DOCUMENT

EarthCARE Product Validation Requirements Document

Level 1b/c and Level 2a/b Products

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additional information ATLD L1b req. description	12/06/2017	Sec 3.1.1	6

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1 DOCUMENTS

1.1 Applicable Documents

[AD 1] EarthCARE Mission Requirements Document, EC-RS-ESA-SY-012, EOP-SM/1567/TW, issue 5.0

1.2 Reference Documents

[RD 1] ATLID L1 Product Definitions, EC.ICD.GMV.ATL.00001, version 1.3
[RD 2] EarthCARE ATLID Level 1 Processor Algorithm Theoretical Basis Overview, EC-TN-ESA-ATL-740, version 6.1
[RD 3] MSI L1 Product Definitions, EC.ICD.GMV.MSI.00001, version 1.2
[RD 4] MSI ECGP Algorithm Theoretical Baseline Document, EC.TN.SSTL.MSI.00014, version 14
[RD 5] BBR L1 Product Definition Document, EC.ICD.GMV.BBR.00001, version 1.2
[RD 6] EarthCARE Broadband Radiometer ECGP Algorithm Theoretical Baseline Document, EC-TN-SEA-BBR-0005, version10
[RD 7] CPR Level 1b Product Definition Document, MAS-110009, Revision B
[RD 8] EarthCARE Cloud Profiling Radar (CPR) Level 1b Algorithm Theoretical Basis Document, SEC-140039, Revision B
[RD 9] System Requirements Document, EC-RS-ESA-SY-0001, version 1a
[RD 10] EarthCARE ESA Product List, EC-ICD-ESA-SYS-0314, version 4
[RD 11] EarthCARE Production Model, EC-TN-ESA-SYS-0380, version 6
[RD 12] EarthCARE ESA Level 2 Product Definitions (zip file) EC-DP-ESA-SYS- 894, version 1.0
[RD 13] EarthCARE ESA Level 2 ATBDs (zip file) EC-DP-ESA-SYS-893, version 1.0

1.3 List of Acronyms

BBR	Broad-Band Radiometer
AD	Applicable Document
ATBD	Algorithm Theoretical Basis Document
ATBO	Algorithm Theoretical Basis Overview
ATLID	Atmospheric Lidar
CPR	Cloud Profiling Radar
EarthCARE	Earth Cloud, Aerosol and Radiation Explorer
L1b	Level 1b
L1c	Level 1c
L2a	Level 2a
L2b	Level 2b
LW	long wave

MRD	Mission Requirements Document
MSI	Multi-Spectral Imager
NEDT	noise equivalent delta temperature
PDD	Product Description Document
PDGS	Payload Data Ground Segment
RD	Reference Document
SNR	signal-to-noise ratio
SRD	System Requirements Document
SW	short wave
TOA	top of atmosphere
TW	total wave (SW + LW)

1.4 Acknowledgement

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2 INTRODUCTION AND OBJECTIVES

The Earth Clouds, Aerosol and Radiation Explorer (EarthCARE) Mission, is being implemented as the sixths Earth Explorer Missions. EarthCARE has been specifically defined with the basic objective of improving the understanding of cloud-aerosol-radiation interactions so as to include them correctly and reliably in climate and numerical weather prediction models. EarthCARE will achieve this by providing global observations of cloud and aerosol profiles with collocated measured as well as modelled long-wave and short-wave radiation. The science objectives and key parameters of the mission have been described in Illingworth et al (2015). The mission requirements have been specified in the Mission Requirements Document [AD 1].

Atmospheric cloud and aerosol properties will be retrieved from EarthCARE's 355-nm lidar with a high-spectral-resolution receiver with co- and cross-polar channels (ATLID), 94-GHz Doppler radar (CPR) and a multi-spectral imager (MSI). Radiative transfer models will be used to derive atmospheric radiative properties and heating rates from the retrieved cloud and aerosol observations. Reflected solar and emitted terrestrial thermal radiation will furthermore be observed by the EarthCARE broad-band radiometer (BBR) and compared to their modelled equivalents.

The EarthCARE mission will be implemented in collaboration with the Japanese Aerospace Agency (JAXA) who will provide one of the core instruments, the cloud Doppler radar, including the associated ground facilities in Japan to process the instrument data.

This document describes the validation requirements for EarthCARE Level 1b (L1b), Level 1c (L1c), Level 2a (L2a) and Level 2b (L2b) products.

2.1 EarthCARE data products

An overview of the EarthCARE data products is given in [RD 10]. Their dependencies within the ESA PDGS are described in the Production Model [RD 11].

Each Data Product is described in its Product Description Document (PDD). A Data Product is generated by a Processor. Each Processor is described either in an Algorithm Theoretical Basis Document (ATBD) or an Algorithm Theoretical Basis Overview document (ATBO).

The level 1 data products are described in [RD 1], [RD 3], [RD 5] and [RD 7], the corresponding algorithms are described in [RD 2], [RD 4], [RD 6] and [RD 8]

The level 2 data products are described in [RD 12] and the corresponding retrieval algorithms in [RD 13].

Product names consist of two parts, separated by a hyphen, where the first part indicates the EarthCARE instrument data used as input, where A stands for ATLID, C for CPR, M for

MSI and B for BBR. The second part of the name is generic and indicates the data product content, for example, TC for target classification. Thus, the level 2 product scene target classification derived from information from both ATLID and CPR is named AC-TC.

Data Products are generated by Processors. A Level 2 Processor may generate one or more than one data product. For example, the C-PRO (CPR Profiles) Processor generates the C-FMR, C-CD and C-TC Products. The C-CLD (CPR Cloud) Processor generates only the C-CLD product.

3 LEVEL 1 DATA

The verification of the accuracy of ATLID, MSI and BBR data up to level 1 falls under the responsibility of ESA, supported by a dedicated team of industry engineers and scientists. The verification of the CPR calibration falls under the responsibility of JAXA. The validation team will be concerned with the validation of the (calibrated) level 1b (for MSI, both level 1b and level 1c) data using scientific methodologies, such as comparison to independent collocated observations. Often, the L1 product validation might be supported indirectly through validation of down-stream L2a products or forward calculations of independently characterised collocated atmospheric scenes.

This chapter describes the scientific L1 validation requirements, independently from any industrial validation obligations defined and agreed elsewhere.

3.1 ATLID L1b

The A-NOM data product is the ATLID level 1b data product and contains the range-corrected geo-located and calibrated ATLID Mie[1] co-polar, Rayleigh and cross-polar attenuated backscatter signals, which serve as input for higher-level ATLID and synergistic products. These signals are defined as absolute atmospheric returns at instrument entrance, i.e. they are calibrated against known atmospheric targets and corrected for background and all known instrument-related effects. Thus, they represent what is usually called “attenuated backscatter” in the literature. Statistical (noise) and systematic (bias) errors are reported considering the applied correction and calibration procedures.

The validation of individual channels, Mie co-polar, cross-polar and Rayleigh, necessitates the simultaneous validation of the cross-talk between the channels reported in the data product.

The full description of A-NOM can be found in [RD 1], the level 1 algorithms are summarised in [RD 2].

3.1.1 ATLID L1b Performance Requirement

The ATLID performance requirement is defined in [RD 9]. It is defined against a simple atmospheric model ARMA specified in ANNEX-1 of [RD 9] .

Specifically, ATLID performance requirements ATL-PR-1 to ATL-PR-10 are applicable in the context of Level 1b validation.

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[1] “Mie” – in the context of the ATLID “Mie channel” – is an EarthCARE colloquialism, which refer to the particulate scattering in general.

With respect to scenes defined in ATL-PR-8, ATL-PR-9, ATL-PR-10, respectively, the following performance requirements are defined:

- The accuracy of the Mie co-polar signal L1b product shall be better than 50% in the cloud of backscatter coefficient 8×10^{-7} $sr^{-1}m^{-1}$, for 10-km horizontal integration length.
- The accuracy of the Rayleigh signal L1b product shall be better than 15% below and above the cirrus cloud, for 10-km horizontal integration length.
- The accuracy of the Mie cross-polar signal L1b product shall be better than 50% in the cirrus cloud.

The ATLID instrument calibration requirements are defined in [RD 9], section 5.2.9 (requirements ATL-CA-1 and -4 to -7) and are as follows:.

ATL-CA-1. Absolute in-flight calibration accuracy of the lidar constant shall better than 10% (TBC) in the Mie copular and Rayleigh channels. The lidar constant in the Mie cross-polar channel shall be calibrated relatively to the Mie co-polar channel to an accuracy better than 15% with a target of 10% (TBC).

ATL-CA-4. The Spectral cross-talk in the Rayleigh channel shall be known to better than 20 % of its value or 0.05 whichever is greatest, with a target of 10 % of its value or 0.025 whichever is greatest.

ATL-CA-5. The Spectral cross-talk in the Mie co-polar channel shall be known to better than 10 % of its value or 0.03 whichever is greatest.

ATL-CA-6. The Polarisation cross-talk in the Mie co-polar channel shall be known to better than 10 % of its value or 0.01 whichever is greatest.

ATL-CA-7. The Polarisation cross-talk in the Mie cross-polar channel shall be known to better than 10 % of its value or 0.01 whichever is greatest.

The long-term stability or degradation of the data products is also subject of validation.

3.1.2 ATLID L1b Validation

Attenuated backscatter signals measured from space cannot be directly compared with airborne or ground-based lidar measurements, because of the different measurement geometry and signal attenuation. High-flying aircraft with internally calibrated down-looking 355-nm high-spectral-resolution/polarization lidar will provide most similar attenuated backscatter signals compared to ATLID, provided that there is negligible particle extinction above the aircraft and multiple-scattering influence is avoided. As described by Rogers et al. (2011), validation of the absolute calibration of the CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) lidar was possible with such an approach with an error of ±4.5%. Currently, two airborne 355-nm high-spectral-resolution lidars are available, one developed at LATMOS (Laboratoire Atmosphères, Milieux, Observations Spatiales), France (Bruneau et al., 2015), and one at NASA Langley Research Center, USA (Burton et al., 2015). A third device is being developed and might become available in time for EarthCARE validation (Binietoglou et al., 2016). Underflying EarthCARE with airborne instruments will require considerable coordination efforts. Respective activities will thus be limited to short-term missions, which must be supplemented with long-term supporting activities from ground.

Mona et al. (2009) described a methodology to derive satellite-like attenuated backscatter signals from ground-based measurements with Raman or high-spectral-resolution lidar by using the extinction and backscatter coefficient profiles independently measured with these instruments. The method was applied to EARLINET (European Aerosol Research Lidar Network, part of the Aerosols, Clouds, and Trace gases Research InfraStructure, ACTRIS) observations during CALIPSO overpasses. In this way, it could be proven that the space-borne L1 data are free of bias (Pappalardo et al., 2010). EARLINET and other ground-based stations equipped with 355-nm Raman and high-spectral-resolution lidars are suitable for long-term ground-based ATLID validation. A specific strategy for collocated observations and statistical evaluation of results has been set up by EARLINET (Pappalardo et al., 2010) and should be adopted for EarthCARE.

In case airborne and/or ground-based measurements will show a disagreement with ATLID L1b data, a detailed check of the ATLID calibration procedures would be required. In particular, the following calibrations should be checked by external means:

- Mie cross-polar channel absolute calibration
- Rayleigh channel absolute calibration
- Mie co-polar channel absolute calibration
- Spectral cross-talk calibration (removal of Rayleigh contribution in Mie co-polar channel and removal of Mie contribution in Rayleigh channel)

A statistical analysis of ATLID L1b profiles constitute a useful approach for evaluating the quality of ATLID L1b data: 1) analysing statistically the L1b collected during the very first weeks/months of the mission allow to identify unphysical measurements due to abnormal instrument behaviours and to calibration errors. 2) a survey of dedicated statistical diagnostics built directly from ATLID L1b profiles all over the mission lifetime allow detecting shifts in instrument characteristics and calibration over time. 3) a comparison between well-defined statistical diagnostics obtained from ATLID L1b and CALIOP L1 give insight on the quality of ATLID data (the wavelength differences between the two instruments is taken into account in the comparison). The height-intensity histograms built by aggregating instantaneous L1b profiles over typical geographical areas and over various period of time should be built for ATLID as it has been done in the past for CALIOP and CloudSat (e.g., Marchand et al., 2008; Chepfer et al., 2010); within such histogram dedicated to ATLID L1b validation, the intensity x-axis should be the Rayleigh signal, the Mie-co polar signal, the Mie cross-polar signal, or the scattering ratio, SR, or the attenuated backscatter, ATB. Then dedicated statistical diagnostics should be built from these height intensity histograms to reach each objectives 1), 2) and 3) mentioned above.

3.2 CPR L1b

The C-NOM data product is the CPR level 1b data product and described in [RD 7]. The level 1b algorithms are described in [RD 8].

The two main CPR measurements are power (calibrated radar reflectivity) and Doppler velocity.

3.2.1 CPR L1b Performance Requirements

The CPR performance requirements are described in [AD 1], section 4.7.2., and [RD 9], section 5.3.

The key requirements are:

- The radar reflectivity sensitivity is -35 dBZ for a 10-km along-track horizontal integration and -30 dBZ for a 1-km horizontal integration.
- The total radiometric accuracy of the derived apparent per-unit-volume radar reflectivity shall at all times be better (i.e. less) than or equal to 2.7 dB for an along-track signal integration distance of 10km.
- For an along track integration distance of 10 km it shall be possible to determine this velocity over the range of -10 m/s to +10 m/s with an accuracy of 1 m/s (threshold) at any PRF at a minimum reflectivity factor of -19 dBZ.

It has to be noted that the vertical range of the radar observations is not constant over all latitudes. In tropical latitudes, the maximum vertical range of the radar is 20 km with a corresponding low PRF (pulse repetition frequency), while in high latitudes, the vertical range is limited, allowing the highest PRF, which would yield the best Doppler performance.

3.2.2 CPR L1b Validation

The validation of the CPR L1b products falls within the responsibility of JAXA. The description here-below is for information, also as it has relevance for CPR L2a validation.

Doppler velocity critically depends on accurate knowledge of the CPR antenna pointing. Statistical methods are suggested for the evaluation and calibration of radar reflectivity and Doppler measurements. First, comparison of ground-based radar observations of nonprecipitating ice clouds is suggested for evaluating the CPR calibrated radar reflectivity (Protat et al., 2009). Similarly, for the CPR antenna pointing comparison of the measured CPR Doppler velocities in ice clouds and the Earth's surface should be used to evaluate the reported antenna pointing in the C-NOM file (Battaglia and Kollias, 2014; Kobayashi and Kumagai, 2003).

In addition to the two primary measurements, Pre-Flight Data are needed to best evaluate the reported CPR L1b variables. Such data include:

1. Radar constant for converting dBZ to dBm. The radar constant includes most of the hardware components including peak power, antenna gain, pulse information etc. This parameter is needed because the C-NOM reports values some times in power units (W) and sometimes in dBZ.

2. The detailed mapping of the relationship between A/D counts and input received power for the logarithmic receiver from the receiver power levels to saturation. This will allow us to verify the linearity of the receiver, evaluate the dynamic range of the receiver and have a complete characterization of the receiver saturation that is expected to happen in about 20% of the time by the Earth's surface and we need to know when to flag the data for saturation and how to represent this receiver saturation in the C-NOM.

3. Saturation level for the linear receiver (counts/power level). We are not interest in the details (non-linear region) since the CPR linear receiver will always be saturated by the Earth's surface signal.

4. An estimate of the CPR radar receiver noise floor in dBm, and the receiver temperature, bandwidth and noise figure.

5. Detail, high resolution mapping of the point target response (PTR) of the receiver. The PTR mapping is desirable to be provided at very high sampling rate (~a few meters) in units of counts or dBm. We would like to have the PTR for 2-3 different level (non-saturated and saturated).

6. Antenna pattern. We need gain and mapping of the main and side lobes as a function of angle.

7. Characterization of the Doppler (linear receiver) under saturation. This requires information about phase or amplitude distortion by the linear receiver under nominal saturation conditions that we expect from the Earth's surface signal (+30 dB above saturation).

8. Transmitted peak power levels. In particular, the total receiver isolation induced by the QOF and the T/R switches is of interest.

The Doppler performance needs to be evaluated for all PRFs. For the validation planning, appropriate geolocation have to be selected in order to cover the full range of PRF settings used.

3.3 MSI L1b and L1c

M-NOM contains the MSI L1b products and L1c products. M-NOM is described in [RD 3] and the corresponding level 1b/c algorithms are described in [RD 4].

The MSI channels centre wavelengths are:

		centre wavelength (µm)
Band 1	VIS	0.67, +/- 0.01
Band 2	NIR	0.865, +/- 0.01
Band 3	SWIR 1	1.65, +/- 0.015
Band 4	SWIR 2	2.21, +/- 0.015
Band 5	TIR 1	8.8, +/- 0.05
Band 6	TIR 2	10.8, +/- 0.05
Band 7	TIR 3	12.0, +/- 0.05

3.3.1 *MSI L1b Performance Requirement*

The performance related key MSI instrument design requirements are listed in this sub-section, as background information. The complete list of MSI design requirements can be found in[RD 9], section 5.4.

The radiometric requirements of the instruments are based on various scenarios: (a) clear-sky conditions to infer aerosol properties, (b) clear-sky conditions to infer surface spectral reflectances and surface temperatures, (c) cloudy skies to infer cloud properties (from dark to bright surfaces).

Dynamic range, SNR and radiometric calibration, NEDT

Dynamic range, SNR and radiometric calibration for solar channels:

		Dynamic range [%]	SNR at 100% TOA reflectivity	*Goal* values at low TOA reflectivity		Absolute radiometric accuracy
				SNR	Reference signal [$Wm^{-2}sr^{-1}\mu m^{-1}$]	
Band 1	VIS	0 – 110	500	75 (*) (**)	30	2% goal 10% threshold (***)
Band 2	NIR	0 – 110	500	65 (*) (**)	17	
Band 3	SWIR 1	0 – 102	250	18 (*)	1.5	
Band 4	SWIR 2	0 – 100	250	21 (*)	0.5	

The radiometric stability shall be better than 1% of the estimated reflectance value over one year. The inter-band accuracy shall be <1%.

(*)The goal values for SNR values and the corresponding signal levels in the solar channels shall be based on the cloud optical thickness (δ_c) for a low water cloud and the requirement to retrieve its variation ($\Delta\delta_c$), with $\delta_c = 0.5$ and $\Delta\delta_c = 0.05$. For SWIR channels, the sensitivity criterion shall be based on a retrieved water droplet size uncertainty of $\Delta r_e = 0.5\mu m$ and ice particle size uncertainty of $\Delta d_e = 5.0\mu m$ for a water cloud with 1km cloud base and an ice cloud with 10km cloud base and an optical thickness of OD=0.5. Requirements shall refer to the individual MSI pixel level.

(**) In addition, the SNR at low reflectivity for band 1 (VIS) and band 2 (NIR) shall also be derived from the aerosol accuracy requirement of 0.02 optical depth over open sea for 10km x 10km area. These values are goal requirements for band 1 and 2.

(***) As a minimum scientific requirement, or threshold requirement, an absolute radiometric accuracy of <10% would allow for scene identification (which is the primary objective of MSI, needed as support to BBR flux retrievals) and retrieval of parameters of optically thick clouds. However, this accuracy would compromise aerosol retrieval capabilities and render the retrievals of thin clouds impossible. Therefore, 5% is considered the scientific breakpoint value, which would significantly improve aerosol and thin cloud retrievals. The design goal requirement should be 2%, which would be the ideal value for accurate cloud and aerosol retrievals. The accuracy shall be achieved over a dynamic range reaching from lowest to the highest TOA spectral radiances that can be expected during daylight.

Dynamic range and NEDT for thermal channels:

		Dynamic range [K]	Threshold requirements NEDT at 220K	Threshold requirements NEDT at 293K	Goal requirements NEDT at 220K	Goal requirements NEDT at 293K
Band 5	TIR 1	170 – 350	0.8	0.25	0.6	0.1
Band 6	TIR 2	170 – 350	0.8	0.25	0.7	0.15
Band 7	TIR 3	170 – 350	0.8	0.25	0.8	0.15

The goal requirement of 0.1K NEDT at 293K is required for the retrieval of cirrus particle sizes which would not be possible with 0.25K. The required radiometric accuracy shall be better than 1K at 280K. The interband accuracy shall be better than 0.25K (goal 0.1K) over one year. The radiometric stability shall be better than 0.3K over one year.

Radiometric resolution solar channels

The SNR of the solar channels shall be higher than the values specified here-below:

Band			Min Signal(1)	Reference Signal(1)		Max Signal(1)	SNR @ Reference Signal	
				Low	High		Low	High
							Goal	Threshold
			$W.m^{-2}.sr^{-1}.\mu m^{-1}$					
B	1	VIS	3.85	30	444.6	489.1	75	500
B	2	NIR	0.95	17	282.7	311.0	65	500
B	3	SWIR 1	0.016	1.5	67.9	69.3	18	250
B	4	SWIR 2	0.0015	0.5	24.6	24.6	21	250

(1) TOA spectral radiance

The NEDT of the thermal channels shall be smaller than the value specified here-below:

Band			Min Signal(1)	Reference Signal(1)		Max Signal(1)	NEDT @ Reference Signal			
				Low	High		Low		High	
							Threshold	Goal	Threshold	Goal
			K	K	K	K	K	K	K	K
B	7	TIR 1	170	220	293	350	0.80	0.60	0.25	0.10
B	8	TIR 2	170	220	293	350	0.80	0.70	0.25	0.15
B	9	TIR 3	170	220	293	350	0.80	0.80	0.25	0.15

(1) TOA brightness temperature

Absolute Radiometric Accuracy

The absolute radiometric accuracy of the data acquired in the solar channels shall be smaller than 10% (5% goal) over the reduced dynamic range, traceable to the SI units.

The absolute radiometric accuracy of the data acquired in the TIR channels shall be smaller than 1 K over the reduced dynamic range, traceable to SI units.

(NB: Reduced dynamic range is defined as low to max signal.)

Geometric Image Quality

The absolute localization accuracy shall be such as to ensure meeting requirement listed under Section 5.1, namely, 500m RMS for MSI Level 1c. As a goal, half of the spatial sampling distance (500m) has been defined.

3.3.2 MSI L1b Validation

MSI Level 1 products should be validated, in particular, with respect to their geometric and radiometric accuracies. The data should include all geographical regions and seasons.

In-flight calibration should monitor the instrument characterisation and parameters. Validation teams shall propose suitable methods.

Stable Earth targets, such as deep convective clouds, Antarctica, ocean and desert, can be used, in combination with radiative transfer calculations, to compare and monitor observed and calculated radiances.

Comparison with corresponding radiance observations from other satellites, such as MODIS/VIIRS (polar satellite) and SEVIRI (geostationary). While collocated observations with other polar satellites will be not very frequent, comparisons with geostationary imagers will provide a very large amount of collocated observations throughout the EarthCARE mission life time. Therefore, comparison to geostationary imagery should be an important Level 1 verification and monitoring activity.

Cross-check with EarthCARE BBR observations should be performed regularly, in particular, in order to monitor any long-term relative change between the two instruments.

The MSI dynamic range could be checked by observing targets with the highest signal levels and comparing and monitoring the MSI observations against other satellite observations of the same target as well as theoretical radiative transfer modelling. Later on during the mission, after good confidence of ATLID observations has already been established, forward-calculations of deep convective clouds retrieved from ATLID could be useful.

High contrast scenes could be used to investigate into stray light or pixel cross talk. Homogeneous (uniform) scenes should be used to search for any non-nominal behaviour of individual MSI pixels.

The geolocation of the MSI channels can be verified, per channel, using sharp geological features, such as coast lines.

3.4 BBR L1b

The BBR instrument measures the total Earth radiance in two spectral channels:

- the short wave (SW) channel [< 0.2 μm , 4 μm] and
- the total wave (TW) channel [< 0.2 μm , > 50 μm]

The SW and TW observations are taking alternatingly so that several SW and TW observations have been taken over each 10 km long distance.

B-NOM contains the BBR L1b SW radiances and the total long-wave (LW) radiance, which is calculated by subtracting the SW signal, integrated over 10 km along-track, from the TW signal, integrated over the same 10 km along-track. Three resolutions are defined where the total short-wave (SW) and total long-wave (LW) radiance per each of the three telescopes is reported. The “standard resolution” of 10 km × 10 km, the “small resolution” of N km × 10 km (where N is a configurable length in across-track direction, centred at nadir, of smaller than 10 km) and “full resolution” of M km × 10 km (where M is the full width of approximately 18 km at nadir corresponding to the BBR detector array size). All resolutions are integrated over 10 km along-track and are oversampled by 1 km.

B-SNG is also a BBR L1b product and contains the SW and TW radiances at their native resolution, i.e., corresponding to the BBR detector array resolution and not integrated over 10 km along-track or any distances across-track. This product provides the data user with the freedom to define any desired spatial integration domain.

The B-NOM and B-SNG products are described in [RD 5] and the corresponding level 1 algorithms are described in [RD 6].

Both B-NOM and B-SNG have not been corrected for the instrument effect. This so-called “unfiltering process” is done within the Level 2 processor BM-RAD. BM-RAD therefore contains the unfiltered radiances.

3.4.1 *BBR L1b Performance Requirements*

The complete list of BBR instrument engineering requirements can be found in [RD 9], section 5.5.

The radiometric absolute accuracy requirement of the BBR measurements (excluding unfiltering errors) is:

For the SW channels	2.5 $Wm^{-2}sr^{-1}$ (threshold), 2.0 $Wm^{-2}sr^{-1}$ (target)
For the LW channels	1.5 $Wm^{-2}sr^{-1}$

The applicable dynamic range is

SW 0-450 $Wm^{-2}sr^{-1}$
LW 0-130 $Wm^{-2}sr^{-1}$
TW 0-550 $Wm^{-2}sr^{-1}$

Pixel geolocation requirement is 1 km (goal 500 m).

3.4.2 Suitable B-NOM and B-SNG validation methodologies

The following list is non-exclusive:

- The time series of detector gain values shall first be analysed to assess the noise level and determine if it is needed to filter the (88 seconds) gain values. In order to separate the noise from the real variation of the detectors gain, B-SNG TW observations during night-time should be analysed.
- The SW gain shall be monitored in-flight via VisCal system, to detect changes in response due to aging (e.g. coatings). Measurement of SW & Monitor Photo Diode (MPD) response to sun-illuminated diffuser, to monitor aging effects. MPDs monitor aging of VisCal.
- In addition of using the VisCal, the SW gain shall also be further verified using bright cold deep convective clouds, as in the “3-channel approach” (Duvel and Raberanto, 2000; Kratz *et al.*, 2002). For this, MSI thermal observations should be used to subtract the (small) thermal contributions to the B-SNG TW and SW channels.
- Instrument linearity is verified by the industry during commissioning by varying the BB temperatures. If non-linearity is detected, the effect on the product should be quantified and a correction proposed.
- The consistency between the individual detector signals shall be validated based on B-SNG observations collected over several orbits. The effect of (systematic) differences in viewing geometries shall be previously addressed for the selection of scene type/geometries. The detector signal consistency shall be done for the B-SNG SW and TW, separately for the 3 views. The study should address the consistency in signal level but the consistency in the noise level as well.
- The consistency should also be addressed for different scenes types like clear ocean, vegetation, desert, snow, deep convective clouds. This should give confidence that the variation in the individual detector spectral response remain within requirements.
- The consistency between the 3 views shall also be addressed on B-SNG and B-NOM. In particular, the fore and aft observations should be statistically compared when the Sun-Earth-Satellite geometries are similar. For the LW some regions with known azimuthal dependency should be discarded. (Clerbaux et al., 2010)
- The solar contamination in the LW channel shall be validated. To this end, the diurnal variation of the ratio between the LW nadir radiances and the Broad-band estimates from MSI shall be assessed.

- The thermal contamination in SW channel (aka quartz filter leakage) shall be validated based on night time BBR observations. In case of significant discrepancy of the quartz filter transmission wrt the ground measurement, it shall be determined if coming from characterization in the cut-off region (around 4 µm) or in the far infra-red (>50 µm). This shall be addressed based on SW observations of the cold and warm calibration BBs and also based on scene observations over an extended range of LW radiance (scene temperature).
- The B-SNG geolocation accuracy shall be verified based on clear-sky earth target observations (e.g. coastlines, lakes). The consistency of the geolocation with MSI shall also be verified given the synergetic use of BBR and MSI data. The relative accuracy of the geolocation shall be assessed by image matching.
- The BBR instrument has 2 quartz filters and only one filter transmission is used in the processing. The consistency between SW signals for the 2 apertures in the chopper mechanism shall be addressed based on B-SNG Earth observations on the full range of SW and LW spectra.
- Although the instrument design should minimise the stray light, the effect of it shall be assessed over homogeneous scenes.
- The instrument degradation shall be monitored using Earth targets. The relative signals of the fore/nadir/aft views over a large ensemble of scene types (clouds, clearocean, snow, vegetation, desert) shall be analysed over time.

4 LEVEL 2 DATA PRODUCTS

The L2 products are distinguished in L2a products derived from one single instrument and L2b products synergistically derived from two or more EarthCARE instruments.

The following sections discuss the products and their parameters according to the products in the EarthCARE production model. However, derived microphysical / geophysical properties that are derived by different means – e.g. ice water content derived by ATLID L2a, CPR L2a and synergistic L2b retrievals – may be validated together by suitable methodologies (e.g. collocated in-situ observations) and are therefore re-appearing or referenced to in dedicated cloud/aerosol/radiation validation sections.

4.1 Validation according to Data Product

4.1.1 ATLID L2a Products

The ATLID instrument measures vertical profiles of thin clouds and aerosols. The profiles observed have a vertical resolution of 103 m and a sampling along-track of approximately 280 m (assuming integration of two consecutive lidar “pixels”). The first processing step is the feature detection, which provides the Feature Mask (A-FM) data product. This product is a native vertical and along-track resolution. Subsequently, at a reduced along-track resolution in order to achieve suitable signal-to-noise ratio, geophysical products are being retrieved and reported at approximately 1 km along-track resolution. These products include the target classification (A-TC), extinction, backscatter, depolarisation product (A-EBD), ice cloud parameters (A-ICE) and aerosol parameters (A-AER). Furthermore, A-CTH defines the cloud top height and A-ALD describes the aerosol layer.

The validation of the ATLID L2 products will require the use of collocated data from ground, air-borne and satellite observations. Geolocation requirements of external validation data sets will have to be individually analysed depending on the observed target. Aerosols are typically far less variable in time and space compared to clouds, therefore, collocation requirements for validation measurements are less stringent than for clouds.

4.1.1.1 A-FM

The ATLID Feature Mask identifies atmospheric features, without classifying them. Significant lidar return, after appropriate signal averaging and smoothing, would suggest that scattering on particular matter exist. This may be, for example, a cloud or aerosol layer, however, the actual particle type will not be determined by A-FM. Where a feature has been detected, subsequent processors will further identify its characteristics. The validation of the feature mask is therefore an important first step for subsequent validation of ATLID retrievals (products such as A-AER, A-EBD, etc.).

The validation of A-FM shall be performed with collocated observations which from active remote sensing observations. Of all collocated observations, the goal is to achieve high confidence in the vertical and horizontal location of detected features.

The following parameters shall be validated:

- geolocation of detected feature (lon, lat, altitude)
- confidence in the detection of a feature (and its assigned value)
- confidence in the clear sky detections
- confidence in the detection of attenuated regions
- correct assessment of the lidar surface altitude (especially in areas with rapid changing surface altitudes and for different surface types).
- detection and correct processing of signals gaps

The maturity of the FeatureMask algorithm is high, even though it has never been adopted on anything else than simulated data up to this point. It will be validated post launch on regular basis by comparing the L1b data itself to the retrieved FeatureMask and especially by monitoring the mean clear sky signal profiles. Well-coordinated aircraft flights along the ATLID track for many different atmospheric states and over different surfaces can be used to provide a thorough evaluation of the processor.

4.1.1.2 A-AER

The 10km+ scale aerosol oriented 355-nm extinction, backscatter and depolarization profiles comprise the main A-AER products. The algorithm producing these products uses, as input, A-FM data as well as A-NOM data. The output is given on the X-JSG grid, however, the horizontal resolution of the products ranges from 10 km to 100 km depending on the SNR of the data. “Strong features” (e.g. clouds) are avoided in the averaging procedure since, due to the non-linear nature of the lidar equation, averaging over both cloud and aerosol regions would not yield an accurate product.

Validation of these products requires comparison with co-located independent retrievals of extinction, backscatter and particle depolarization, preferably, at the wavelength of ATLID. In order to reduce the uncertainty in the validation data, HSRL or Raman lidar data is preferred. Both airborne and ground-based network observations could be suitable for validation purposes.

Since aerosol fields are often ‘relatively’ homogeneous on the 100 km horizontal scale [Pappalardo et al, 2010], validation using well co-located aircraft observations could be carried out using a relatively few aircraft tracks. This has been demonstrated during previous work with CALIPSO and airborne lidar observations [McGill et al., 2007].

Longer-term (e.g. observations collected over weeks or months) ground-based lidar network observations could also be used for validation purposes. The data would be used in a statistical manner by collecting observations which are ‘close enough’ in time and space to ATLID overpasses. This method has also been demonstrated in the case of CALIPSO [Pappalardo et al, 2010].

One caveat that applies to the use of both aircraft and ground-based observations is that the validation cases should cover an appropriate range of aerosol conditions. For example, large (e.g. dust) particles may require multiple scattering to be accounted for in the ATLID retrievals, hence, it is desirable to sample a range of conditions where multiple-scattering effects may or may not be significant.

4.1.1.3 A-EBD

The 355 nm cloud and aerosol extinction, backscatter and depolarization profiles at the 1-km horizontal scale are the primary products of the A-EBD retrieval procedure. From a product point-of-view, the key difference between these products and their A-AER counterparts are the horizontal scale (1 km vs 10-100 km) and the inclusion of both clouds and aerosols. Due to the limited penetration of the lidar into water clouds, most of the cloud retrievals will indeed be for ice (e.g. cirrus) clouds.

The aerosol profiles could be validated using the same approach as described for A-AER. However, since clouds are, in general, much more inhomogeneous than aerosols, co-location between the ATLID and aircraft/ground-based observations is a much more important consideration. This argues for the use tightly coordinated aircraft-ATLID cirrus cloud observations for validation purposes. Ground-based lidar network observations could also be used. However, on account of the variability present in clouds – even in “well-behaved” cirrus – stricter co-location criteria will be required, which will result in larger validation periods.

4.1.1.4 A-TC

The ATLID target classification products are produced using A-AER and/or A-EBD optical properties as inputs and classify the detected targets as being ice cloud, water cloud, or aerosol (type). The discrimination of ice and water cloud can likely largely be accomplished by *inspection*, that is, by comparing the retrievals to manual expert judgement based on the optical retrievals and the lidar L1 data. However, the assignment of aerosol class cannot be accomplished so readily.

A certain degree of zero-level validation may be accomplished by comparing the A-TC aerosol classification products against suitable atmospheric chemical/aerosol models (e.g. ECMWF MACC fields [Morcrette 2009]). Further validation could be achieved by comparing lidar network observations which have been analysed using multi-wavelength and auxiliary information including, e.g., back-trajectory information. Ultimately, however, the validation of assigned aerosol type can only be considered to be validated, if *in situ* aircraft-based aerosol measurements are used. These measurements should include:

- Aerosol size distribution
- Aerosol mass
- Aerosol chemical composition
- Aerosol extinction
- Aerosol phase function.

For aerosol type/composition, the co-location requirements between the aircraft and ATLID observations would not need to be as tight as is required in the case for validating the optical properties, which can change on a local scale.

The measurements, however, should span a reasonable range of aerosol types. Cases where different aerosol types with different composition exist at different heights (e.g., transported dust and/or smoke layers over marine aerosol layers) would be of particular interest.

4.1.1.5 A-ICE

A-ICE is comprised of empirical estimates of ice-water content (IWC) and effective particle size based on lidar-derived extinction and auxiliary temperature information. For this particular product validation would have to rely on in-situ aircraft-based measurements. These measurements should include:

- IWC
- Particle Size distribution
- Particle imagery
- Extinction

4.1.1.6 A-CTH

Cloud top height (CTH) belongs to the ATLID layer products. It serves as input for the synergistic ATLID-MSI retrievals and is therefore defined on the EarthCARE Joint Standard Grid (JSG). The cloud top height is defined as the upper geometrical boundary of the uppermost cloud layer in the atmosphere. The A-CTH product is derived from the ATLID Mie co-polar signal by searching for characteristic signal gradients with a wavelet covariance transform (WCT) algorithm (Brooks, 2003; Baars et al., 2008) under consideration of configurable threshold settings. Depending on the cloud optical thickness and the signal-to-noise ratio, the boundaries are detected with a horizontal resolution of 1 JSG pixel (thick clouds) or 11 JSG pixels (thin clouds). The product contains a simplified classification of the uppermost cloud as well as quality indicators in terms of level of confidence of the detection and level of consistency with the ATLID Target Classification (A-TC) product.

The maturity of the A-CTH product is very high. In general, space-borne lidars can well detect the uppermost cloud top and in particular are very sensitive to high and optically thin ice clouds. Validation of the product shall focus on the accurate geometrical retrieval of the top height (required accuracy <300 m, [AD1]), the correct discrimination between optically thin clouds and aerosol layers, and the identification of multi-layer clouds (semi-transparent above opaque clouds). The validation of A-CTH shall be performed with collocated active remote-sensing observations, preferably with lidar or combined lidar-radar setups to allow for the detection of thin ice clouds. Measurements from aircraft flying above the cirrus level are most useful, since all kinds of cloud systems including ice and water clouds can be covered. Ground-based validation with lidar will be possible only when the laser beam is not fully attenuated (pure ice cloud scenes). Ground-based radar observations may fail in detecting high ice clouds and should not be used as stand-alone validation instruments for this product.

4.1.1.7 A-ALD

ATLID Aerosol Layer Descriptor (A-ALD) belongs to the ATLID layer products and contains geometrical and optical information on aerosol layers. It serves as input for the synergistic ATLID-MSI retrievals. The same WCT algorithm as in the A-CTH retrieval is used to derive aerosol layer boundaries from the ATLID Mie co-polar signal, averaged over 11 JSG pixels horizontally with 1 JSG pixel step width. Appropriate threshold settings allow the discrimination of clouds and aerosol. The A-ALD product provides the upper and lower geometrical boundaries of significant aerosol layers, the optical thickness of each layer (ALOT), the column and the stratospheric AOT at 355 nm. ALOT and AOT are calculated by integrating the ATLID extinction profile taken from the ATLID Extinction, Backscatter and Depolarization (A-EBD) product. In addition, layer-mean values of extinction and backscatter coefficient, lidar ratio and particle linear depolarization ratio are calculated from the A-EBD product. The A-ALD product is defined for cloud-free conditions only. It contains quality indicators in terms of level of confidence for the aerosol layer detection and level of consistency with the A-TC product.

While the maturity of the layer boundary detection is comparably high, the accuracy of layer-mean optical properties strongly depends on the quality of the ATLID profile products. Validation of A-ALD can be performed with airborne or ground-based lidar measurements. The validation shall focus on the accurate geometrical retrieval of layer boundaries, including the height of the planetary boundary layer (required accuracy <500 m, [AD1]). For the validation of aerosol layer optical thickness, layer-mean extinction and backscatter coefficients, lidar ratio and particle linear depolarization ratio respective measurements of these quantities with 355-nm Raman or high-spectral-resolution lidar with polarization capability at this wavelength are required. Since the A-ALD product is derived for cloud-free conditions only, its quality can be fully monitored over the mission lifetime with the help of standardized aerosol lidar network observations (fiducial reference measurements) as performed in EARLINET (European Aerosol Research Lidar Network, part of ACTRIS, the Aerosols, Clouds, and Trace gases Research InfraStructure, Pappalardo et al., 2014) or other contributors to GALION (GAW Aerosol Lidar Observation Network, GAW Report 178, 2008), provided that the instruments operate at 355 nm. Respective strategies regarding collocation and coverage have been developed in the framework of CALIPSO validation activities and should be adapted for EarthCARE (Pappalardo et al., 2010).

4.1.2 *CPR L2a Products*

The CPR is the main EarthCARE sensor capable of providing range-resolved Doppler radar observations from optically thick clouds ($\tau > 3$). The CPR measurements will be used to derive hydrometeor locations (C-FMR), Doppler velocities (C-CD), target classifications (C-TC) and microphysical retrievals. The validation of the CPR L2a products uses data obtained from remote sensors and in-situ measurements that are ground-based, and possibly aircraft-mounted. A large suite of ground-based sensors (not limited to radar observations) provides the opportunity to derive the microphysics profile using multiple instruments and methodologies. The availability of airborne dataset may refine and verify the ground-based retrieval. The main problems related to the validation of the satellite algorithm are the lack of satellite observations close to the ground, the blind zone, and the matching of the observations (due to the punctual nature of used ground/airborne measurements).

The validation projects of interest are either based on the data, possibly at long term, from measurement sites such as various ARM sites or CloudNET, or based on more sophisticated observational and instrumentation strategy during intensive field campaigns that focus on a specific algorithm component, e.g. cirrus/ice clouds, precipitating snow, liquid clouds, etc.., and require participation of research aircraft providing coordinated airborne measurements besides enhanced suites of instrumentation. The validation based at long term systematic measurements at the selected sites is mainly statistical and structural assessment comparing only statistical properties of the derived retrieval products. The case study direct comparison is mainly via intensive field experiment.

4.1.2.1 C-FMR

The CPR Feature Mask and Reflectivity product deal with the quality control of the CPR reflectivity measurements. The primary component of the C-FMR algorithm is the Feature Mask algorithm that identifies all CPR resolution volumes that contain significant return signals from hydrometeors and the ground. The C-FMR algorithm also provides Path Integrated Attenuation (PIA) and two-way gaseous attenuation estimates and the geometrical properties of the CPR reflectivity best estimate after correction for gaseous attenuation. Finally, the presence of multiple scattering in the CPR observations is identified and appropriate flags are generated.

The maturity of the Feature Mask algorithm is high and it will be validated post launch by comparing statistics of CPR reflectivities and morphology as a function height above the ground with those collected by ground-based radars operated at 35- and 94-GHz (Protat et al., 2009). Well-coordinated aircraft flights along the CPR track can be used to develop time-height plots of hydrometeor echoes that can be directly compared with segments of CPR observations. Similarly, the evaluation of the PIA estimates can be evaluated using either Liquid Water Path statistics from ground-based sites in light-to-moderate precipitation conditions (from drizzle to 3-4 $\mathrm{mmhr^{-1}}$) and compare with the PIA statistics from similar periods (within 200 km from the ground-based site and within ±1 hour of the CPR overpass) or aircraft observations with a nadir looking 94-GHz radar and estimate of the sigma zero (σ_0) over the ocean.

The C-FMR reflectivity is derived from and closely related to the reflectivity in the C-NOM product. See also validation requirements discussed in section 3.2

4.1.2.2 C-CD

The C-CD product provides the quality-controlled bias-corrected mean Doppler velocity estimates (Doppler measurements corrected for antenna mis-pointing, non-uniform beam filling, and velocity folding). In addition, the estimates of the Mean Doppler Velocity Best Estimate are provided where the mean Doppler best estimate is the bias-free mean Doppler velocity evaluated using a variable length-height integration window.

The maturity of the C-CD algorithms is low, especially the part related to the antenna pointing correction and the selection of the optimum integration along-track length. Fortunately, Doppler velocity statistics of clouds from ground-based sites are well documented (Kalesse and Kollias, 2013) and two natural targets have been suggested to provide evaluation of the best estimate CPR Doppler velocities: the Earth’s surface with an expected, averaged Doppler velocity zero (Kobayashi and Kumagai, 2003; Battaglia and Kollias, 2014a) and cirrus clouds (Battaglia and Kollias, 2014b).

The C-CD Doppler product is derived and closely related to the Doppler product in the C-NOM product. See also validation requirements discussed in section 3.2

4.1.2.3 C-TC

The C-TC product provides the location of cloud boundaries, cloud and precipitation classification, melting layer identification flags and Doppler velocity classification. In particular, the C-TC provide the following classifications: melting layer detection, cloud-precipitation distinction, drizzle-free and light drizzling clouds and CPR Doppler velocity classification as sedimentation only, vertical air motion only and mixed.

The maturity of the C-TC algorithm is very high. Cloud or target classification schemes based on similar principles as C-TC have been developed for Cloudnet (Hogan and O’Connor, 2004) and ARM (Kollias et al., 2007) programs and for CloudSat (http://gcmd.nasa.gov/records/GCMD_CloudSat_2B-CLDCLASS.html). An addition of observed Doppler velocity to the cloud and precipitation algorithms is expected to improve the quality and robustness of the classifications, especially the detection of the melting layer and thus the classification of different precipitation types. Ground-based observations from Cloudnet and ARM can help us to evaluate the performance of the C-TC. From the ground, there are cloud and precipitation algorithms that combine radar reflectivity and Doppler velocity. In the case of strong precipitation conditions, airborne observations at 94-GHz are preferred since they capture the attenuated profile of the CPR reflectivity.

4.1.2.4 C-CLD

The C-CLD products provide information on cloud and precipitation retrieved using an optimal estimation method determining vertical profiles of hydrometeor water content and particle characteristic size from reflectivity and mean Doppler velocity previously corrected for air motion. An ensemble-based method is used to obtain the forward model relations and the associated uncertainty. The ensemble is determined by the spread of uncertainties in the several different microphysical models applied to map the microphysical quantities to the radar observables. The ensemble mean relations and its spread defined by standard deviation represent the forward model relations and their microphysics associated uncertainty.

Liquid clouds: The validation of the liquid cloud retrieval products requires i) the identification of the presence of drizzle, liquid water path (LWP) measurements, cloud base measurements and drizzle properties at the cloud base level. Such measurements are available at island-based sites such as the US DOE ARM program Eastern North Atlantic (ENA) site and continental sites, such as Cloudnet observatories (for example, JOYCE site (Lohnert et al., 2014) operated by the U. of Cologne). Profiling radar observations combined with calibrated ceilometer observations will be used to retrieve the drizzle properties at the cloud base level (O'Connor et al., 2005). The LWP measurements are provided by the microwave radiometer and cloud LWC retrievals can be derived using radar-radiometer techniques (Frisch et al., 1998) or dual-wavelength radar techniques (Hogan et al., 2005; Huang et al., 2009). Below the cloud base, the differences in backscatter at two different lidar wavelengths (Westbrook et al. 2010; Lolli et al. 2013) can be added to retrieve drizzle microphysics. The C-CLD algorithm retrieves only the drizzle mass flux at the cloud base, and not below, however, the continuity requirement at the cloud base could be useful.

Ice clouds: The ice/snow retrieval products can be validated from ground-based instrumentation using multi-wavelength radar approach (e.g., Leinonen et al., 2015; combined with the backscatter lidar and infrared radiometer (Delanoe and Hogan, 2008). These technique can provide well constrainted ice/snow microphysical retrievals that can be used to evaluate the single radar frequency approach used in C-PRO. The multi-wavelength method is more useful in the retrieval in the presence of deeper systems with larger particles dominating radar returns. The radar-lidar technique becomes main technique for ice clouds with optical thickness not too high due to the rapid extinction of the lidar signal (Illingworth et al., 2007). The synergy of cloud radar with lidar to retrieve the vertical microphysical profile using the variational synergistic algorithm is described in Delanoe and Hogan (2008). In the dual-wavelength technique various combinations of wavelengths are chosen in different studies, including triple-wavelength approach

(Matrosov et al., 2009, 2011; Kneifel et al. 2011, 2015; Szyrmer and Zawadzki, 2014). The snow density estimation derived from the differential reflectivity (or independently from in-situ observations) is used to computed the mean mass-weighted diameter D_m.

In the ice/snow retrieval an important source of error is linked to error associated with the mass-size relationship. However, this relation cannot be directly obtained from any airborne probes, neither from the two-dimensional video disdrometer at the ground. Indirect derivation of mass dimensional relationship together with the particle size distribution (PSD) can be done from a combination of airborne probes that measure size-resolved and bulk microphysics properties. The probes that can be used are, par example:

- 2-D Cloud Probe (2DC; 25 - 800 µm)
- 2-D Precipitation Probe (2DP; 200 - 6400 µm)
- 2-D Stereo Probe (2DS; 10 - 1500 µm)
- Cloud Imaging Probe (CIP; 25 -1550 µm)
- Precipitation Imaging Probe (PIP; 100 - 620 µm)

There are also a few probes that have been developed recently. A combination of probes is needed to detect a large range of particle populations, when each probe has its own specific limitations. Moreover, the sensor measuring total condensed water content (CVI: Counterflow Virtual Impactor or CSI: Cloud Spectrometer and Impactor) has to be included to the airborne package. The dataset provided by the probes, after the reduction of the shattering effect (and do not take into account the smallest particles), the mass-size relation can be derived. The two common methods for estimating mass-size relationship from the two-dimensional particle image and number concentration are: 1) using fixed area-mass relation and 2) separating into predefined categories with mass-size relationship unique for each category. However, the observed important morphological diversity even within one habit, particles with imperfect or complex shapes, widespread occurrence of aggregates and polycrystals may be difficult to take into account with these two methods to obtain mass dimensional relationship, even with mass closure from measured total condensed water mass content. The method based on fractal geometry (Schmitt and Heymsfield 2010) is rather appropriate for cases with high concentrations of aggregates only. The method that is well adapted to the radar-based study has been proposed recently by Maahn et al. (2015). This method relies on a functional relation between reflectivity and reflectivity-weighted velocity. At the ground level, the mass-size relationship can be derived from 2D-video disdrometer that provides particle size and terminal velocity for each size interval (Szyrmer and Zawadzki, 2010; Huang et al., 2015). The derived mass-size relationship used in conjunction with the PSD information provides the two bulk quantities being the main algorithm products: IWC (ice water content) and D_m (mean mass melted diameter). All other bulk quantities can be derived, as well.

Stratiform Precipitation: The large-scale precipitation retrieval products can be validated from airborne-based instrumentation using multi-wavelength radar approach (e.g., Leinonen et al., 2015; Battaglia et al., 2016). Airborne observations are preferred since PIA estimates are needed and can only be reliably derived by airborne systems.

As examples for campaigns, which would be useful for EarthCARE radar product validation, two recent experiments are mentioned here-below. These campaignes were carried out in the framework of the GPM ground validation.

1. The joint NASA *Integrated Precipitation and Hydrology Experiment* (IPHEx) and *Radar Definition Experiment 2014* (RADEx-14) field campaign [Barros et al., 2014] was conducted in the Eastern U.S. from 1 May to middle of June 2014 (https://pmm.nasa.gov/IPHEx). It offers unprecedented observations of deep convective cores and precipitating systems from multi-frequency active and passive air-borne sensors. The NASA ER-2 plane was flying at an altitude of 20 km equipped with:

   a. Two radiometers: the Conical Scanning Millimeter-wave Imaging Radiometer (CoSMIR) with channels in the high-frequency band (85-183 GHz) and the Advanced Microwave Precipitation Radiometer (AMPR) operating in the frequency bands between 10 and 85 GHz
   b. Three different radar systems: an upgraded Cloud Radar System (CRS) [Li et al., 2004], the High-Altitude Wind and Rain Profiler (HIWRAP) [Li et al., 2016], and a new scanning ER-2 X band Radar (EXRAD).
   All radars have Doppler capabilities and were operated in the same configuration, looking at the nadir and sampling data every 50 m along track. The combination of measurements at these frequencies gives us an insight into micro-physical properties of hydrometeors ranging from ice crystals to hailstones. It is an ideal test bed for better understanding the potential of multi-wavelength suite of microwave active and passive observations in deep convection, by disentangling the different contributions of attenuation, non-Rayleigh, and MS effects.

2. *OLYMPEX* was a ground validation campaign for GPM which took place on the Olympic Peninsula (Washington State, USA) during November and December 2015 (https://pmm.nasa.gov/OLYMPEX). It gathered numerous ground-based and airborne radar observations. Particularly interesting for this work are the multifrequency radar and radiometer observations collected by the NASA DC-8 aircraft (Ku, Ka, W-band radars, radiometers at various microwave frequencies) and ER-2 aircraft (X, Ku, Ka, W-band radars, radiometers at various microwave frequencies) aircrafts. More than 50 hours of 3-frequency radar observations of frontal systems with typical stratiform structure are available above ocean or complex mountainous terrain (see Fig. 1.15 for an example). Furthermore, one some occasions the flights were coordinated with in-situ aircraft measurements of ice microphysics (Citation aircraft).

Multifrequency ground-based Doppler radars also offer unique validation opportunities. Particularly appealing is the recent technique proposed by Tridon et al, 2013 and Tridon and Battaglia, 2015 involving Ka-W band spectra that could be used as a baseline vs the W-band C-PRO.

4.1.3 MSI L2a Products

The MSI shall provide scene context information around the ATLID and CPR cross-section measurements along the nadir ground track. The first step in the MSI processing chain is therefore the calculation of the cloud mask (M-CM), followed by retrieved cloud properties (M-COP) and aerosol optical thickness (M-AOT).

The cloud retrieval algorithms for the MSI instrument take advantage of the spectral information of the 7 MSI channels and consider the spatial distribution of spectral features across the whole MSI swath.

4.1.3.1 M-CM

The cloud mask for the MSI will be based on the analysis of the spectral information. The cloud detection will determine, for every pixel of the 150 km MSI swath, if it is cloudy or cloud-free. The cloud-type algorithm will contain information of major cloud classes: cirrus, high, medium and low clouds for all pixels identified as cloudy. Additionally, for the cloudy pixels the cloud phase of the uppermost cloud layer will be assigned by the M-CP algorithm. The cloud detection is not straight forward to validate as the horizontal scale from, e.g., ground-based measurement is not the same. The main validation approach should be visual inspection of MSI images and the retrieved cloud masks by an experienced scientist. The cloud mask thresholds should be verified by a variety of defined scene types covering a wide range of geographical and illumination conditions.
Scene types with clouds:

- coastal
- dark spots
- Artic/Antarctic snow/ ice
- Cb over ocean
- desert

Further the cloud mask should be compared to different cloud detection methods from various instruments. First the onboard instruments (lidar and radar) should be used along the nadir track to ensure consistency among the cloud detection methods. As the lidar is much more sensitive to thin clouds we have to restrict the comparison to clouds which do not fall below the theoretical limit of MSI detection. The imagers of geostationary Meteosat satellites and polar orbiting satellite (i.e. MODIS, VIIRS) offer the possibility of cross-calibration as they are already calibrated (Karlsson, 2015). Synoptic observations from ground are useful for validating time series.

4.1.3.2 M-COP

The M-COP algorithm makes use of an iterative 1D-var optimal estimation technique (OE) to obtain simultaneously the cloud-top temperature, cloud optical thickness and (water/ice) cloud particle effective radius for each MSI pixel. From these parameters an estimated liquid/ice water path is derived as well. MSI products depending on VIS and NIR channels can be retrieved during daytime only.

The active instruments onboard EarthCARE can be used to cross-check the cloud top altitude, phase, optical depth and effective radius at the MSI track considering the different sensitivities for lidar and imager products. The whole MSI swath can be validated against the operational cloud products from SEVIRI on the geostationary Meteosat satellites as well as with polar-orbiting instruments. The disadvantage of the polar orbiting instruments is to find collocation of the different orbits. The different view and solar geometries have to be considered.

4.1.3.3 M-AOT

The M-AOT product provides information about the aerosol optical thickness (AOT) at 670 nm above land and ocean and 865 nm above ocean using the optimal estimation technique. Additionally, the surface reflectance will be retrieved at 670 nm above vegetated land surfaces. Finally, the Ångström exponent is calculated based on the retrieved AOT, only above ocean. M-AOT product information will also be used for the ATLID-MSI Aerosol Column Descriptor (AM-ACD, see Sec. 4.1.4.2). Hence, the validation of the M-AOT product will be a first important step for validating the synergy product, too.

The validation shall be performed using collocated ground-based and satellite observations and, if applicable, measurements based on aircraft campaigns. In order to validate M-AOT AOT and Ångström exponent, ground-based observations shall be used, for instance:

- AERONET (Holben et al., 1998; Dubovik et al., 2000; Dubovik et al., 2006)
- Marine AERONET (Smirnov et al., 2009)
- SKYNET (Takamura et al., 2004)
- Pandonia (will be available from 2018 onwards, http://pandonia.net/)

Further, not only for AOT and Ångström exponent validation, but also validation of the surface reflectance, the following satellite products should be used:

- Sentinel 3 - aerosol products [2]
    - Land
    - Water
- MODIS / VIIRS aerosol products (Levy et al., 2013; Jackson et al., 2013; Liu et al., 2013)
- 3MI aerosol products (when available)
- along-swath bias monitoring.

Especially over ocean, the requirement that the 670 nm and 865 nm MSI channels are able to measure aerosol optical thickness with a detection threshold of 0.05 and to an absolute accuracy of 0.02 for an integrated area of 10 km × 10 km shall be verified [AD 1].

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[2] https://sentinel.esa.int/web/sentinel/technical-guides/sentinel-3-synergy/level-2/aerosol-retrieval

4.1.4 ATLID-MSI L2b Products

ATLID and MSI are synergistically used to retrieve cloud and aerosol parameters, to which both instruments are sensitive. A synergistic cloud top height product is retrieved by exploiting the profiling capability of the lidar with the swath of the imager, and aerosol optical properties are retrieved by adding spectral information from the imager to the lidar observations.

4.1.4.1 AM-CTH

For the synergistic ATLID-MSI Cloud Top Height (AM-CTH) product, information from A-CTH is used to improve MSI CTH retrievals across track. The MSI CTH retrieval is based on an optimal estimation approach, which infers optical and physical properties of the cloud from measured satellite radiances. The algorithm uses an absorption-free and an absorption solar channel as well as an infrared-window channel at 10.8 μm. Thus, M-CTH represents an infrared effective radiating height. This is a reasonable estimate for the geometrical CTH in case of optically thick clouds, but leads to a significant underestimation of the CTH for semi-transparent multi-layer clouds. The method may also overestimate the CTH of thick clouds in the presence of temperature inversions at cloud top. Thus, the synergistic retrieval is based on the systematic investigation and classification of differences in CTH obtained with ATLID and MSI along track. The CTH difference for the entire swath is extrapolated from the track by use of the cloud classification and different homogeneity criteria. The AM-CTH product contains information on ATLID and MSI CTH differences along and across track, together with a quality indicator.

Extending information on CTH from the ATLID track to the MSI swath is a novel approach. Once validation of the A-CTH has been performed as described above, the validation of AM-CTH shall focus on investigating the appropriateness of cloud classification and homogeneity criteria for the extrapolation of ATLID-MSI CTH differences from the track to the swath and the accuracy of the respective AM-CTH values across track. In addition to measurements of the actual CTH across track with the means described in Sec. 4.1.1.6, the correct identification and classification of different cloud types and multi-layer cloud systems shall be proven. Combined lidar-radar observations from high-flying aircraft or ground and the application of target classification schemes as described in Sec. 4.1.6.1 are suited for this purpose, with limitations for ground-based observations as discussed in Sec. 4.1.1.6.

4.1.4.2 AM-ACD

The ATLID-MSI Aerosol Column Descriptor (AM-ACD) product provides information on columnar aerosol optical properties. It contains the spectral AOT (355–670 nm over land and 355–670–865 nm over ocean) and the respective Ångström exponents. From the AOT and Ångström exponents the predominating aerosol type is estimated with the help of a look-up table. In the first step, ATLID and MSI collocated data along track are combined. By investigating the horizontal homogeneity of the MSI AOT at 670 nm (identification of aerosol plumes), the product is spread over the swath or parts of it, if possible. The AM-ACD product is defined for cloud-free conditions only. The product also contains a quality indicator, which considers information on multiple aerosol layers provided by the A-ALD product.

The direct combination of lidar measurements in the UV and imager retrievals in the VIS-NIR range to derive Ångström exponents and support aerosol typing is a novel approach. The applicability of the method strongly depends on the accuracy of the input parameters (A-ALD, Sec. 4.1.1.7 and M-AOT, Sec. 4.1.3.3), which have to be validated first. The synergistic product can then be evaluated with ground-based sun-photometer observations as available, e.g., from AERONET (Holben et al., 1998) and SKYNET (Takamura et al., 2004) or with multi-wavelength lidar observations from which the columnar AOT in the UV to NIR spectral range and respective Ångström exponents are available. As for the ATLID stand-alone aerosol products, long-term monitoring over the mission lifetime by aerosol measurement networks is most beneficial (see Sec. 4.1.1). Network observations may also be used to investigate homogeneity criteria used to extend aerosol information from the ATLID track to the MSI swath. Aerosol type validation is further discussed in Sec. 4.3.2.3.

4.1.5 BBR-MSI L2b Products

The TOA radiances and fluxes derived from BBR observations fall into the category of synergy products, because MSI is being used to provide additional information to improve both products. As noted in Sec. 3.4.1, the BBR L1b products (B-NOM, B-SNG), are not corrected for instrument effects. This so-called "unfiltering" is taking place in the BM-RAD processor, because MSI information are needed for improved product performance. The various resolutions of the radiances are found in the BM-RAD product, therefore, it is recommended, that the data user interested in TOA radiances uses the BM-RAD product, rather than the BBR L1b products.

BM-RAD is derived from and closely related to B-NOM and B-SNG. See requirements and validation discussion in section 3.4.1.

The TOA fluxes are reported in the BMA-FLX product, which is based on the radiances in BM-RAD and retrieved under consideration of scene characteristics derived from MSI (scene type) and ATLID (determination of reference height of the three viewing angles).

4.1.5.1 BM-RAD

The BBR instrument measures the total radiance, consisting of both the emitted thermal and the reflected solar components, with a detector sensitive over the full spectral range. The solar component is measured by switching a short-wave filter into the optical path. Subsequently, the thermal component is estimated as the difference of the alternatingly acquired total and solar radiation. The BM-RAD Processor furthermore removes the instrument function from the observation ("unfiltering"). The data product, reported for each of the three BBR viewing directions, finally consists of solar and thermal measurements at various spatial resolutions intended for different scientific applications.

The validation using collocated ground reference sites shall be performed. Such ground reference sites shall be well characterised and the instrumentation and methodologies used for the site characterisation shall be described. However, due to the EarthCARE orbit repeat cycle of 25 days, it will take long to collect significant numbers of samples. It shall be analysed how long it would take to collect significant data sets.

It will therefore be important to compare BBR radiances to those of other radiometers, such as GERB (Meteosat satellites), CERES (Aqua, SNPP), ScaRaB (Megha Tropique), ERM-2 (FY-3E, FY-3G). Comparisons to GERB should be a priority since GERB is on a geostationary satellite and will provide numerous collocations, albeit with comparably coarse spatial resolution.

Furthermore, the validation shall make use of Earth targets like deep convective clouds for absolute calibration/verification and calibration transfer (cross-reference) to other instruments.

Cross-checks against MSI shall be performed, to check the consistency of the MSI narrow-band channels in both the solar and the thermal region with the BBR nadir channels. These activities should commence once confidence on the MSI radiances/brightness temperatures has been gained.

Finally, the ACM-RT product (see below, Sec. 4.1.7.2) contains broad-band radiances. They are planned to be operationally verified against BM-RAD and BMA-FLX in the ACMB-DF (see below, Sec. 4.1.8.1) product. Dedicated activities to analyse ACMB-DF and evaluate BM-RAD against ACM-RT will be required at a time when sufficient confidence has been built on the reliability of the various cloud and aerosol profile retrievals (which are inputs to ACM-RT).

The ACM-RT processor uses one-dimensional and three-dimensional radiative transfer calculations, however, due to constraints in PDGS processing power and required timeliness, the number of scenes subjected to full three-dimensional Monte Carlo calculations (see ACM-RT algorithm in [RD 13] for details) are limited. A very valuable validation activity would be to perform case studies with full three-dimensional Monte Carlo radiative transfer, followed by comparison to BM-RAD, in regions or for scenes, where this is not done operationally in the PDGS.

Methodologies and suitable targets shall be proposed to inter-compare the three BBR views, analyse their consistency and monitor potential long-term deviations.

For long-term monitoring of BBR radiances and their potential degradation over time, known and well characterised ground targets shall be used as well as suitable natural targets, such as deep convective clouds.

4.1.5.2 BMA-FLX

Top-of-atmosphere fluxes are estimated from the BBR's three viewing directions measuring radiances. Its validation does not require co-angulated views, as for radiance inter-comparisons, but in order to validate BBR fluxes, the validating data sets should be of better quality, in terms of instantaneous fluxes, than the BBR instantaneous fluxes. The validation of instantaneous fluxes is therefore expected to be challenging.

Satellite comparison of fluxes shall be the main tool for BBR flux validation, in particular, because of the high number of collocated data sets. GERB observations are available over the Meteosat field of view, ScaRaB and CERES observation need to be used where their orbits cross the EarthCARE orbit.

The validation of BBR fluxes shall be performed as a function of scene identifier (as identified in the MSI-based scene identification, see BMA-FLX PDD in [RD 12] and algorithm description in [RD 13] for details) and as function of solar zenith angle (for the shortwave channel), under consideration of cloud fraction, cloud optical density, surface broad-band albedo, and other relevant parameters.

It shall be noted and taken into account that the BBR short-wave algorithm dependency models, which are at the core of the radiance-to-flux conversion process (see BMA-FLX algorithm description in [RD 13]) are based on artificial neural networks trained with CERES data. It could therefore be expected flux comparisons with CERES might turn out apparently more favourable than with other satellites.

BBR fluxes shall also be verified against the ACM-RT products, equivalent as described above for BM-RAD validation.

Eventually, it should be verified if the BBR retrieved fluxes are globally balanced in order to be properly used by the climate modelling community. Given the orbit and the foreseen lifetime of the mission, a direct assessment cannot be performed. Instead, comparisons with balanced datasets such as the CERES EBAF shall be performed.

4.1.6 ATLID-CPR-MSI L2b Cloud and Aerosol products

The retrieval of a full cloud profiles can be done by synergistic exploitation of the ATLID observations, which are valid for thin clouds, and CPR observations, which can penetrate through even deep clouds, but are not as sensitive as ATLID to thin clouds. Furthermore, CPR can be used to estimate (light) precipitation. Additional information on a cloud is provided by MSI. Similar, ATLID and MSI are both sensitive to aerosol. The three instruments are therefore used in a synergistic retrieval for, firstly, classifying the target (AC-TC) and, subsequently, retrieving the full atmospheric state vector in an optimal estimation scheme from ATLID, CPR and MSI together (ACM-CAP). These synergistic retrievals are available along the nadir track.

4.1.6.1 AC-TC

AC-TC is a merged product which combines the A-TC (Sec. 4.1.1.4) and C-TC (Sec. 4.1.2.3) products, as a result the requirements for validation are similar to those described for A-TC and C-TC. The validation of AC-TC should therefore consider also the validation of A-TC and C-TC.

In order to validated the a target classification product, the target, which EarthCARE is observing, needs to be verified with in-situ and remote sensing techniques. Ideally, this would be done by aircraft campaigns.

Aircraft in-situ validation

Aircraft in-situ observations would give a direct verification of the satellite's target classification. Aircrafts can under-fly the satellite at the exact location of the ATLID and CPR observations and would provide the most direct validation of AC-TC. Such payloads have been used, for example, for CloudSat/CALIPSO validation, as shown in Cesana et al. (2016) and Mioche et al. (2017) for cloud phase identification products.

Example of in-situ payload, which could be useful to identify the cloud phase:

- The Cloud Particle Imager (CPI, Lawson et al., 2001) captures cloud particle images on a 1024 × 1024 pixels CCD camera with a pixel resolution of 2.3 µm and with 256 grey levels. At least 5 pixels are necessary to identify a cloud particle, so the particle sizes derived from the CPI range from 15 µm to around 2 mm. In particular, it provides particle size distribution (PSD) and derived parameters (particle concentration, effective diameter, extinction coefficient and ice water content) as well as a particle habit classification.
- The PMS Forward Scattering Spectrometer Probe (FSSP-100, Baumgardner et al., 2002; Knollenberg, 1981) provides the droplet size distribution from 3 to 45 µm. The derived parameters from the PSD are the droplet concentration, the effective diameter, the extinction coefficient and the liquid water content (LWC).
- The Polar Nephelometer (PN, Gayet et al., 1997) measures the scattering phase function of an ensemble of cloud particles (either droplets, ice crystals or a mix), from a few micrometers to about 800 µm. These measurements are useful to identify spherical from non-spherical particles and thus discriminate the dominant cloud thermodynamical phase.
- The Nevzorov probe (Korolev et al., 1998) uses the hot-wire technique to retrieve the liquid water content and the total water content.

Legs at different altitudes can allow verifying the cloud phase detection and especially the mixed phase conditions.

Aircraft remote sensing validation

Aircraft remote sensing techniques would provide an indirect verification of the target classification, since the aircraft remote sensing observations are using their own target classification assumptions, which must have been thoroughly validated before being used for satellite product validation. Aircrafts equipped with at least a cloud radar (94GHz or 35GHz) and a high spectral resolution lidar (355nm or 532nm) should be used. Compared to remote sensing ground stations, the aircraft remote sensing observations have the advantage of potentially ideal spatial and temporal collocation with the satellite.

However, air-borne remote sensing observations (lidar and radar, similar to EarthCARE) would allow the direct comparison / validation of the lidar attenuated backscatter and radar reflectivity and Doppler which is a pre-requisite to comparing and validating retrieved target parameters.

Another advantage of air-borne remote sensing observation is the significantly higher spatial resolution compared to the satellite, which allows to study and correct for the effect of non-uniform beam filling of the satellite instruments and effects of multiple scattering.

Such a field campaign has taken place in fall 2016 and could serve as a good example for future EarthCARE validation aircraft campaigns. The NAWDEX (http://www.nawdex.org) campaign took place in Iceland and aimed at testing and validating parameterization schemes within numerical weather prediction models with the general objective to improve the accuracy of one-day to two-week high impact weather forecasts. The observational payload is therefore mostly dedicated to cloud, precipitation, wind and humidity characterisation. The German HALO aircraft and French Falcon 20 aircraft had very complementary payloads. Both aircraft boarded a high spectral resolution lidar (355 nm on the French Falcon and 532 nm on the HALO), a Doppler radar at 36 GHz (HALO) and 95 GHz (Falcon) and in-situ measurements. At European level, this is the most complete setup to simulate the EarthCARE active payload.

Aircraft combined in-situ and remote sensing

The most desirable validation method would be using both airborne in-situ and remote sensing (cloud radar, high spectral resolution lidar) at the same time, ideally with two separate aircrafts for in-situ (flying inside the target) and remote sensing (flying outside the target, e.g., above).

Using a statistical approach from the ground

Additionally, although space remote sensing measurements present the great advantage to cover the almost entire globe, they suffer from inherent shortcomings at low altitude levels (Blanchard et al., 2014; Liu et al., 2017; Marchand et al., 2008). Ground-based measurements could be used to verify the performance of the AC-TC in the first two kilometres. Cloud radar and lidar measurements are mandatory to identify cloud phase and cloud/aerosol distinction (Illingworth et al., 2007). Individual direct overpasses are not relevant, since they will be rare, but statistical approaches over as many sites as possible and over long time periods should be defined and their expected significance quantified.

Using CloudSat and CALIPSO statistics

While an overlap of EarthCARE with CloudSat and CALIPSO observations is not likely, a statistical approach using their data – specifically, synergistic target classification products such as 2B-GEOPROF-LIDAR (Mace et al., 2014) and DARDAR products (Delanoë and Hogan, 2010; Ceccaldi et al., 2013) – could allow to assess AC-TC against the multi-years statistics of the CloudSat/CALIPSO target classifications.

4.1.6.2 ACM-CAP

ACM-CAP produces a synergetic retrieval of clouds, aerosol and precipitation properties combining HSRL lidar, Doppler radar, and infrared and short-wave radiances using a variational formulation approach. ACM-CAP relies on C-FMR (Sec. 4.1.2.1) and C-CD (Sec.

4.1.2.2) for radar reflectivity and corrected Doppler signal, A-EBD for the lidar particle and molecular attenuated backscatter profile and M-RGR for MSI radiances, while the input target classification with combined information from lidar and radar is provided by AC-TC. The validation of these products is therefore the first step towards the full validation of ACM-CAP. A key aspect of ACM-CAP validation will be in the radiative transfer closure calculations with evaluation of predicted broadband radiances against BBR observations. But the retrieved quantities need validation individually, as outlined here.

ACM-CAP validation requirements are similar to those of single-instrument retrievals such as C-PRO, A-ALD or M-COP. Obviously, it is only useful to evaluate EarthCARE against other remote-sensing retrievals when there is good reason to believe the latter to be more accurate. This could be because they have lower noise (e.g., ground-based HSRL/Raman lidar), use a less attenuated wavelength (e.g., ground-based rain radar) or use a measurement unavailable to EarthCARE (e.g., microwave radiometry).

Retrieved aerosol extinction profile and AOT at 355 nm (for each aerosol type provided in AC-TC), should be evaluating using dedicated campaigns combining surface and airborne Raman or HSRL lidar observations. Comparison against a surface network of sun-photometers such as AERONET (Holben et al., 1998; Dubovik et al., 2000; Dubovik et al., 2006) is less direct because it relies on the assumed Ångström exponent of the retrieved aerosol type but it can still provide a further constrain on the total AOT, especially when used in combination with multi-wavelength lidar observations.

The retrieval of liquid cloud properties from EarthCARE is challenging due to the attenuation and multiple scattering of the lidar, and the presence of drizzle for the radar. Information on the presence would be valuable as described for C-PRO (section 4.1.2.4). Retrieved liquid water path should be compared to independent estimates from satellite-borne and surface microwave radiometers. Under-flights with suitably instrumented aircraft could evaluate in more detail the profiles of liquid water content and effective radius estimated by ACM-CAP.

Rain retrievals from EarthCARE are uncertain because of the strong 94-GHz attenuation by rain itself and by the melting layer. Surface scanning polarimetric rain radar observations shall be used to evaluate the retrieved rain rate and mean raindrop size. Note that the radar must have polarimetric capability for the added accuracy in rain rate estimation, and the ability to estimate drop size. Ideally, a coastal radar would be used since EarthCARE rain retrievals would be best over ocean where PIA provides an important constraint on the rain retrieval. A number of cases would be required to cover the range of rainfall types.

Retrieved bulk and size-resolved microphysical properties of ice/snow crystals are best compared against measurements from airborne probes in dedicated *in situ* campaigns. For example the Cloud Particle Imager (section 4.1.6.1) or a combination of 2D probes (section 4.1.2.4) can be used to resolve the in-situ particle size and habit distribution and the bulk ice water content and extinction coefficient of ice clouds.

4.1.6.3 ACM-COM

ACM-COM produces potentially multiple renditions of atmospheric profiles based on L2 products. As a default it takes profiles from ACM-CAP and appends layers, with information from ECMWF products, on top that extend to ~80 km. It also adds surface optical properties based on MODIS and ECMWF products. These properties are generally viewed as being beyond the purview of the EarthCARE mission but they are essential for performing radiative transfer calculations with EarthCARE data. ACM-COM also produces, as a back-up for ACM-CAP, profiles that are composites of L2a products: i.e., radar-only and lidar-only retrievals. In many respects, this composite resembles the C3M product produced at NASA-Langley (Kato et al., 2010). Like ACM-CAP, upper atmospheric and surface properties are added here, too. All atmosphere-surface systems that emerge from ACM-COM are used as input to radiative transfer models that lead to radiative products produced by ACM-RT.

Verification of ACM-COM products are essentially covered in the section on ACM-CAP. That is, a subset of methods used to assess ACM-CAP products can be applied equally well to additional composite configurations produced by ACM-COM.

4.1.7 L2b Radiation Products

The primary purpose of the radiation products is to provide the user with heating rate profiles and TOA fluxes collocated with and calculated from the retrieved cloud and aerosol profiles (plus auxiliary data like temperature profiles and surface parameters). This will allow to fulfil the primary EarthCARE mission objective, namely, linking clouds and aerosols to radiation.

In addition, calculated TOA radiances simulating the observations of the BBR will allow to compare those to the independent BBR observations (BM-RAD) as well as the simulated TOA fluxes to BMA-FLX. These inter-comparisons will be used to investigate the consistency of the cloud-aerosol profile retrievals.

The radiation products (ACM-RT) are calculated over defined three-dimensional domains where radiative transfer calculations are applied. These domains are created and reported in the ACM-3D product.

4.1.7.1 ACM-3D

The portion of ACM-3D that lends itself to verification/validation studies is the Scene Construction Algorithm (SCA). The SCA produces a 3D atmosphere around the active-passive retrieved cross-section (RXS) thereby enabling: 3D RT solvers to compute radiances and fluxes; and computation of domain-averaged 1D RT calculations when 1D models are applied only to columns in the RXS (i.e., directly to products emerging from ACM-COM). The main reason for doing this in EarthCARE is to compare modelled radiometric quantities to measurements made by, and inferred from, the broadband radiometer (see sections on BM-RAD and BMA-FLX). This closure assessment of cloud and aerosol property retrievals represents the final step in EarthCARE's production model (see section on ACMB-DF).

The SCA exploits the existence of a series of active-passive cloud-aerosol profiles, which forms the RXS at nadir amidst an across-track swath of multi-spectral imager (MSI) data. It was developed and tested by Barker et al. (2011, 2014). There are several potential verification/validation studies for this product. Ideally, verification data will come from platforms other than satellites. That is, they will represent a distinct separation from the data source used by the SCA. For instance, if satellite or high-flying aircraft, with near-nadir viewing radiometers, produce data suitable to enact the SCA in the vicinity of ground-based instruments, such as scanning cloud radar or other radiometers (e.g., pyranometers), off-nadir estimates produced by the SCA can be compared to the surface-based estimates. These comparisons can involve either cloud properties, such as profiles of extinction, or radiation products that are produced by applying radiative transfer models to the SCA's 3D fields. A similar set of experiments could involve data collected by coordinated off-nadir aircraft that have *in situ* samplers. Given the nature of the SCA and observational systems, it would likely be necessary to conduct such analyses on a 'statistical basis' involving as many samples as possible.

4.1.7.2 ACM-RT

There are two main reasons why radiative transfer (RT) computations are performed within EarthCARE. First, since much of what makes Earth's climate system so worthy of, yet difficult, to study is the four-dimensional interaction of radiation with the three phases of water, each with their own distinct optical properties, it was viewed, early in EarthCARE's planning, that basic properties to have are estimates of broadband fluxes and heating rates. Moreover, the intention of EarthCARE is to maintain continuity with at least one of its progenitors, the CloudSat mission, and perform routine 1D RT calculations for each retrieved profile.

Second, having built into EarthCARE, via its Broadband Radiometer (BBR), the plan to perform an ongoing radiative closure assessment of its retrieved cloud and aerosol properties (see section on ACMB-DF), it was decided that use of only the 1D RT solutions would be inadequate. Thus, for the first time in the atmospheric sciences, 3D RT models will be employed at the operational level of EarthCARE for the express purpose of performing a radiative closure assessment.

Hence, ACM-RT produces profiles of broadband flux profiles for each nadir JSG column. Verification of these by themselves is not feasible. When they are averaged-up to domains of arbitrary sizes (e.g., the default assessment domain size of 5 km × 21 km using products from ACM-3D), verification of surface flux estimates become feasible. Presumably, these would involve observations from ground sites that are integrated over suitable spatial arrays or suitable time periods. EarthCARE also produces profiles of broadband solar fluxes based on a 3D RT model and averaged over assessment domains (5 km × 21 km defaults). These can be assessed the same ways as the averaged 1D products. One could also use measurements of fluxes from aircraft at specific altitudes. These aircraft could be under-flying a satellite (e.g., EarthCARE) and verify fluxes along the nadir-line. In principle, these kinds of assessments depend on off-nadir conditions as well as local nadir conditions. As such, they could/should involve constructed atmospheres from ACM-3D. A more demanding version would be for aircraft to be flying off-nadir for then ACM-3D products are vital. Note that upwelling flux for longwave radiation is produced by the 3D RT model, but only at the 'reference' altitude as dictated by BMA-FLX.

As yet, heating rates (and their profiles) have not been measured directly. Indeed, it is even difficult to make very limited, and reliable, estimates of them from up- and down-welling pyranometer and pyrgeometer data on coordinated aircraft (Marshak et al., 1998).

4.1.8 Closure Products

4.1.8.1 ACMB-DF

This product assists the comparison of ACM-RT and BM-RAD / BMA-FLX as an element of the closure assessment. It is therefore not directly subject to validation. See also 4.2.

4.2 Closure assessment

The retrieval of cloud and aerosol profiles and, eventually, three-dimensional scenes are subject to numerous uncertainties in the retrieval assumptions itself, such as microphysical properties of the scatterers and *a priori* information. In case of a perfect retrieval and construction of a perfect three-dimensional cloud-aerosol scene, radiative transfer calculations would provide accurate estimates of outgoing short-wave and long-wave radiances and fluxes. Those estimates would compare very well to corresponding measurements made by EarthCARE's BBR and radiance-to-flux conversion models; provided, of course, that both radiance measurements and conversion models were perfect, too.

In actuality, retrievals, radiance measurements, and flux estimates have errors. It is the overarching objective of the EarthCARE mission to quantify the effect of clouds and aerosols on TOA fluxes to an accuracy of 10 Wm^{-2} for an instantaneous scene of ~100 km^2. In order to achieve and verify this goal, statistical analyses of substantial datasets are required. Aside from direct verification of cloud and aerosol retrievals, comparisons of calculated radiative properties reported in ACM-RT against BBR observations (BM-RAD, BMA-FLX; Sec. 4.1.5.1 and 4.1.5.2) are expected to provide insights into the qualities of cloud and aerosol retrievals. Discrepancies between estimates from ACM-RT and BM-RAD/BMA-FLX are expected to help elucidate any issues with cloud and aerosol retrievals.

The systematic analysis of ACM-RT against BM-RAD/BMA-FLX and their consistency assessment will be an important part of EarthCARE verification/validation process. The systematic analysis of ACMB-DF products would be a starting point for such analyses. Beyond this, however, are many more options of working on radiative-transfer-related assessments. Extended radiative transfer activities beyond the scope of ACM-RT would be valuable contributions to the assessment of calculated versus observed TOA radiances and fluxes. In particular, due to computational constrains in the operational EarthCARE product generation, the three-dimensional Monte Carlo radiative transfer calculations are limited to a subset of the complete dataset. Expanded application of three-dimensional radiative transfer calculations, be they with the Monte Carlo models used for EarthCARE or other models altogether, to large domains or specific regions/scenarios of interest, with subsequent evaluation against BBR-related products and possibly other coincidental observations, would be valuable for advanced verification of both single-instrument and synergistic retrieval methodologies.

4.3 Validation according to geophysical/microphysical parameter

4.3.1 Cloud products

The Mission Requirements Document [AD 1] requires the following product accuracies, for a reference sample horizontally integrated over 10 km.

Property	Detectability Threshold[3]	Accuracy
Ice cloud top/base	N/A	300 m
Ice cloud extinction coefficient	0.05 km^{-1}	15%
Ice water content	0.001 gm^{-3}	± 30%
Ice crystal effective size	N/A	± 30%
Water cloud top/base	N/A	300 m
Water cloud extinction coefficient	0.05 km^{-1}	15%
Liquid water content	0.1 gm^{-3}	±15-20%
Water droplet effective radius	N/A	± 1-2 µm
Fractional cloud cover	5%	5%
Vertical velocity within clouds	N/A	± 0.2 to 1 ms^{-1}

Furthermore, the rain rate shall be validated, which will be retrieved by several products. (No quantitative accuracy requirement.)

4.3.2 Aerosol products

The Mission Requirements Document [AD 1] requires the following product accuracies, for a reference sample horizontally integrated over 10 km.

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[3] Detectability is defined as the value measurable with not more than 100% RMS error.

Property	Detectability threshold[4]	Accuracy
Boundary layer optical depth	0.05	10-15%
Top/base and profile	N/A	500 m

4.3.2.1 Aerosol geometrical properties

Information on the presence and vertical location of aerosol is primarily derived from ATLID observations, with some support from MSI regarding the horizontal spread. Aerosol features are indicated in the target classification schemes of the A-TC (Sec. 4.1.1.4) and AC-TC (Sec. 4.1.6.1) products. Aerosol layer boundaries are provided in A-ALD (Sec. 4.1.1.7).

Validation efforts shall aim at investigating the consistency of the different products. For instance, the “level of consistency” provided as part of A-ALD shall be verified. Airborne and ground-based lidar observations as described in Sec. 4.1.1 are suitable for this purpose.

4.3.2.2 Aerosol optical properties

Vertically resolved aerosol optical properties are derived from ATLID Mie co-polar, Rayleigh and cross-polar signals and provided in terms of profiles of extinction and backscatter coefficient, lidar ratio and particle linear depolarization ratio at 355 nm in the A-EBD (Sec. 4.1.1.3) and A-AER (Sec. 4.1.1.2) products. Layer-mean values of these parameters are given in A-ALD (Sec. 4.1.1.7), together with the aerosol layer optical thickness at 355 nm. Aerosol extinction coefficient profiles are also available from ACM-COM (Sec. 4.1.6.3) using aerosol types consistent with A-TC. Column AOT at 355 nm is contained in A-ALD (Sec. 4.1.1.7), values at 670 nm (over land and ocean) and 860 nm (over ocean only) can be taken from M-AOT (Sec. 4.1.3.3), and synergistic columnar products (Ångström exponents) are given in AM-ACD (Sec. 4.1.4.2).

Aerosol optical properties shall be validated with focus on the overall consistency of the data set. Since these data constitute the basis for aerosol typing, validation efforts may be combined with aerosol-type validation (see following section). Most suitable will be combined multi-wavelength/polarization lidar and radiometer (sun photometer) observations from aircraft and ground, which can provide spectrally resolved profiles of optical data as well as the spectral AOT.

4.3.2.3 Aerosol type

Aerosol typing is the basis for separating natural and anthropogenic contributions to the aerosol load (see [AD1]) and for allocating radiative properties of aerosol in radiative-transfer calculations. Vertically resolved aerosol type information based on the optical parameters measured with ATLID at 355 nm is given in the A-TC product (Sec. 4.1.1.4). An estimate on the dominant aerosol type in the column by using the combined information on the spectral AOT from ATLID and MSI is provided in AM-ACD (Sec. 4.1.4.2).

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[4] Detectability is defined as the value measurable with not more than 100% RMS error.

Validation of aerosol classification will require a careful analysis of high-quality optical data, which allow the inversion of particle microphysical properties, the separation of major aerosol components, and/or a direct aerosol classification based on specific algorithms (e.g., Burton et al., 2013; Müller et al., 2014; Mamouri and Ansmann, 2014). Data sets as used for the validation of aerosol optical properties (see previous section) are suitable for this purpose. In addition, air-mass transport shall be investigated with backward trajectory analysis and/or transport models in order to allow aerosol source apportionment. These efforts may be supported by measurements of aerosol microphysical (size distribution, shape, refractive index) and optical properties (scattering and absorption coefficients) from aircraft properly equipped with in-situ instrumentation.

4.3.3 Radiation products

Covered under 4.1.7 and 4.2

5 GEOLOCATION AND INSTRUMENT CO-REGISTRATIONS

The geolocation of each instrument's observation at the surface is calculated in the data ground processing as a function of the satellite location and instrument field-of-view pointing direction. The geolocation per instrument needs to be verified with in-orbit data.

Furthermore, the relative collocation of each instrument's observation to the other three instruments – called instrument co-registration – must be verified.

5.1 Geolocation verification

The geolocation accuracy of EarthCARE L1b products (for MSI, L1c) shall be better than 500 m RMS, accounting for all errors introduced by satellite pointing, navigation and timing ([RD 9], requirement OBS-GR-1).

5.2 Instrument Co-registrations

According to the MRD [AD 1] it is furthermore required that the observations of the four instruments are co-registered with an accuracy of 350 m (200 m goal) between ATLID, CPR and MSI and 1000 m between BBR and any of the other three instruments.

BBR: The above-stated requirement of BBR co-registration of 1000 m had been established assuming a BBR instrument with a single detector pixel per viewing direction with an on-ground pixel size of 10 km × 10 km, i.e., before the current BBR detector-array-based concept was devised. Due to the various BBR products, in particular, high spatial resolution sampling on the Joint Standard Grid, it would be desirable to achieve a co-registration with the other instruments better than the original 1000 m requirement.

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