteosat-10 and Meteosat-11 are scheduled for launch 2011 and 2013.

4.1.1 Spinning Enhanced Visible and Infrared Imager SEVIRI

The SEVIRI (Spinning Enhanced Visible and Infrared Imager) radiometer is the main element of the MSG satellites. Among the products operationally derived from SEVIRI data are: cloud and atmospheric motion vectors, cloud type, coverage, height and temperature, 7-day clear sky radiances, fire detection, atmospheric instability index, precipitation estimate, surface albedo maps, sea surface temperature, total ozone, (upper) tropospheric humidity, and volcanic ash detection. It scans the Earth's surface sufficiently quickly to permit a repeat cycle of 15 minutes at a spatial resolution between 1 and 3 km in 12 spectral bands between 0.6 and 13.4 μm. The related bandwidths are between 0.3 to 2 μm.

The retrieval of cloud properties (effective radius and optical thickness) is usually performed using a lookup-table method (Nakajima and King, 1990; Mayer et al., 2004). The forward model for this algorithms calculates broad band radiances for the SEVERI channels. A correlated-k method is appropriate for this task. This method neglects 3D effects, taking them into account properly requires a 3D cloud-resolving radiative transfer code.

4.1.2 Geostationary Earth Radiation Budget instrument GERB

MSG satellites also carry the Geostationary Earth Radiation Budget (GERB) instrument (Luhmann, 2002). This instrument monitors the Earth's radiation budget at the top of the atmosphere allowing short- and long-wave radiation calculations, essential for understanding the Earth's climate balance. The spatial resolution is approximately 40 km the temporal resolution 15 minutes. It estimates the outgoing and incoming flux by measuring radiances in a solar band at 0.32 to 4 μm and in a terrestrial band at 4 - 30 μm. The synthetic "long wave" radiance is obtained by subtraction of the short wave from the total radiance. The unfiltered radiances are then obtained by removal of the effects of the non-flat spectral responses in the short wave and synthetic long wave channels. Fluxes are estimated by modelling the angular distribution of the observed radiation (Smith et al., 2004). More information about GERB is available at `http://www.sstd.rl.ac.uk/gerb/`.

4.2 Meteosat Third Generation

The next generation Meteosat satellites (Meteosat Third Generation, MTG, EUMETSAT (2006)) is planned to carry 5 different observation missions: The High Resolution Fast Imagery (HRFI) mission, the Full Disk High Spectral Imagery (FDHSI) mission, the Lightning Imagery (LI) mission, the Infrared Sounding (IRS) mission, and the UV-VIS Sounding (UVS) mission. At the moment phase A studies are under way in parallel at EUMETSAT and ESA. A first satellite is scheduled ready for launch in 2015.

4.2.1 High Resolution Fast Imagery - HRFI

The HRFI mission is extending the current MSG/SEVIRI high resolution visible mission. 4 channels at VIS, NIR, and TIR wavelengths are planned to provide radiance observations of the sunlight reflected and thermal radiation emitted by the surface and atmosphere at high spatial (0.5 - 1.0 km) and temporal resolution (approx. 2 min). The main goals of HRFI are nowcasting applications as the detection of clouds and the derivation of cloud and atmospheric motion at high spatio-temporal resolution, as well as the determination of cloud top temperature and cloud top microphysics. Spectral bands at 0.6, 2.2, 3.8 and 10.5 μm at moderate spectral resolution (0.05 - 0.7 μm) have to be simulated with respect to this mission.

4.2.2 Full Disk High Spectral Imagery - FDHSI

The FDHSI is the core mission inherited from the normal resolution MSG/SEVIRI channels. For 16 channels between 0.444 and 13.3 μm radiance observations are planned at spatial resolutions of 1 - 2 km and temporal resolution of approx. 10 min. The multitude of goals of the FDHSI mission can be summarised under nowcasting and very short range forecasting, numerical weather prediction at regional and global scales, and climate monitoring. Among the products to be determined within the FDHSI are: cloud mask, type, temperature/pressure, cloud phase, optical thickness, droplet size information, aerosol optical thickness and size distribution information, volcanic ash and sand storm detection, atmospheric instability, layer humidity, cloud and atmospheric motion, land surface temperature, snow and sea ice cover, vegetation stress, fire detection. The spectral resolution of these observations and of related simulations is again of a moderate order between 0.03 in the VIS/NIR to 0.7 in the TIR.

4.2.3 Lightning Imagery - LI

It's purpose is the targeted real time detection and location of lighting in support of nowcasting and severe weather warning. Lighting can also serve as a proxy of for vertical motion, adiabatic and latent heating and is an important input information for atmospheric chemistry. It should be able to continously detect lightning pulses of 4.0 to 400 μJ/m^2 sr on a 10 km square at 777.4 nm with a spectral width of 0.34 nm.

4.2.4 Infrared Sounding - IRS

The infrared sounding mission's primary objective is the support of numerical weather forecast through provision of height resolved atmospheric motion vectors, temperature and water vapour profiles, as well as level 1b radiance data for direct assimilation into NWP models. The mission specifications are based on the experience with similar sounders like IASI. Two bands in the longwave (700-1210 cm^{-1}, 8.2 - 14.3 μm) and the midwave infrared (1600-2175 cm^{-1}, 4.6 - 6.3 μm) should be covered with spectral radiance measurements at a spectral resolution of 0.625 cm^{-1}. To simulate these information on the H_2O, O_3, CO, CO_2, NO, NO_2, surface, clouds, aerosol is needed.

4.2.5 UV-VIS Sounding - UVS

The UVS mission's objective is the profiling of O_3, NO_2, SO_2, and H_2CO. The mission specifications are based on the experience with GOME, SCIAMACHY, OMI, and GOME2. Spectrally resolved coverage between 290 and 450 nm as well as 758 and 772 nm (O_2A) is requested. The spectral resolution needed here is high: 0.4 - 0.8 nm at the UV band and 0.06 nm (!) at the O_2A band.The former request for polarimetric measurements within UVS was canceled. The measurements at the O_2A band may be used to retrieve cloud top pressure (Fischer et al., 2003). This retrieval method requires a multiple scattering radiative transfer model including different cloud and surface types. The simulation of the high spectral resolution of the measurements requires a line-by-line model.

5 Earth Explorers

The ESA Earth Explorer series of satellites are designed to address critical environmental issues providing an important contribution to the global endeavour to further our understanding of the Earth system. Detailed information about the Earth Explorer missions can be found at `http://www.esa.int/esaLP/LPearthexp.html`.

5.1 Core Missions

Core missions respond directly to specific areas of public concern and are selected through widespread consultation with the science community.

5.1.1 EarthCare

EarthCare is a near polar orbit satellite that has the goal to provide vertical profiles of the atmosphere with information about ice and water clouds as well as aerosols. To fulfill this, EarthCare is equipped with four instruments that will complement each other and provide the possibility of consistency checks. An important feature in the processing of the data is the synergy effect of different instruments.

EarthCare will be equipped with a 94 GHz cloud profiling radar capable of detecting ice clouds and drizzle. Furthermore, by analysing the difference in phase of backscattered radar signals between successively transmitted pulses it is possible to derive the net vertical motion of the cloud particles.

A high spectral resolution lidar (HSRL) onboard will detect ice and water cloud profiles as well as aerosol profiles. The high spectral resolution will be used to distinguish molecular backscatter—which Doppler shifts the photon wavelength due to the thermal motion of the molecules—and large particle backscatter (cloud particles, aerosols)—which does not change the photon wavelength. Given the molecular profile, e.g. from NWP models, the molecular (Rayleigh) backscatter can be used to determine the extinction α by aerosols and thin clouds (given by the difference of observed molecular backscatter and the one expected for a cloud/aerosol free atmosphere), while the so-called backscatter signal β is determined by the (Mie) backscatter from aerosols and cloud particles. The lidar ratio, $S \equiv \alpha/\beta$, gives information about the effective radius of the particles.

Furthermore, the HSRL is capable of measuring the polarization of the backscatter signal. This gives additional information about the shape of the ice and aerosol particles. Also, combining the signals of the HSRL and the radar provides an independent measure of the mean ice particle size in ice clouds, and of the ice water content.

The multispectral imager with four solar and three thermal narrow bands is needed for scene identification as well as supplementary information like e.g. surface albedo, total optical thickness, and cloud top temperature. It is also meant to derive the particle size independently of the radar/lidar system.

Finally, the broad-band radiometer is meant to measure the top-of-atmosphere (TOA) flux. As a consistency check the TOA flux is compared with the the TOA fluxes from simulations which use the profiles derived by the other EarthCare instruments.

The retrieved results from EarthCare will be used to improve numerical weather prediction (NWP) models as well as climate models and are meant to be assimilated by the NWP model of the ECMWF. Further synergy effects together with the data from other instruments (airborne and space-located) are expected.

Earth Care retrievals require a radiative transfer model that simulates radar as well as lidar measurements. The most appropriate method to simulate active sensors is the Monte Carlo method.

5.1.2 ADM Aeolus

The Earth Explorer Atmospheric Dynamics Mission (ADM-Aeolus), expected to launch in 2009, will provide global observations of wind profiles from space to improve the quality of weather forecasts, and to advance our understanding of atmospheric dynamics and climate processes. An overview of the mission can be found in (Ingmann and Endemannt, 2005).

The core space element of ADM-Aeolus is ALADIN (Atmospheric Laser Doppler Instrument), a direct detection lidar incorporating a fringe-imaging receiver (analysing aerosol and cloud backscatter) and a double-edge receiver (analysing molecular backscatter).

ALADIN is an active instrument which fires laser pulses towards the atmosphere and measures the Doppler shift of the collected return signal, backscattered at different levels in the atmosphere. The frequency shift results from the relative movement of the scatter elements along the line of sight of the instrument. Light is scattered either by interaction with aerosol or cloud particles (Mie scattering) or by interaction with air molecules (Rayleigh scattering). The two scattering mechanisms exhibit different spectral properties and different wavelength dependencies such that instruments evaluating only one signal type or both in separate processing chains can be constructed.

For Mie backscattering, the spectrum of the received Doppler shifted light equals the transmitted spectrum slightly broadened by the wind variability within the measurement volume. In case of molecular scattering, the Brownian motion of air molecules significantly broadens the received spectrum to a width equivalent to wind speed such that the spectral width resembles Doppler shifts equivalent to several 100 m/s.

The wind speed is computed from the Doppler shift of the lidar return. Details about the retrieval algorithm can be found in (Tan et al., 2008). The performance of the wind retrieval algorithm is very good for homogeneous conditions, then the calculation of the Doppler shift does not require a radiative transfer model and the vertical velocity can be assumed as negligible over larger areas.

Whether an evaluation of ALADIN measurements is possible for inhomogeneous conditions has not yet been proven. In order to answer this question more research is needed. To this end a sophisticated forward model is needed in order to test retrieval algorithms in inhomogeneous conditions. Such a model would have to be able to correctly take into account multiple scattering effects and highly anisotropic phase functions in a 3D (cloud) field and should be able to correctly derive the Doppler shift due to wind effects. Such a model is likely to be based on the Monte Carlo method.

As secondary output ALADIN would provide vertical profiles of clouds and aerosols and be able to pin down the altitudes of the planetary boundary layer and of the tropopause.

5.1.3 GOCE

Launching in the summer of 2008, ESA's Gravity field and steady-state Ocean Circulation Explorer (GOCE) has been developed to bring a new level of understanding of the Earth's gravity field and the 'geoid' (the shape of a global ocean at rest used as a reference). The mission objectives are to determine gravity-field anomalies with an accuracy of 1 mGal (where 1 mGal = 10^{-5}ms^{-2}), to determine the geoid with an accuracy of 1-2 cm, and to achieve the previous at a spatial resolution better than 100 km. (Haagmans et al., 2006) provide a good overview of the GOCE mission.

GOCE will employ a three-axis electrostatic gravity gradiometer that will allow gravity gradients to be measured in all spatial directions for the first time. It is designed specifically for determining the stationary gravity field. The measured signal is the difference in gravitational acceleration at the test-mass location inside the spacecraft caused by gravity anomalies from attracting masses of the Earth. The analysis of such measurements does not require a radiative transfer model.

5.2 Opportunity Missions

Opportunity missions are smaller, low-cost satellites that are relatively quick to implement so that they are to address areas of immediate environmental concern. The user-driven approach is fundamental for both type of mission.

5.2.1 CryoSat-2

The primary payload of CryoSat-2, due to launch in 2009, is the SAR/Interferometric Radar Altimeter (SIRAL), which has extended capabilities to meet the measurement requirements for ice-sheet elevation and sea-ice freeboard. CryoSat-2 will also carry three star trackers for measuring the orientation of the baseline. In addition, a radio receiver called Doppler Orbit and Radio Positioning Integration by Satellite (DORIS) and a small laser retroreflector ensures that CryoSat-2's position will be accurately tracked. The mission is described in (Wingham, 1999, CryoSat - Science and Mission Requirements). The analysis of CryoSat-2 measurements is based on the time shift and the resulting phase differences of the radar pulses which are reflected at the surface by the sea ice or water. The backscatter signal can be used to distinguish between water and ice. The retrieval algorithms do not require an atmospheric radiative transfer model since interactions with the atmosphere are negligible. Also the error due penetration in sea ice is small.

5.2.2 SMOS

The Soil Moisture and Ocean Salinity (SMOS) mission to be launched in 2009 has been designed to observe soil moisture over the Earth's landmasses and salinity over the oceans. The data acquired from the SMOS mission will lead to better weather and extreme-event forecasting, and contribute to seasonal-climate forecasting. As a secondary objective, SMOS will also provide observations over regions of snow and ice, contributing to studies of the cryosphere.

The mission will demonstrate a new measuring technique by adopting a completely different approach in the field of remote sensing of the Earth. The 2-dimensional interferometic L-Band radiometer (1.4 GHz) measures emitted microwave radiation and thus provides information about both soil moisture and ocean salinity.

The forward model for this mission needs to simulate polarized microwave brightness temperatures for all viewing angles of the measurements. The inversion algorithm for sea surface salinity, that is based on an iterative Levenberg-Marquard method is described in detail in ESL (2006b, SMOS-SSS ATBD). The forward radiative transfer model needs to take into account sea surface roughness, foam generated by breaking waves, galactic noise contamination, Faraday rotation induced by the Earth's magnetic field and atmospheric effects on microwave radiation (clouds, rain, water vapor). The inversion algorithm for soil moisture is based on an optimal estimation method (ESL, 2006a, SMOS-SSM ATBD). The main retrieved quantity is the surface reflectivity which is the integral of the surface scattering coefficient over all scattering directions. This requires detailed emissivity models for the various surface types, for instance dry soils, vegetation, rocks etc. It also needs to take into account Faraday rotation atmospheric effects on microwave radiation.

5.2.3 Swarm

The objective of the Swarm mission is to measure the geomagnetic field and its temporal evolution, and gain new insights into improving our knowledge of the Earth's interior and climate.

High-precision and high-resolution measurements of the strength and direction of the magnetic field will be provided by three satellites. GPS receivers, an accelerometer and an electric field instrument will provide supplementary information for studying the interaction of the magnetic field with other physical quantities.

The main instrument of the mission will be the Absolute Scalar Magnetometer (ASM). Two configurations are proposed, one is based on the Electron Spin Resonance (ESR) principle and makes use of the Zeeman effect which splits the emission and absorption lines of atoms in a ambient magnetic field. The other is a Proton Free-precession scalar magnetometer which operates on the principle that protons are spinning around an axis aligned with the magnetic field. Details about the technical configuration are described in ESA (2004, SWARM - Technical and Programmatic Annex).

Both suggested configurations do not require a radiative transfer model for analysing the measurements. Details about the forward model as well as the inversion algorithms are given in (Vennerstrom et al., 2005).

5.3 Future Missions

The candidate missions described in this section have been selected in May 2006 for dedicated assessments. Inversion algorithms are not yet available. Bensi et al. (2007) provides an overview of all future missions.

5.3.1 TRAQ

The objective of the TRAQ mission is to assess air quality changes at global and regional scale and to determine the strength and the distribution of the sources and sinks of trace gases and aerosols. A new synergetic sensor concept is proposed: a high spectral resolution pushbroom shortwave spectrometer (SWS) in the range from ultraviolet to near-infrared; a high spectral resolution across-track scanning longwave spectrometer (LWS) in the thermal-infrared with an embedded cloud imager and a multi-view polarisation-resolving pushbroom radiometer. A shortwaveinfrared band is also required; it would be included either in the LWS or SWS. Measured parameters are: O3, NO2, SO2, HCHO, H2O, HCOOCH, CO, CH4 and the tropospheric aerosol characterisation. The inversion algorithms for these measurements will require advanced forward radiative transfer models, including line-by-line calculations of polarized radiances in the UV/VIS/IR spectral ranges and a flexible aerosol treatment which allows to simulate arbitrary compositions of tropospheric aerosol.

5.3.2 PREMIER

The primary aim of PREMIER is to explore the processes that control the composition of the mid/upper troposphere and lower stratosphere (altitude 3/10–51/58 km). PREMIER will observe the distributions of trace gases, particulates and temperature. PREMIER will fly in tandem with the MetOp satellite, the synergy of both allows to discriminate the composition of the lower troposphere from that of higher levels. The instruments will be two complementary limb-sounders at infrared and mm/sub-mm wavelength. The inversion algorithms will be based on the optimal estimation method and require line-by-line radiative transfer modelling in a spherical model atmosphere in the IR to submm wavelength regions.

5.3.3 FLEX

The objective of the FLEX mission is to improve our knowledge of the carbon cycle by globally measuring the efficiency of photosynthesis of ecosystems. Photosynthesis by land vegetation is an important component of the global carbon cycle,closely linked to the hydrological cycle through transpiration. The core instrument is a spectrometer to measure the fluorescence in the blue, red and far-red using the “Fraunhofer Line Discriminator” method. The fluorescence of chlorophyll in the red and far-red is the key for monitoring photosynthesis. Blue-green fluorescence adds information about the vegetation’s status and health. The complementary instruments are a coarse resolution visible/near-infrared spectrometer and a 6-channel shortwave infrared imager for basic vegetation parameters, a thermal infrared radiometer with four channels for estimating the temperature of the vegetation canopy. The forward model for analysing the FLEX measurements must be able to simulate fluoreszenz in vegetation chlorophyll. Apart from this radiance simulations at a coarse spectral resolution are required to evaluate the measurements of the complementary instruments.

5.3.4 A-Scope

A-SCOPE will observe carbon dioxide from space and will provide an innovative source of data for understanding the carbon cycle and validating inventories of greenhouse gas emissions. It would provide near-global coverage with good time resolution, mapping the sources and sinks of carbon dioxide on a scale of 500 km or better. The main instrument is an active “Differential Absorption Lidar” (DIAL) sensor. A camera operating in the visible, near-infrared and thermal-infrared with a narrow swath width of 50 km would put the measurements in context with a broader view of the clouds and Earth s surface texture. The data analysis requires forward modelling of the backscattered lidar signal. The lidar equation provides an approximate solution; for detailed analysis a multiple scattering lidar simulator is required.

5.3.5 CoReH2O

The CoReH2O mission would focus on detailed observations of important snow, ice and water-cycle parameters and would improve our understanding and modelling of surface processes and surface/atmosphere exchange mechanisms in regions where snow and ice play a major role in the water and energy cycles, as well as in biospheric processes. The measurements are conducted by a synthetic aperture radar at X- and Ku-band at relatively high resolution. Measurements of the polarisation of the reflected radar pulses are important for separating surface and volume scattering and for estimating the snow water equivalent. A polarized radar simulator (9.6/17.2 GHz) would be useful to analyze the measurements in detail although the traditional radar retrieval method does not need it.

5.3.6 BIOMASS

The objective of the BIOMASS mission is to acquire global measurements of forest biomass to assess terrestrial carbon stocks and fluxes. A spaceborne P-band synthetic aperture polarimetric radar operating at 435 MHz and a 6 MHz bandwidth will be used. A polarized radar simulator in the MHz frequency range would be useful.

6 GMES-Sentinels

The five Sentinels missions are part of the GMES program (Global Monitoring for Environment and Security) which is designed for environment and security services. Sentinel 1 to 3 are currently in development and will be launched in 2011/2012. Sentinel 4 and 5 are foreseen for later deployment. All sentinels will fly in sun-synchronous low earth orbits.

6.1 Sentinel 1

Sentinel 1 is a C-Band SAR. The atmosphere has some impact in the C-band, in particular heavy rain. Such data are usually excluded from the analysis. Radiative transfer might be helpful for assessing the impact of weather on SAR imagery.

6.2 Sentinel 2

The prime objectives of the GMES sentinel 2 mission (Gascon and Berger, 2007) are to obtain generic maps of land cover for agricultural, urban, and forest management, as well to measure geo-biophysical variables such as leaf area index or vegetation state. Furthermore data is used to predict and monitor and mitigate of natural hazards like floods, storms, earthquakes, landslides, forest fires . . .
The main demand on the data of this mission are high (HR a few tens of meter) and even very high (VHR 1 to 10m) spatial resolution, an appropriate coverage time in the order of a few days and multi-spectral imaging. The 13 intended spectral channels are enhancements of the Landsat and SPOT sensors. They cover the range from the visible/near infrared up to the short-wave infrared (443nm to 2190nm). The new spectral properties of the channels allow for better corrections of the atmosphere, aerosols and cirrus clouds as well as a better classification of land surface types especially vegetation. The orbit is sun-synchronous in order to archive a comparable viewing and illumination geometry simplifying the detection of land surface changes.

As the focus of this mission is the remote sensing of land surface, a variety of spectral surface albedos and BRDF of land surface types is essential for simulation of this mission. Furthermore band parameterisations for the 13 channels, correlated-k or quasi spectral, are required. Rayleigh and aerosol and cirrus cloud scattering has to be accounted for. The restriction to viewing angle smaller than 15 degree and the sun synchronous orbit allow in good approximation to assume plane parallel radiative transfer. However, the development of an operational correction for adjacency effects of the data might require the use of a 3DRT. Moreover, the retrieval of land geophysical parameters might require canopy radiative transfer modelling capabilities.

6.3 Sentinel 3

The Sentinel 3 mission, described by Drinkwater and Rebhan (2007, Mission Requirements Document), will consist of a series of satellites performing for a duration of 20 years. The goal is to deliver a consistent, long-term collection of remotely sensed marine and land data.

The instruments onboard will be an advanced Radar Altimeter (RA) and one or two multichannel optical imagers with performance equivalent to an Advanced Along Track Scanning Radiometer (AATSR) and a Medium Resolution Imaging Spectrometer (MERIS).

The RA is meant to deliver oceanic information such as sea surface height and significant wave height. The MERIS will deliver ocean and land color, and the AATSR will detect the sea and land surface temperatures. Measuring the ocean color and the sea surface temperature jointly will make it possible to quantify circulation in the upper ocean layer, e.g. by detecting algae bloom in coastal upwelling zones. Therefore the AATSR and MERIS must be suited on the same satellite, whereas the RA could be launched on a different platform. The AATSR will be equipped with two viewing angles in order to allow for aerosol corrections.

The output will be used in several ways, for instance for biological monitoring, e.g. detecting pollution and fires, for weather warning in offshore regions, and for assimilation in NWP models.

Radiative tranfer modelling requirements for MERIS and AATSR have been adressed in section 2.

6.4 Sentinels 4 and 5

Langen (2007, Mission Requirements Document) provides information about the objectives as well as on the planned instrumentation of the Sentinels 4 and 5 missions. The mission will contribute to three major environmental themes: (a) Stratospheric ozone and surface UV radiation, (b) air quality and (c) climate change. The requirements that can not be met by planned other missions are space based measurements of the tropospheric composition including the planetary boundary layer for air quality applications, high precision monitoring of tropospheric climate gases (CH_4, CO and CO_2) and aerosols, and high vertical resolution ozone measurements in the upper troposphere/lower stratosphere region.

The following implementation priorities are recommended by ESA, subject to further system analyses:

1. a satellite with UV-vis, SWIR and thermal IR spectrometers serving air quality and climate protocol monitoring in LEO. It is possible that the IR spectrometer can be dropped if IASI and CRIS data will be available. This satellite is common to all temporal sampling / geographical coverage requirement scenarios and will provide continuity and improvement with respect to the OMI and SCIAMACHY missions.

2. an extension of this mission to obtain regularly (less than 1–4 hours) revisit time as required for air quality applications. This extension could consist of other LEO satellites or a GEO platform carrying instrumentation with similar Level 1b performance specifications.

3. a limb-sounding mission observing the UTLS either in the mm-wave or infrared region to serve stratospheric ozone / surface UV near real time and assessment applications. Maturation of this application needs to be awaited.

The inversion algorithms for the UV-vis, SWIR and thermal IR spectrometers will require line-by-line radiative transfer simulations of radiances for trace gas retrievals. The model needs to handle multiple scattering (Rayleigh, Raman, Mie). A spectral surface albedo is required for modelling UV radiances. Detailed modelling of aerosol is required to be able to retrieve aerosol phase functions. To retrieve cirrus optical depth it is necessary to simulate scattering by aspherical particles. The limb measurements (if included) require line-by-line radiative transfer simulations in spherical geometry in the IR, as well as in the mm/submm wavelength ranges.

7 Mars Express 2003

Information about Mars Express is provided at `http://www.esa.int/SPECIALS/Mars_Express/`.

Mars Express's orbiter was initially planned to operate for a whole Martian year (687 Earth days). The mission was then extended until the end of October 2007. Thanks to a further extension, the mission will now operate for almost two more Earth-years, until May 2009.

From orbit, Mars Express is scanning the surface and atmosphere of the planet with seven instruments. The high resolution mapping of the Martian surface is one the main interests. Further projects contain the search for life and the gain of knowledge about Mars which can give hints about the evolutionary processes on Earth itself. Mars Express is complementary to all other mission to Mars.

Mars Express has an elliptical orbit. On that account there are two special points, one in a minimum distance of 258 km (Pericenter) and one at a maximum distance of 11 560 km (Apocenter).

The instruments cover a range of wavelength extending from ultraviolet to thermal infrared. Data and information that can be simulated using a radiative transfer model are the following:

- **OMEGA Visible and Infrared Mineralogical Mapping Spectrometer**
  OMEGA is building up a map of surface composition in 100 square meters. It determines mineral composition from the visible and infrared light reflected from the planet's surface in the wavelength range 0.5-5.2 microns. As light reflected from the surface must pass through the atmosphere before entering the instrument, OMEGA also measures aspects of atmospheric composition and dust.

- **SPICAM Ultraviolet and Infrared Atmospheric Spectrometer**
  SPICAM determines the composition of the atmosphere from the wavelengths of light absorbed by the constituent gases. An ultraviolet (UV) sensor measures ozone, which absorbs at 250 nm, and an infrared (IR) sensor measures water vapour, which absorbs at 1.38 μm.

- **Planetary Fourier Spectrometer (PFS)**
  The PFS determines the composition of the Martian atmosphere by measurements of reflected sunlight (in the range 1.2- 45 micrometers). In particular, it measures the vertical pressure and temperature profile of carbon dioxide which makes up 95% of the Martian atmosphere, and look for minor constituents including water, carbon monoxide, methane and formaldehyde.

The instruments of the Mars Express mission are similar to Earth observation instruments. Realistic assumptions about the atmospheric composition of Mars have to be made in radiative transfer modelling.

8 Venus Express 2005

The objectives of the Venus Express mission is to study the atmosphere, the plasma environment an the surface of Venus. Venus Express has been launched on November 9, 2005 and entered Venusian orbit on 11 April 2006. The mission will last until May 2009 (over four Venusian years). Information about Mars Express is provided at `http://www.esa.int/SPECIALS/Venus_Express/`.

The spacecraft's operational orbit is a 24-hour elliptical, highly excentric quasi-polar orbit. At its closest point (Pericentre), Venus Express is at an altitude of 250 kilometers and at the apocentre at 66000 kilometres.

The Venus Express Mission is based on the same design as the Mars Express Mission. Spare instruments designed for ESA's Mars Express and Rosetta Mission have been upgraded and adapted to cope with the thermal and radiation environment in Venus orbit. The instruments cover a range of wavelength extending from ultraviolet to thermal infrared. Among the seven instruments, the following record informations that can be computed with a radiative transfer model:

- **Planetary Fourier Spectrometer (PFS)**
  This instrument is heritated from Mars Express. The objectives are measurements of the temperature of the atmosphere between altitudes of 55-100 kilometers at a very high resolution, by infrared Fourier spectroscopy. It is also able to measure the surface temperature and therefore be able to search for volcanic activity. In addition to its temperature measurements, PFS is able to make composition measurements of the atmosphere. A line-by-line radiative transfer code for the IR is required.

- **Ultraviolet and Infrared Atmospheric Spectrometer (SPICAV/SOIR)**
  SPICAV is inherited from Mars Express and new developments have been made for SOIR. The objective is to provide atmospheric spectrometry by sun or star occultation observations. SPICAV assists in the analysis of Venus's atmosphere. In particular, it searches for the small quantities of water expected to exist in the Venusian atmosphere. It also looks for sulphur compounds and molecular oxygen in the atmosphere. It determines the density and temperature of the atmosphere at 80-180 kilometers altitude. A spherical radiative transfer code for the VIS spectral range is required. It needs to handle the sun and other stars as radiation sources.

- **Ultraviolet/Visible/Near-Infrared mapping spectrometer (VIRTIS)**
  This instrument has been heritated from Rosetta. The objective is a spectrographic mapping of atmosphere and surface of Venus. VIRTIS is able to study the composition of the lower atmosphere between 40 kilometers altitude and the surface. It tracks the clouds in both ultraviolet and infrared wavelengths and allows scientists to study atmospheric dynamics at different altitudes.

- **Venus Monitoring Camera (VMC)**
  This instrument has been newly developed reusing parts of Mars Express's High Resolution Stereo Camera. The VMC objective is to perform UV and visible imaging. VMC

is a wide-angle multi-channel camera that is able to take images of the planet in the near infrared, ultraviolet and visible wavelengths. VMC is able to make global images and studies the cloud dynamics and image the surface. In addition it assists in the identification of phenomena seen by other instruments.

- **Venus Radio Science Experiment (VeRa)**
  This instrument is heritated from Rosetta and its objective is to provide radiosounding of the atmosphere. VeRa uses the powerful radio link between the spacecraft and Earth to investigate the conditions prevalent in the ionosphere of Venus. It is also used to study the density, temperature, and pressure of the atmosphere from 35-40 km up to 100 km from the surface, and to determine roughness and electrical properties of the surface. It also allows investigations of the conditions of the solar wind in the inner part of the Solar System.

There are two operation phases for Venus Express in its operational orbit: the Earth Pointing phase and the Observation phase. The Earth pointing phase is dedicated to communication with Earth and battery charging. There are several different phases of observation, depending on the payload configuration and spacecraft orientation. In particular, those that interest us are:

- *Nadir pointing*
  The instrument points directly at the planet and analyses solar radiation that has traveled through the atmosphere after being reflected by the planet surface. This observation phase is preferably performed during pericentre pass, but possible on any portion of the orbit. VIRTIS, PFS, SPICAV and VMC may operate in this mode.
- *Limb observation*
  The instrument points across the atmosphere as during the star mode, but not toward a star. The instrument can analyses the atmospheric glow (emission of light by the atmosphere). VIRTIS, PFS, SPICAV and VMC may operate in this mode.
- *Star occultation*
  The instrument points tangentially through the atmosphere towards a star, or the Sun, which is observed through the atmosphere as it rises or sets. The instrument analyses the absorption of light components by the planet atmosphere. SPICAV can be used in this mode.

As for Mars the instruments are similar to those used for remote sensing of the Earth's atmosphere. In principle the same radiative transfer modelling capabilities are required. The main difference is the completely different composition of the Venus atmosphere that needs to be used is the radiative transfer simulations.

9 Summary

A large number of current and future ESA satellite missions have spectrometers on board that operate in the solar and/or in the thermal wavelength region. To simulate these measurements a radiative transfer model for the visible and/or thermal spectral range is required. The model needs to handle multiple scattering by molecules, clouds and aerosols. To estimate the error induced by cloud inhomogeneity a three-dimensional atmospheric geometry is needed. For nadir mesaurement geometry the model atmosphere can be assumed to be plane-parallel, whereas for limb or occultation measurement geometry, a spherical model is required. In this case also atmospheric refraction becomes important. Retrievals of surface temperature, cloud top height and other parameters are often based on regression schemes. For such application the spectral integration may be performed using a correlated-k approach or the so called exponentional sum fitting method. The retrieval of cloud properties (optical thickness and effective radius) is often performed using look-up-table techniques. Here as well a correlated-k approach is sufficient. The retrieval of for instance trace gas or temperature profiles is usually performed using an optimal estimation method. This requires a line-by-line model that calculates Jacobians, i.e. the derivatives of the radiance with respect to those parameters that shall be retrieved from the measurements. If surface properties are retrieved, for instance the spectral albedo or the BRDF, the model needs the option to use arbitrary albedos and BRDFs as input. Some sensors will measure the polarisation state of the radiation, so naturally a forward model that handles polarisation is required. For trace gas retrievals the exact line shape is important, besides the detailed line-by-line computations Raman scattering has to be considered in some cases. For stellar occultation measurements, the extraterrestrial stellar spectra of the observed stars are required. For lunar occultation a spectrum of the solar radiation reflected by the moon is needed as radiation source input for the radiative transfer model.

Several instruments operate in the microwave or sub-millimeter spectral region. The analysis of those measurements require a microwave radiative transfer model. These models do not need to take into account aerosol or molecular scattering. Since the wavelength is much larger than aerosol particles and molecules, microwave radiation is insensitive to them. Cloud particles and precipitation have an impact, so that the microwave models need to handle multiple scattering by clouds and precipitation.

Standard retrieval methods of active instruments (radar and lidar) are mostly based on the Doppler shift of the return signal. For lidar analysis, single scattering models are often used to analyse the measurement signal. To retrieve detailed cloud and aerosol properties from active instruments, for instance from EarthCare, a radar/lidar simulator that includes multiple scattering in (cirrus) clouds is required. Such a simulator can be implemented in a Monte Carlo model.

For the Mars and Venus missions the additional requirement is that the models can be opertated in Mars and Venus standard atmospheres.

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