Algorithm Theoretical Baseline Document (ATBD) for product H01 – PR-OBS-1

Precipitation rate at ground by MW conical scanners

Version: 1.1
Date: 16 May 2011
Algorithm Theoretical Baseline Document ATBD-01
Product PR-OBS-1
Precipitation rate at ground by MW conical scanners

INDEX

Acronyms 04

1. The EUMETSAT Satellite Application Facilities and H-SAF 06

2. Introduction to product PR-OBS-1 08
   2.1 Sensing principle 08
   2.2 Main operational characteristics 08
   2.3 Architecture of the products generation chain 09
   2.4 Product development team 09

3. Processing concept 10
   3.1 Instrument data structure 10
   3.2 Introduction to the SSM/I and SSMIS processing chains 10

4. Algorithms description 12
   4.1 The Cloud Resolving Model 12
   4.2 The Radiative Transfer Model 15
   4.3 The instrument model 17
   4.4 The Cloud-Radiation Database 17
   4.5 The precipitation retrieval model 19
   4.6 The uncertainty estimator model 24
   4.7 Algorithm validation/heritage 24

5. Examples of PR-OBS-1 products 25

References 26
List of Tables

Table 01 List of H-SAF products 06
Table 02 Development team for product PR-OBS-1 09
Table 03 Parameters for the different hydrometeors used in the radiative transfer scheme: particle size distribution (PSD), min radius, max radius, slope/intercept, and density. PSD = 1 correspond to monodispersed hydrometeors, PSD = 2 to constant intercept and PSD = 3 to constant slope 16

List of Figures

Fig. 01 Conceptual scheme of the EUMETSAT application ground segment 06
Fig. 02 Current composition of the EUMETSAT SAF network (in order of establishment) 06
Fig. 03 Geometry of conical scanning for SSMIS 08
Fig. 04 Architecture of the PR-OBS-1 product generation chain 09
Fig. 05 Flow chart of the precipitation rate processing chain from SSM/I and SSMIS 11
Fig. 06 Inner domains of the 60 NMS simulations, divided by season 17
Fig. 07 Correlation between the TBs at 91.66 and 150.0 GHz for the simulated (top-left), and observed data (top-right) over land. For each point the log of occurrences is shown. The overlapping of simulated and observed points is also shown (down). The two distribution are very similar. This fact confirms a correct parametrization of the atmospheric ice scattering 18
Fig. 08 Block diagram of the CDRD Bayesian Algorithm for precipitation profile retrieval. The box on the right represents the “inverse problem”; the box on the left corresponds to the database generation and represents the “forward problem” 20
Fig. 09 Detailed block diagram of the “inverse problem” 20
Fig. 10 Screening procedure for land 21
Fig. 11 Screening procedure for coast 22
Fig. 12 Screening procedure for ocean 22
Fig. 13 Screening procedure for ice 23
Fig. 14 Example of an intensive convective event over Sicily. The strong convective system caused the Messina city flood during the night between 01 and 02 January 2010 - Left: retrieved precipitation [mm/h]; right: brightness temperature in channel 85.5 GHz, H polarisation [K] - Satellite DMSP-F16,SSMIS, day 01/10/2009 18:07 UTC, ascending pass 25
Fig. 15 Example of moderate perturbation over the central Mediterranean region - Left: retrieved precipitation [mm/h]; right: brightness temperature in channel 85.5 GHz, V polarisation [K] - Satellite DMSP-F15, SSM/I, day 15/01/2010 14:22 UTC, ascending pass 25
Fig. 16 Example of high-latitude light rain situation over Northern Britain - Left: retrieved precipitation [mm/h]; right: brightness temperature in channel 85.5 GHz, V polarisation [K] - Satellite DMSP-F16, SSMIS, day 05/04/2010 07:47, descending pass 25
<table>
<thead>
<tr>
<th>Acronyms</th>
<th>Description</th>
</tr>
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<tr>
<td>AMSU</td>
<td>Advanced Microwave Sounding Unit (on NOAA and MetOp)</td>
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<td>AMSU-A</td>
<td>Advanced Microwave Sounding Unit - A (on NOAA and MetOp)</td>
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<td>AMSU-B</td>
<td>Advanced Microwave Sounding Unit - B (on NOAA up to 17)</td>
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<td>ATDD</td>
<td>Algorithms Theoretical Definition Document</td>
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<tr>
<td>AU</td>
<td>Anadolu University (in Turkey)</td>
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<tr>
<td>BfG</td>
<td>Bundesanstalt für Gewässerkunde (in Germany)</td>
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<tr>
<td>CAF</td>
<td>Central Application Facility (of EUMETSAT)</td>
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<td>CDOP</td>
<td>Continuous Development-Operations Phase</td>
</tr>
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<td>CESBIO</td>
<td>Centre d’Etudes Spatiales de la BIOsphere (of CNRS, in France)</td>
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<td>CM-SAF</td>
<td>SAF on Climate Monitoring</td>
</tr>
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<td>CNMCA</td>
<td>Centro Nazionale di Meteorologia e Climatologia Aeronautica (in Italy)</td>
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<tr>
<td>CNR</td>
<td>Consiglio Nazionale delle Ricerche (of Italy)</td>
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<td>CNRS</td>
<td>Centre Nationale de la Recherche Scientifique (of France)</td>
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<td>DMSP</td>
<td>Defense Meteorological Satellite Program</td>
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<td>DPC</td>
<td>Dipartimento Protezione Civile (of Italy)</td>
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<td>EARS</td>
<td>EUMETSAT Advanced Retransmission Service</td>
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<td>ECMWF</td>
<td>European Centre for Medium-range Weather Forecasts</td>
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<tr>
<td>EDC</td>
<td>EUMETSAT Data Centre, previously known as U-MARF</td>
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<td>EUM</td>
<td>Short for EUMETSAT</td>
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<tr>
<td>EUMETCast</td>
<td>EUMETSAT’s Broadcast System for Environmental Data</td>
</tr>
<tr>
<td>EUMETSAT</td>
<td>European Organisation for the Exploitation of Meteorological Satellites</td>
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<td>FMI</td>
<td>Finnish Meteorological Institute</td>
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<td>FTP</td>
<td>File Transfer Protocol</td>
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<td>GEO</td>
<td>Geostationary Earth Orbit</td>
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<tr>
<td>GRAS-SAF</td>
<td>SAF on GRAS Meteorology</td>
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<tr>
<td>HDF</td>
<td>Hierarchical Data Format</td>
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<td>HRV</td>
<td>High Resolution Visible (one SEVIRI channel)</td>
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<td>H-SAF</td>
<td>SAF on Support to Operational Hydrology and Water Management</td>
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<tr>
<td>IDL</td>
<td>Interactive Data Language</td>
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<tr>
<td>IFOV</td>
<td>Instantaneous Field Of View</td>
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<tr>
<td>IMWM</td>
<td>Institute of Meteorology and Water Management (in Poland)</td>
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<tr>
<td>IPF</td>
<td>Institut für Photogrammetrie und Fernerkundung (of TU-Wien, in Austria)</td>
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<td>IPWG</td>
<td>International Precipitation Working Group</td>
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<tr>
<td>IR</td>
<td>Infra Red</td>
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<td>IRM</td>
<td>Institut Royal Météorologique (of Belgium) (alternative of RMI)</td>
</tr>
<tr>
<td>ISAC</td>
<td>Istituto di Scienze dell’Atmosfera e del Clima (of CNR, Italy)</td>
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<td>ITU</td>
<td>Istanbul Technical University (in Turkey)</td>
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<td>LATMOS</td>
<td>Laboratoire Atmosphères, Milieux, Observations Spatiales (of CNRS, in France)</td>
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<td>LEO</td>
<td>Low Earth Orbit</td>
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<td>LSA-SAF</td>
<td>SAF on Land Surface Analysis</td>
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<td>Météo France</td>
<td>National Meteorological Service of France</td>
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<td>METU</td>
<td>Middle East Technical University (in Turkey)</td>
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<tr>
<td>MHS</td>
<td>Microwave Humidity Sounder (on NOAA 18 and 19, and on MetOp)</td>
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<td>MSG</td>
<td>Meteosat Second Generation (Meteosat 8, 9, 10, 11)</td>
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<td>MVIIRI</td>
<td>Meteosat Visible and Infra Red Imager (on Meteosat up to 7)</td>
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<td>MW</td>
<td>Micro Wave</td>
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<td>NESDIS</td>
<td>National Environmental Satellite, Data and Information Services</td>
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<td>NMA</td>
<td>National Meteorological Administration (of Romania)</td>
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<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration (Agency and satellite)</td>
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<tr>
<td>NWC-SAF</td>
<td>SAF in support to Nowcasting &amp; Very Short Range Forecasting</td>
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<td>NWP</td>
<td>Numerical Weather Prediction</td>
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<td>NWP-SAF</td>
<td>SAF on Numerical Weather Prediction</td>
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<td>O3M-SAF</td>
<td>SAF on Ozone and Atmospheric Chemistry Monitoring</td>
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<td>OMSZ</td>
<td>Hungarian Meteorological Service</td>
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<td>ORR</td>
<td>Operations Readiness Review</td>
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<td>OSI-SAF</td>
<td>SAF on Ocean and Sea Ice</td>
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<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<tr>
<td>PDF</td>
<td>Probability Density Function</td>
</tr>
<tr>
<td>PEHRPP</td>
<td>Pilot Evaluation of High Resolution Precipitation Products</td>
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<tr>
<td>Pixel</td>
<td>Picture element</td>
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<td>PMW</td>
<td>Passive Micro-Wave</td>
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<td>PP</td>
<td>Project Plan</td>
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<td>PR</td>
<td>Precipitation Radar (on TRMM)</td>
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<td>PUM</td>
<td>Product User Manual</td>
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<td>PVR</td>
<td>Product Validation Report</td>
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<td>RMI</td>
<td>Royal Meteorological Institute (of Belgium) (alternative of IRM)</td>
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<td>RR</td>
<td>Rain Rate</td>
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<tr>
<td>RU</td>
<td>Rapid Update</td>
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<tr>
<td>SAF</td>
<td>Satellite Application Facility</td>
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<tr>
<td>SEVIRI</td>
<td>Spinning Enhanced Visible and Infra-Red Imager (on Meteosat from 8 onwards)</td>
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<td>SHMU</td>
<td>Slovak Hydro-Meteorological Institute</td>
</tr>
<tr>
<td>SSM/I</td>
<td>Special Sensor Microwave / Imager (on DMSP up to F-15)</td>
</tr>
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<td>SSMIS</td>
<td>Special Sensor Microwave Imager/Sounder (on DMSP starting with S-16)</td>
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<tr>
<td>SYKE</td>
<td>Suomen ympäristökeskus (Finnish Environment Institute)</td>
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<tr>
<td>$T_{bb}$</td>
<td>Equivalent Blackbody Temperature (used for IR)</td>
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<td>TBB</td>
<td>Teknillinen korkeakoulu (Helsinki University of Technology)</td>
</tr>
<tr>
<td>TMI</td>
<td>TRMM Microwave Imager (on TRMM)</td>
</tr>
<tr>
<td>TRMM</td>
<td>Tropical Rainfall Measuring Mission UKMO</td>
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<tr>
<td>TMS</td>
<td>Turkish State Meteorological Service</td>
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<tr>
<td>TU-Wien</td>
<td>Technische Universität Wien (in Austria)</td>
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<tr>
<td>U-MARF</td>
<td>Unified Meteorological Archive and Retrieval Facility</td>
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<tr>
<td>UniFe</td>
<td>University of Ferrara (in Italy)</td>
</tr>
<tr>
<td>URD</td>
<td>User Requirements Document</td>
</tr>
<tr>
<td>UTC</td>
<td>Universal Coordinated Time</td>
</tr>
<tr>
<td>VIS</td>
<td>Visible</td>
</tr>
<tr>
<td>ZAMG</td>
<td>Zentralanstalt für Meteorologie und Geodynamik (of Austria)</td>
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The EUMETSAT Satellite Application Facilities and H-SAF

The “EUMETSAT Satellite Application Facility on Support to Operational Hydrology and Water Management (H-SAF)” is part of the distributed application ground segment of the “European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT)”. The application ground segment consists of a “Central Application Facility (CAF)” and a network of eight “Satellite Application Facilities (SAFs)” dedicated to development and operational activities to provide satellite-derived data to support specific user communities. See Fig. 01.

Fig. 01 - Conceptual scheme of the EUMETSAT application ground segment.

Fig. 02 reminds the current composition of the EUMETSAT SAF network (in order of establishment).

Fig. 02 - Current composition of the EUMETSAT SAF network (in order of establishment).

The H-SAF was established by the EUMETSAT Council on 3 July 2005; its Development Phase started on 1st September 2005 and ended on 31 August 2010. The SAF is now in its first Continuous Development and Operations Phase (CDOP) which started on 28 September 2010 and will end on 28 February 2012. The list of H-SAF products is shown in Table 01.
# Algorithms Theoretical Baseline Document for product H01 – PR-OBS-1

Version 1.1, 16 May 2011

## Table 1: List of H-SAF Products

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<thead>
<tr>
<th>Acronym</th>
<th>Identifier</th>
<th>Name</th>
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<td>PR-OBS-1</td>
<td>H-01</td>
<td>Precipitation rate at ground by MW conical scanners (with indication of phase)</td>
</tr>
<tr>
<td>PR-OBS-2</td>
<td>H-02</td>
<td>Precipitation rate at ground by MW cross-track scanners (with indication of phase)</td>
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<tr>
<td>PR-OBS-3</td>
<td>H-03</td>
<td>Precipitation rate at ground by GEO/IR supported by LEO/MW</td>
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<tr>
<td>PR-OBS-4</td>
<td>H-04</td>
<td>Precipitation rate at ground by LEO/MW supported by GEO/IR (with flag for phase)</td>
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<td>PR-OBS-5</td>
<td>H-05</td>
<td>Accumulated precipitation at ground by blended MW and IR</td>
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<td>PR-OBS-6</td>
<td>H-15</td>
<td>Blended SEVIRI Convection area/LEO MW Convective Precipitation</td>
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<td>PR-ASS-1</td>
<td>H-06</td>
<td>Instantaneous and accumulated precipitation at ground computed by a NWP model</td>
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<td>SM-OBS-2</td>
<td>H-08</td>
<td>Small-scale surface soil moisture by radar scatterometer</td>
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<tr>
<td>SM-OBS-3</td>
<td>H-16</td>
<td>Large-scale surface soil moisture by radar scatterometer</td>
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<tr>
<td>SM-DAS-2</td>
<td>H-14</td>
<td>Liquid root zone soil water index by scatterometer assimilation in NWP model</td>
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<td>SN-OBS-1</td>
<td>H-10</td>
<td>Snow detection (snow mask) by VIS/IR radiometry</td>
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<tr>
<td>SN-OBS-2</td>
<td>H-11</td>
<td>Snow status (dry/wet) by MW radiometry</td>
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<td>SN-OBS-3</td>
<td>H-12</td>
<td>Effective snow cover by VIS/IR radiometry</td>
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<td>SN-OBS-4</td>
<td>H-13</td>
<td>Snow water equivalent by MW radiometry</td>
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</table>
Introduction to product PR-OBS-1

1.1 Sensing principle

Product PR-OBS-1 is fundamentally based on the instruments SSM/I and SSMIS flown on the DMSP satellites. These conical scanners provide images with constant zenith angle, that implies constant optical path in the atmosphere and homogeneous impact of the polarisation effects (see Fig. 03).

Also, conical scanning provides constant resolution across the image, though changing with frequency. It is noted that the IFOV is elliptical, with major axis elongated along the viewing direction and the minor axis along-scan, approximately 3:5 of the major. Its size is dictated by the antenna diameter (actually, the antenna is slightly elliptical, to partially compensate for the panoramic distortion), but also by the portion of antenna effectively illuminated (this enables to obtain the same IFOV for a group of different frequencies, if co-registration is a strong requirement). As for the 'pixel', i.e. the area subtended as a consequence of the bi-dimensional sampling rate, the sampling distance along the satellite motion, i.e. from scan line to scan line, is invariably 12.5 km, dictated by the satellite velocity on the ground and the scan rate. Along scan, the sampling rate is selected differently for different frequencies or set of frequencies, as necessary to fulfil the radiometric accuracy requirement and to minimise aliasing.

For more information, please refer to the Products User Manual (specifically, volume PUM-01).

1.2 Main operational characteristics

The operational characteristics of PR-OBS-1 are discussed in PUM-01. Here are the main highlights.

The horizontal resolution ($\Delta x$). The IFOV of SSM/I-SSMIS images changes with frequency from ~ 13 km at 90 GHz to ~ 55 km at 19 GHz). We consider the 37 GHz, with IFOV ~ 30 km, as effective for most precipitation types. Sampling is performed at ~ 16 km intervals. Thus:

- resolution $\Delta x \sim 30$ km - sampling distance: ~ 16 km.

The observing cycle ($\Delta t$) depends on the instrument swath and the number of satellites carrying the addressed instrument. For PR-OBS-1 there are 4 DMSP satellites but, because of the limited instrument swath, they provide a total service equivalent to that one of two satellites, around 7:00 and 18:00 LST. In average the observing cycle over Europe is $\Delta t \sim 6$ h, with actual interval ranging from 2 to 10 hours. Gaps are filled by product PR-OBS-2, that also has observing cycle $\Delta t \sim 6$ h, but LST around 9:30 and 14:00, with actual intervals ranging from 4.5 to 7.5 hours. Conclusion:

- for PR-OBS-1 as stand alone (i.e. from DMSP satellites): cycle $\Delta t = 6$ h, sampling 2÷10 h;
- for the composite PR-OBS-1 + PR-OBS-2 system: cycle $\Delta t = 3$ h, sampling 2÷4.5 h.

The timeliness ($\delta$). In the case of PR-OBS-1 it is strongly conditioned by the availability of DMSP data at CNMCA, through NOAA and UKMO. The outcome is

- timeliness $\delta \sim 2.5$ h.

The accuracy is evaluated a-posteriori by means of the validation activity. See Product Validation Report PVR-01.
1.3 Architecture of the products generation chain

A main feature of the architecture of PR-OBS-1 is the unavailability of DMSP data by direct reception or by EUMETCast. This strongly conditions the timeliness for product delivery. The data are acquired within the DoD system for global DMSP data, and conveyed to NOAA, that re-transmits them to the UK Meteorological Office (UKMO). CNMCA acquires the data from UKMO already pre-processed.

The figure reminds that the PR-OBS-1 product, in addition to be disseminated to the users, is also used internally to CNMCA to feed the frequent Rapid-Update product (PR-OBS-3) and Morphing product (PR-OBS-4, not yet implemented).

In CNMCA, the PR-OBS-1 product is generated on the base of the algorithms and the databases developed and provided by CNR-ISAC.

The product, that includes some online quality control information, is disseminated to the Users by FTP.

1.4 Product development team

Names and coordinates of the main actors for PR-OBS-1 algorithm development and integration are listed in Table 02.

Table 02 - Development team for product PR-OBS-1

<table>
<thead>
<tr>
<th>Name</th>
<th>Role</th>
<th>Email</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alberto Mugnai (Leader)</td>
<td>CNR Istituto di Scienze dell'Atmosfera e del Clima (ISAC)</td>
<td><a href="mailto:a.mugnai@isac.cnr.it">a.mugnai@isac.cnr.it</a></td>
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<tr>
<td>Paolo Sanò</td>
<td>CNR Istituto di Scienze dell'Atmosfera e del Clima (ISAC)</td>
<td><a href="mailto:p.sano@isac.cnr.it">p.sano@isac.cnr.it</a></td>
</tr>
<tr>
<td>Daniele Casella</td>
<td>CNR Istituto di Scienze dell'Atmosfera e del Clima (ISAC)</td>
<td><a href="mailto:d.casella@isac.cnr.it">d.casella@isac.cnr.it</a></td>
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<tr>
<td>Marco Formenton</td>
<td></td>
<td><a href="mailto:m.formenton@isac.cnr.it">m.formenton@isac.cnr.it</a></td>
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</table>
2. Processing concept

2.1 Instrument data structure

Product PR-OBS-1 is fundamentally based on SSM/I and SSMIS. These conical scanners provide images with constant zenith angle, that implies constant optical path in the atmosphere and homogeneous impact of the polarisation effects.

Also, conical scanning provides constant resolution across the image, though changing with frequency. It is noted that the IFOV is elliptical, with major axis elongated along the viewing direction and the minor axis along-scan, approximately 2/3 of the major. Its size is dictated by the antenna diameter (actually, the antenna is slightly elliptical, to partially compensate for the panoramic distortion), but also by the portion of antenna effectively illuminated (this enables to obtain the same IFOV for a group of different frequencies, if co-registration is a strong requirement). As for the ‘pixel’, i.e. the area subtended as a consequence of the bi-dimensional sampling rate, the sampling distance along the satellite motion, i.e. from scan line to scan line, is invariably 12.5 km, dictated by the satellite velocity on the ground and the scan rate. Along scan, the sampling rate is selected differently for different frequencies or set of frequencies, as necessary to fulfil the radiometric accuracy requirement and to minimise aliasing.

To ‘rasterise’ this complicated sequence of pixels stemming from the conical scanning geometry so that it can be easily accessed from the precipitation processing chain, and to apply all necessary co-registration and calibration operations, also accounting for the actual satellite/instrument attitude and housekeeping, is not an easy task. An ‘instrument processor’ performs this task, considered as a black-box procured from external sources, thus not be described in this ATDD.

2.2 Introduction to the SSM/I and SSMIS processing chains

SSM/I and SSMIS have many similarities, but also important differences. Specifically, SSMIS includes all ‘window’ channels of SSM/I (19, 37 and 90 GHz with two polarisations) and the water-vapour channel (23 GHz) for water vapour correction, with pixel 25 x 12.5 km² (19, 23 and 37 GHz) and 12.5 x 12.5 km² (90 GHz). SSMIS adds a set of channels with pixel 37.5 x 12.5 km², for temperature profile in the troposphere (8 channels between 50.3 and 60.8 GHz) and water vapour profile (4 channels: 150 GHz and 3 channels in the 183 GHz band). Further 5 channels in the interval 60.8 to 63.3 GHz, with pixel 75 x 12.5 km², are for stratospheric temperature profile, probably of no interest for precipitation retrieval.

Determining precipitation rate at the ground from the few channels of SSM/I is an extremely ill-conditioned problem. The precipitation at the ground, that in no way can be directly observed from space, is derived from the knowledge of everything that happens in the vertical column, specifically in terms of hydrometeors. SSMIS includes more information on the vertical atmospheric structure, but not as cloud microphysics is concerned. Consequently, information on cloud microphysics needs to be input from external. There are two approaches for this.

- To assimilate MW brightness temperature \(T_B\) in a NWP model that provides information on cloud microphysics. This is the approach of ECMWF. The problem is that real-time assimilation currently is only possible with coarse-resolution models (‘coarse’ in relative terms in respect of the convection scale). These models cannot retrieve microphysical parameters with the necessary degree of detail, and tend to smooth-out extreme events. This approach is probably suitable for the global scale, at least from the statistical viewpoint.
- Microphysical parameters are conveniently retrieved by Cloud Resolving Models (CRM). The problem here is that it is currently not possible to run these models in-line with the flow of satellite data. It is therefore necessary to do this off-line, for a number of well-documented events (generally, results of re-analysis exercises) and collect the results in a database. This also allows using more complex Radiative Transfer Models (RTM), as it is particularly necessary when ice is
involved in the precipitation event. The collection of samples of meteorological events, with added cloud microphysics by the CRM, and converted into $T_b$'s at the instrument channel frequencies by the RTM, constitutes the Cloud-Radiation Database (CRD).

In the deep future, when it will be possible to run CRM's assimilating the satellite data flow in-line, the first approach could prevail. For the moment, we have adopted the second approach, that is currently considered the most advanced. It was originally developed for SSM/I, then it has been extensively used after the launch of the TRMM satellite to process the data from TMI (a special configuration of SSM/I), and it is presently baselined for processing the data from the GPM mission to come.

Fig. 05 illustrates the flow chart of the SSM/I-SSMIS processing chain. The off-line part refers to the activities leading to implement the Cloud-Radiation Database. They consist of:

- collecting well-documented meteorological events (analysis or re-analysis);
- applying a Cloud Resolving Model to simulate the cloud microphysics missing in the analysis;
- applying a Radiative Transfer Model to convert the cloud pattern in a pattern of (monochromatic) radiances at all frequencies and polarisations of the SSM/I-SSMIS channels;
- convoluting the monochromatic radiances with the instrument model so to simulate brightness temperatures comparable with those that would be measured from the satellite;
- finally collect the simulated $T_b$'s in the Cloud-Radiation Database.

When the satellite passes, the acquired data are pre-processed by the instrument processor and made available for the precipitation generation chain, that includes:

- an initial preparation of the dataset to be processed (sea-land mask, emissivity, preventive classification of cloud nature, …)
- the retrieval algorithm that searches for the maximum-likelihood solution in the hydrometeor profiles available in the CRD, also using the error structure available in a database;
- the uncertainty estimator, that appends the retrieved precipitation rate with information on likely error; this information is also used for updating the error structure database.
In the Figure, the [blue] boxes indicate the algorithms/models that will be described in this ATDD:
- the Cloud Resolving Model; the Radiative Transfer Model; the instrument model; the precipitation retrieval model; the uncertainty estimator model.
3. Algorithms description

The following Sections describe the algorithms used in the various modules of the precipitation products generation chain. The degree of detail is consistent with the requirement of a manageable document. Detailed algorithm descriptions are available within the H-SAF project inside an electronic forum at the site:  ftp://ftp.meteoam.it - username: hsaf - password: 00Hsaf ⇒ hsaf ⇒ algorithm-forum.

3.1 The Cloud Resolving Model

A meteorological situation (analysis or re-analysis) is generally described in terms of parameters measured by the ground-based or the space-based observing system. These parameters do not generally include the details of the cloud structure, specifically the cloud microphysical structure that determines precipitation. This will to be reconstructed by applying an atmospheric model. We will make use of the "University of Wisconsin – Non-hydrostatic Modeling System" (UW-NMS).

The UW-NMS model represents the further development of the regional atmospheric modelling system maintained at Colorado State University (see Tripoli and Cotton 1981, 1982, 1986; Cotton et al. 1982, 1986; Tripoli 1992 a,b).

The UW-NMS is a numerical weather prediction model capable of simulating atmospheric phenomena with horizontal scales ranging from the microscale (turbulence) to the synoptic scale (extratropical cyclones, fronts, etc.). It is based on the non-Boussinesq quasi-compressible dynamical equations. Model thermodynamics are based on the prediction of a moist ice-liquid entropy variable $\theta_{li}$ (Tripoli and Cotton 1981) designed to be conservative over all ice and liquid adiabatic process.

Dynamic properties of flow such as vorticity, kinetic energy and potential enstrophy are conserved by the advection scheme in the UW-NMS. The model uses variable step topography capable of capturing steep topographical slopes, while at the same time accurately representing subtle topography variations. Conservation equations for the specific humidity of total water and several ice and liquid water hydrometeor categories are also included. The model is formulated on a two-way multiply nested Arakawa “C” grid system, cast on a rotated spherical grid system. The grid system includes multiple 2-way nesting capability to allow locally enhanced resolutions. The nesting system mod can be programmed to move along a specified trajectory or to move with a predicted variable such as a surface pressure minimum.

The UW-NMS microphysical module used for this study is a modified form of the scheme described by Flatau et al. 1989 and Cotton et al. 1986. Specifically, in UW-NMS the treatment of ice categories and specifics of the precipitation physics tendencies has been modified from the original published works to enhance their performance. The microphysics is a bulk microphysics parameterization, which includes six hydrometeor categories labelled as: suspended cloud droplets, precipitating rain drops, suspended pristine ice crystals, and precipitating low-density graupel particles (or snow), ice aggregates and high-density graupel particles. Depending on the application, all or some of these categories may be selected. Any combination of frozen and liquid hydrometeors can coexist within the same grid volume at any given time to allow hydrometeor category interaction to take place.

A negative exponential size distribution $N(D)$ is assumed for all categories (except cloud droplets and pristine crystals, which are considered monodispersed), and it is given by:

$$N(D) = N_0 e^{-\lambda D}$$

where $N_0$ is the intercept and $\lambda$ is the slope of the distribution. The total concentration of hydrometeors in the distribution can be found by an integration of the distribution:

$$N_r = \int_{0}^{\infty} N(D)dD = \frac{N_0}{\lambda}$$
The mean diameter and the liquid water content are quantities frequently used in cloud modelling applications. The mean diameter \( D_m \) is the first moment of the distribution, and it is defined as:

\[
D_m = \frac{\int_{\infty}^{\infty} D N(D) dD}{\int_{\infty}^{\infty} N(D) dD}
\]

For a negative exponential it becomes:

\[
D_m = \frac{1}{\lambda}
\]

The liquid water content or ice water content is proportional to the third moment of the distribution:

\[
l_h = \int_{\infty}^{\infty} m(D) N(D) dD
\]

where \( m(D) \) is the mass of particles of diameter \( D \). For spherical particles of density \( \rho_h \) with negative-exponential size distribution, it becomes:

\[
l_h = \pi N_l D_l^3 m \rho_h
\]

An alternative to the liquid water content to describe the mass content of hydrometeors within the cloud is the mixing ratio defined as:

\[
r_h = \frac{l_h}{\rho_0}
\]

where \( \rho_0 \) is the dry air density. It is always predicted in UW-NMS, and it is related to the size distribution parameters by:

\[
\lambda = \left[ \frac{\pi \rho_h N_0}{\rho_0 r_h} \right]^{\frac{1}{2}}
\]

One can see that the distribution can be completely described by assigning a value of either the slope, or the intercept, or the concentration. The model always predicts the total mixing ratio of all condensate (liquid and ice), water vapor mixing ratio, and the mixing ratio of each hydrometeor category, except for cloud droplets whose mixing ratio is diagnosed.

For each hydrometeor category, the UW-NMS model offers the possibility to specify the value either for the slope, or for the intercept, or for the total number concentration. A different method for parameterising each hydrometeor category can be selected where the total concentration (number of particles per unit mass) can be predicted. This option allows the parameters of the size distribution \( \lambda \) and \( N_0 \) to be diagnosed from the mixing ratio and the total concentration, obtaining different values of the slope and the intercept at each grid volume. Mixed-phase particles (i.e. melting graupel) are not included but any combination of liquid and frozen particles is allowed to occur at a given grid point.

For the aim of this project it is very important to describe the parameterization of each hydrometeor category, explaining the major assumptions in the conversion process between one category and the other, and to describe the parameterization of their microphysical properties. Particular emphasis will be given below to the size distribution and density (for the frozen hydrometeors) parameterization, because these are the parameters that directly determine the optical properties.
**A - Cloud droplets** - The cloud water drops are assumed to be of constant size except with respect to the formulations for autoconversion and ice splintering where they are cast in the form of a modified Gamma distribution (Tripoli and Cotton 1981). The cloud droplet concentration is specified a priori and for this study, is taken to be 500 cm$^{-3}$. Besides the implicit diffusional growth and decay of cloud water due to production of supersaturation built into a diagnostic system, cloud water may be converted to any of the other hydrometeor categories through collection, phoretic contact freezing, or autoconversion directly to rain. Stochastic broadening is parameterized to be dependent on the average cloud-droplet size.

**B - Rain drops** – For this study, the rain water category is assumed to be distributed in a Marshall-Palmer distribution of specified constant slope. This is given by an assumed characteristic droplet radius of 270 μm and does not allow for size variation resulting from non-equilibrium rain spectra, that might be typical of immature rain formation processes, such as melting of snow. Rain droplets arise primarily through the collision-coalescence process (warm rain) and the melting of precipitating ice particles (cold rain). In warm-based clouds, like those typical of summertime Alabama or tropical cyclone, both processes are important. Rain droplets are lost to the system primarily through conversion to ice categories (droplet freezing and riming) or evaporation and through loss due to precipitation.

**C - Pristine ice crystals** - The original pristine ice category of the Flatau parameterization (Flatau et al. 1989) is divided into a snow and pristine category. The original version grouped both nucleated and new crystals together. Since a constant size distribution had been assumed, massive nucleation at cold temperatures would drastically alter the average crystal size and would remove all memory of the growth that some of the larger crystals had been through. Here, riming growth processes are assumed to convert pristine crystals at their predicted mass to a snow category which represents rimed crystals. Hence, new and mature populations of crystals continue to exist as pristine crystals where massive nucleation occurs, whereas crystals that have substantially increased in mass through riming are separated out in can evolve independently. This was specially important for the simulations of cirrus anvils where influxes of pristine crystals would dominate the old inclusive pristine category sometimes preventing the precipitation of the rimed particles. The modified pristine category is assumed to be composed of newly nucleated hexagonal plate crystals of uniform mass $m = 1.5 \times 10^{-6}$ g; the concentration is explicitly predicted. The density $\rho_i = 0.22$ g/cm$^3$ is calculated from:

$$\rho_i = \frac{6K}{\pi a^3} \left( \frac{2r_{ic}}{a} \right)^{b-3}$$

$$r_{ic} = \frac{a}{2} \left( \frac{m_{ic}}{K} \right)^{1/b}$$

The three parameters $K$, $a$, and $b$ are dependent on mass (see Smith et al. 1992): $K = 1$ g; $a = 19.2$ cm; $b = 2.0$. The only source of new crystals are primary and secondary nucleation including sorption and deposition, contact nucleation and splintering. Pristine crystals can be lost through conversion to hard graupel resulting from collection directly onto the graupel surface or through contact freezing of rain droplets, by conversion to soft graupel through the riming of cloud droplets or the conversion to aggregates through the aggregation process. Because pristine ice crystals tend to remain quite small in mass, they can be assumed to melt instantaneously when the temperature of the air exceeds freezing.

**D - Ice aggregates / Snowflakes** - The aggregate category consists of aggregated crystals formed by collisions among pristine crystals, or pristine crystals other aggregates. Aggregates are assumed to be in a Marshall-Palmer distribution of constant assumed slope, with mean radius of 1650 μm. The implicit assumption (similar to that used for rain) is that break-up balances formation. Additional growth is possible from riming and deposition, although strong riming will result in conversion to graupel at a specified rate. Aggregates represent the major source of graupel embryos. Aggregates are lost to melting, evaporation, precipitation fallout processes and conversion to snow pellets through riming processes. For aggregates the size dependent density $\rho_{sa}$ is given by:

$$\rho_{sa} = \frac{0.015}{(2r)^{0.6}} \frac{g}{cm^3}$$
E - Soft graupel / Snow pellets - The snow pellets (or soft graupel) category is assumed to follow a Marshall-Palmer distribution with slope and intercept derived from an explicit predicted number concentration per unit mass. The snow pellets are assumed to grow from their initiation size through vapour-deposition processes and riming of both rain and cloud droplets. There is an assumed conversion formula to convert the soft graupel to the hard graupel category, which is dependent on the riming rate by rain droplets compared to growth rates by other processes and the relative size of collected rain droplets compared to the snow particle size.

F - Hard graupel / Hailstones - The hard graupel category is also assumed to be in a constant slope Marshall-Palmer distribution but with a characteristic radius of 500 μm and constant density $\rho = 0.9$ g/cm$^3$. This value was derived from explicit axis-symmetric simulations with predicted graupel mixing ratio and concentration, where it was found to be characteristic of the graupel size predicted. It is also the best compromise for the representation of graupel formation in a warm-based summertime cloud where much of the graupel rises from contact freezing of rain droplets, which themselves tend to have a near-constant-slope distribution. As a result, initial graupel growth is accelerated because it begins at a mature size and then rapidly accretes ambient liquid water. Therefore, assuming a constant intercept for graupel would be inappropriate because it would implicitly assume that initial graupel size is small and thus they delay the early growth process. On the other hand, the constant-slope assumption does not allow for any growth in the relative portion of hail-sized particles as water content increases.

Hard graupel grows or decays from vapour deposition, riming, and melting and conversion from rain, pristine crystals, aggregates and soft graupel categories. Wet growth or dry growth are both modeled and depend on the diagnosed equilibrium temperature of the graupel surface. This temperature depends on the energy balance at the surface of the droplet resulting from conduction with the air versus latent heating or cooling due to evaporation or sublimation onto the particle, and freezing of collected liquid water. At sub freezing, air temperatures, the energy balance determines the proportion of any collected liquid water that can be frozen, given the rate that the particle can conduct heat away to the air. Any excess water that cannot freeze is assumed to be shed as rain. Hence wet or dry growth or melting is modeled at below or above freezing temperatures dependent on the diagnosed energy balance. The results of this balance can be made available for radiative transfer calculations since the existence of a liquid coating dramatically alters radiative properties of the graupel particle.

3.2 The Radiative Transfer Model

In order to simulate the upwelling brightness temperatures ($T_B$) that would be observed by the satellite radiometer, we plan to apply to the UW-NMS simulated events a 3D-adjusted plane-parallel radiative transfer model, RTM. The RTM has been described in the studies of Roberti et al. 1994, Liu et al. 1996, Bauer et al. 1998, and Tassa et al. 2004. For most applications, RTM-generated upwelling $T_B$’s over simulated satellite footprints would be calculated at the model resolution (higher than the radiometer resolution) and at different incident viewing angle. The $T_B$ would then be spatially filtered in order to reconcile with the radiometer’s effective resolutions for different channels.

However, for the first version of the algorithm we make use of a simplified approach. Namely, every vertical profile generated by the model at high resolution is used to generate a plane-parallel precipitating environment, to which the RTM is then applied to compute the upwelling TBs that would be measured by the satellite radiometer at an observation angle of 53.1°. [Note that with this assumption, the different spatial resolutions and antenna patterns of the various frequencies don’t come into play.] The 3D-adjusted approach will be used for the second version of the algorithm.

The required inputs to the RTM are: suitable temperature / moisture profiles and temperature / emissivity of the surface, as well as vertical profiles of liquid/ice water contents (LWC/IWC) of the various hydrometeors - along with their single-scattering properties. Surface temperature and vertical profiles are provided by the UW-NMS simulation. Absorption by atmospheric gases at microwave
frequencies are calculated according to the Liebe and Gimmestad 1978 and Liebe 1985 clear-moist air refractivity model that provides a combined water vapour – oxygen volume absorption coefficient.

Surface emissivity is dependent upon frequency and surface characteristics (land/ocean, surface roughness, type of soil and soil cover, soil humidity, etc.). Thus, we have selected three different surface emissivity models to best represent the different surface backgrounds of the selected CRM simulations. The three surface emissivity models that have been implemented, are:

- For land surfaces, the forest and agricultural land surface emissivity by Hewison 2001;
- For a sea surface, the fast and accurate ocean emissivity model of English and Hewison 1998 (see also Hewison and English 2000, and Schlüssel and Luthardt 1991), which provides accurate estimates of surface emissivity between 10 and 200 GHz for view angles up to 60° and wind speeds from 0 to 20 m/s;
- For snow covered surfaces, the snow emissivity model that has been empirically derived by Hewison 1999 from satellite retrievals and ground-based measurements; in particular, five different snow cover types have been considered that cover the full range of snow emissivity presented by the previous authors – i.e., forest +snow, deep dry snow, fresh wet snow, frozen soil, first year ice, compact snow.

The uncertainty in surface emissivity is taken into account within the Bayesian retrieval scheme developed by Mugnai et al. 2001 and Di Michele et al. 2003. This is accomplished by means of an error covariance matrix (see Di Michele et al. 2004), which accounts for $T_B$ sensitivity to parameter uncertainties and approximations used in the forward RTM model (e.g., Tassa et al. 2003, 2004).

The determination of the single scattering properties of the various hydrometeors species would be a straightforward calculation in Mie scattering if only pure water and ice spheres are considered, but can be a major challenge due to the wide variety of sizes, densities, and shapes of natural ice hydrometeors - especially for snowflakes and ice aggregates which are hydrometeors large enough to interact with the radiometer frequencies of interest, but whose shapes are typically in radical departure from spheres. However, whereas the UW-NMS model provides hydrometeor size distributions and densities, information on shape is not available from its microphysical parameterization scheme - which is designed strictly to exchange H$_2$O mass between vapour and the different species of hydrometeors (under the allowed gas-hydrometeor or hydrometeor-hydrometeor mass transfer schemes) without considering the habits under which the mass transfers take place. For this reason, we take the customary assumption that all particles are spherical and homogeneous so that Mie theory can be applied (Bohren and Huffman 1983, Wiscombe 1980).

Graupel particles are assumed to be spherical with densities nearly that of pure ice (0.9 g cm$^{-3}$). They are assumed to be “equivalent homogeneous spheres” having an effective dielectric function obtained by combining the dielectric functions of ice and air (or water, in case of melting) according to the effective medium Maxwell-Garnett mixing theory for a two-component mixture of inclusions of air (water) in an ice matrix (see Bohren and Huffman 1983). On the other hand, snowflakes and aggregates are low-density, fluffy ice particles (as long as they are completely frozen). As a result, they should not be modelled according to the Maxwell-Garnett mixing theory – the resulting “equivalent homogeneous soft-ice spheres” would have very large asymmetry factors (> 0.9) at the higher microwave frequencies and would not adequately “cool” the upwelling radiation. The parameters used in the RTM are listed in Table 03.

<table>
<thead>
<tr>
<th>HYDROMETEOR TYPE</th>
<th>PSD</th>
<th>$R_{min}$ (cm)</th>
<th>$R_{max}$ (cm)</th>
<th>Slope (cm$^{-1}$) / Intercept (cm$^{-3}$)</th>
<th>Density (g/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloud</td>
<td>1</td>
<td>0.0009</td>
<td>0.0011</td>
<td>-</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 03 - Parameters for the different hydrometeors used in the radiative transfer scheme: particle size distribution (PSD), min radius, max radius, slope/intercept, and density. PSD = 1 correspond to monodispersed hydrometeors, PSD = 2 to constant intercept and PSD = 3 to constant slope.
Pristine ice particles are highly non-spherical, and we chose to use the Grenfell and Warren 1999 approximation (see also Neshyba et al. 2003). The single-scattering properties of each nonspherical ice particle are computed by means of a collection of ns equal-size solid-ice spheres having a diameter determined by the volume to cross-sectional area ratio \( V/A \) of the original nonspherical ice particle. The volume \( V \) is provided by the UW-NMS simulations. For calculating the cross-sectional area \( A \), we use the observational relationship \( A / (\pi D^2/4) = C_0 D C \) that has been published by Heymsfield and Miloshevich 2003 for several different individual particle habits – here, \( D \) (in cm) is the maximum diameter of the particle, while the coefficients \( C_0 \) and \( C \) (in appropriate CGS units) depend on ice particle habit. For pristine ice crystals we use values \( C_0 = 0.18 \) and \( C = 0.2707 \), that are indicated by the same authors as appropriate averages for midlatitude, continental mixed-habit cirrus clouds. As a result, the diameter (\( D_s \)) and the number (\( n_s \)) of the equivalent solid-ice spheres are given by:

\[
D_s = \frac{\rho}{\rho_{ice}} \frac{D}{C_0 D^C} \\
n_s = \frac{C_0}{1 - C} \frac{D^{3C}}{D_s^3}
\]

where \( \rho_{ice} = 0.916 \text{ g cm}^{-3} \) while the densities \( \rho \) of the pristine ice crystals is usually equal to 0.1 g cm\(^{-3} \). Snowflakes and ice aggregates are low-density, fluffy ice particles (as long as they are completely frozen) that can not be modelled according to Maxwell-Garnett mixing theory – the resulting “equivalent homogeneous soft-ice spheres” would have, according to Mie theory, very large asymmetry factors (> 0.9) at the higher microwave frequencies and would not adequately “cool” the upwelling radiation. To overcome this problem, we used the Surussavadee and Staelin 2006 model in which non-spherical scattering results were fitted using Mie calculations for spheres having a density that is a function of the wavelength.

### 3.3 The instrument model

The transfer function of the MW radiometer is required to convert the radiance at the antenna input to brightness temperatures at the instrument output. In the second version of the algorithm, we plan to implement a simplified instrument model that is based on the SSM/I - SSMIS channel requirements (central frequency, bandwidth, radiometric absolute and relative accuracy) and assuming that the antenna acts as a low-pass Gaussian filter – namely, a two-dimensional Gaussian antenna pattern having a half-power total width (3 dB) equal to the nominal footprint at any frequency. However, this approach can not be applied to the first version of the algorithm due to the horizontal homogeneity of the simulated precipitating environments.

### 3.4 The Cloud-Radiation Database

To generate the Cloud-Radiation Database (CRD), now re-named Cloud Dynamics and Radiation Database (CDRD), for the European region to be used within the H-SAF project, sixty simulations of different precipitation events over the European area for the March 2006 - February 2007 one-year period were performed by means of the cloud resolving model UW-NMS, in such a way as to take into account the various climatic regions, types of precipitation and seasonal variations. Fig. 06 shows their inner domains.
In essence, we have generated CRD and CDRD databases for the European region, that cover one entire year from March 1, 2006 to February 28, 2007 and are divided by seasons and equally distributed over them – specifically, for each season there are 15 simulations that are selected in order to make the database as complete as possible.

For each simulation, three nested, concentric and steady grids were used. The first and outer grid was set at 50 km resolution, covering a large region of 4550 km x 4550 km (Domain A). The second and intermediate grid was set at 10 km resolution, covering a 910 km x 910 km region (Domain B). The third and inner grid was set at 2 km resolution, covering a 502 km x 502 km region (Domain C). For all grids, 35 vertical levels were used up to about 18 km.

Each simulation was run for 24 or 36 hours with a 12-hour spin-up time. This initial period is necessary to better initialize the model by adapting the initial data to the maximum resolution of the model. The NOAA National Centers for Environmental Prediction (NCEP) Global Forecasting System (GFS) gridded analysis fields at about 100 km resolution were used as initial conditions and to nudge the boundaries of the outer grid every six hours throughout the simulation period. After the first 12 hours, the model extracts hydrometeor profiles over the inner domain C – this is done every hour of the remaining simulation time.

To analyze the database in terms of consistency and completeness a sample of experimental TBs was built collecting data from 9976 SSM/I and 1011 SSMIS overpasses. With reference to the “consistency” analysis, Fig. 07 shows the results of a study on the correlations between couples of TBs both in the simulated and in the observed data. For a detailed comparison with the observations dataset see visiting scientist activity final report (Mugnai et al. 2009).
Fig. 07 - Correlation between the TBs at 91.66 and 150.0 GHz for the simulated (top-left), and observed data (top-right) over land. For each point the log of occurrences is shown. The overlapping of simulated and observed points is also shown (down). The two distribution are very similar. This fact confirms a correct parametrization of the atmospheric ice scattering.
3.5 The precipitation retrieval model

As for the retrieval of precipitation, we will use the latest version of a physically-based algorithm for precipitation profile retrieval, that has been developed and is continuously being improved at CNR-ISAC. In the early version, described by Mugnai et al. 1993, Marzano et al. 1994, Pierdicca et al. 1996, the solution profiles were derived without iteration by a Bayesian method based on weighing different database profiles according to the proximity of measured and modeled TB’s and on a priori probabilities of occurrence of given profile structures. Surface rain rates are derived from the estimated hydrometeor profiles using fallout equations. After Panegrossi et al. 1998, it was evident that precision and accuracy of the precipitating cloud structure estimation, and hence of the surface rainfall rate retrieval, are strictly related to the appropriate generation of the cloud profile dataset associated to the typology of the observed precipitation event more than to an a-posteriori statistical treatment of uncertainties. Thus, it is important to use several cloud model simulations for different types of precipitation systems and to generate the corresponding cloud-radiation databases, in order to specialize the algorithm to different storm structures. As a consequence, more recent releases improve the algorithm performance by means of a set of specific simulations to represent meteorological events occurring in the zone and season under investigation. As mentioned before, the simulation of the meteorological events is performed by the UW-NMS.

The latest release of the ISAC algorithm has been published with the name of BAMPR (Bayesian Algorithm for Microwave Precipitation Retrieval) - see Mugnai et al. 2001; Di Michele et al. 2003; 2004; Tassa et al. 2003. It is characterized by a detailed description of the estimation uncertainties, a careful coupling of the forward and inverse problem and a quantitative evaluation of the representativeness of the cloud-radiation database. For this project, we have developed a more advanced version of the algorithm – which we call CDRD Algorithm since it is thought to be used within a new approach for passive microwave precipitation retrieval, which we call the Cloud Dynamics and Radiation Database (CDRD) approach for it is based on extending the CRD method by incorporating an extensive mix of the CRM’s dynamical, thermodynamical, hydrometeorological, and microphysical variables (Mugnai et al. 2006).

The block diagram of the CDRD algorithm is shown in Fig. 08, where the two boxes represent the two main blocks of the algorithm, generally referred as the “forward problem” and the “inverse problem”. As described earlier, the forward problem consists of the generation of a database (the CDRD), in which the simulated $T_B$ that would be measured by a spaceborne radiometer are associated to the various cloud structures generated by the UW-NMS cloud-resolving model. The frequency-dependent model and instrumental errors are evaluated by means of the error covariance estimator module by using ancillary information and numerical sensitivity tests. The output of the forward modelling procedure is the construction of a statistically significant CDRD.

The inverse problem consists in retrieving the hydrometeor profiles by means of a Bayesian method that compares the measured (SSM/I & SSMIS) and modeled (CDRD) $T_B$’s. Fig. 09 shows the flowchart of our CDRD Bayesian Algorithm. Note that some portions of this block diagram refer to the CDRD approach we are presently developing with the purpose of reducing the retrieval uncertainty by increasing the number of constraints.
Fig. 08 - Block diagram of the CDRD Bayesian Algorithm for precipitation profile retrieval. The box on the right represents the “inverse problem”; the box on the left corresponds to the database generation and represents the “forward problem”.

Fig. 09 - Detailed block diagram of the “inverse problem”.
Note that there are several steps before the Bayesian retrieval is performed. First, the measured $T_B$’s at the various frequencies are convolved so as to enhance their resolution up to that of the 85 GHz channels. Then, all pixels with unrealistic $T_B$’s are discarded ($T_B < 50 \text{ K} \& T_B > 325 \text{ K}$). Finally, different screening procedures are applied in order to identify the regions/pixels where precipitation is unlikely or precipitation retrieval would be ambiguous. Such regions/pixels are not considered by the retrieval algorithm.

Different screening procedures have been developed depending on the characteristics of the surface background. **Fig.s 10 to 14** show the block diagrams for the screening procedures over land, coast, ocean and ice, respectively. Here, the term MASK indicates pixels that are not associated to precipitation (MASKI is for ice; MASKO for ocean; MASKP is for polarization information). Since screening over coasts is particularly difficult due to the concomitant presence of different land/ocean portions within each pixel, we have considered together with the tests of Fig. 10 the so-called Polarization Corrected Temperature (PCT) technique (Kidd 1998). [PCT(85) = $T_{85V} + \Theta*(T_{85V}-T_{85H})$, where $\Theta$ is an empirical constant].

**Screening on Land**

![Screening procedure for land.](image)

**Fig. 10 - Screening procedure for land.**
Screening on Coast

Fig. 11 - Screening procedure for coast.

Screening on Ocean

Fig. 12 - Screening procedure for ocean.
Screening on Ice

In the second phase, the Bayesian Minimum Mean Square (MMS) inversion algorithm is applied using only the selected class of the CRD. Output products are the hydrometeor and/or precipitation rate profiles, columnar liquid water contents and surface rain rates. Within the MMS Bayesian criterion, the hydrometeor profile estimate is given by the expected value of the hydrometeor profile conditioned to the space borne measured multi-frequency T_B, i.e. it is practically an ensemble weighed average of the hydrometeor profiles (belonging to the selected CRD) whose radiative signature lie around the observed T_B. The MMS approach helps in overcoming some stability problems due to the numerical implementation of the Maximum A-posteriori Probability (MAP) algorithm (Marzano et al. 1999).

If we indicate with \( \mathbf{g} \) the geophysical (hydrometeor water content) vector related to a profile set of the CRD and with \( \mathbf{t}_m \) the multi-spectral vector of the simulated brightness temperatures, the MMS estimate \( \hat{\mathbf{g}}_{MMS} \) is defined as the expected value of \( \mathbf{g} \), given a set of measurements \( \mathbf{t}_m \), i.e.

\[
\hat{\mathbf{g}}_{MMS} = \left\langle (\mathbf{g} \mid \mathbf{t}_m) \right\rangle,
\]

where the angle brackets indicate an ensemble averaging with respect to \( \mathbf{g} \). The previous equation can be given in an explicit form as

\[
\hat{\mathbf{g}}_{MMS} = \int_0^\infty \mathbf{g} \mathbf{p}(\mathbf{g} \mid \mathbf{t}_m) d\mathbf{g}
\]

where \( \mathbf{p}(\mathbf{g} \mid \mathbf{t}_m) \) is the conditional probability density function (PDF) of \( \mathbf{g} \). Using the Bayes theorem, \( \mathbf{p}(\mathbf{g} | \mathbf{t}_m) \) can be transformed in the following way:

\[
p(\mathbf{g} \mid \mathbf{t}_m) = p(\mathbf{t}_m \mid \mathbf{g}) p(\mathbf{g}) / p(\mathbf{t}_m) = p[\mathbf{e}(\mathbf{g})] p(\mathbf{g}) / p(\mathbf{t}_m)
\]

where the \( p(\mathbf{g}) \) is the a priori PDF due to \( \mathbf{g} \), and \( \mathbf{e}(\mathbf{g})=[\mathbf{t}(\mathbf{g})-\mathbf{t}_m] \) is the T_B error vector with \( \mathbf{t}(\mathbf{g}) \) the simulated vector, related to \( \mathbf{g} \) through the radiative transfer model.
The implementation of the last equation can be carried out by noting that, since the CRD consist of a discrete number of profiles \(N_{\text{CRD}}\), the available PDFs are not continuous functions, unless we choose analytical expressions. The PDF \(p(g)\) for each profile may be approximated as

\[
p(g) \sim h(g, \Delta g),
\]

where \(h(g, \Delta g)\) is the histogram relative to the sample \(g\) within a variable bin \(\Delta g\). Thus, the \(i\)-th element \(g(i)\) of the hydrometeor profile \(g\) can be estimated as follows:

\[
\hat{g}_{\text{MMS}}(i) = k \sum_{j=1}^{N_{\text{CRD}}} g_j(i) e^{-0.5(t(g_j) - t_\omega)^T C^{-1}_{\epsilon}(t(g_j) - t_\omega)} h(g_j(i), \Delta g_j)
\]

where \(g_j\) is the \(j\)-th sample of the CRD, \(t(g_j)\) is the corresponding \(T_B\), and \(C_{\epsilon}\) is the error covariance matrix. The constant \(k\) is such that

\[
\sum_{j=1}^{N_{\text{CRD}}} e^{-0.5(t(g_j) - t_\omega)^T C^{-1}_{\epsilon}(t(g_j) - t_\omega)} h(g_j(i), \Delta g_j) = 1.
\]

### 3.6 The uncertainty estimator model

The strong non-linearity of the forward problem implies a non-uniqueness feature of the inverse problem so that very different microphysical structures can produce similar \(T_B\) vectors. A remarkable feature of the BAMPR retrieval is that each estimate is accompanied by its relative uncertainty (Marzano et al. 2000, Bauer 2001). The Minimum Mean Square (MMS) algorithm, described in the previous Section, can provide a measure of this inherent uncertainty according to equation

\[
\sigma^2_{g_{\text{MMS}}} = \langle [g | t_m] - \hat{g}_{\text{MMS}} \rangle^2
\]

where \(\sigma^2_{g_{\text{MMS}}}\) is the variance vector of the estimated profile \(\hat{g}_{\text{MMS}}\). The amount of this uncertainty depends on the capability of the cloud radiative model simulation to reproduce the spatial structure and the dynamical range of the upwelling radiation as well as on the typology of the meteorological event observed. It has been shown in Tassa et al. 2003 that the impact of the uncertainties is extremely large at light rainfall rates (below 2 mm/h), and it tends to rapidly decrease for increasing rain rates. This is probably due to the fact that the events studied in that case were tropical hurricanes and storms, where the presence of light rainfall rate is not well stressed out. Moreover, the current CRD contains only two hurricanes simulations, so that only the radiative appearance of the hurricane is better represented. The uncertainties could be reduced, for instance, by improving the event typology and adding different precipitating systems.

It is worth noticing that the database classification into moderate and intense rain regimes plays an important role in this regard as it reduces the inherent dispersion of cloud profiles associated to a given \(T_B\) vector. The importance of the representativeness has been stressed. For this reason during the last years a great effort has been done in simulating different events especially over northern Europe and the Mediterranean Sea. In this way, the precipitation database over Europe is represented by the mid-to-high latitude type of events.

### 3.7 Algorithms validation/heritage

The physical foundations of the CRD approach were defined in the early 90’s by Mugnai et al. 1990, 1993 and Smith et al. 1992, 1994a. At about the same time, multifrequency inversion-type precipitation-profile retrieval schemes based on such approach began to evolve (see Smith et al. 1994b; Kummerow and Giglio 1994a, 1994b; Marzano et al. 1994) and to successfully participate in algorithm validation/intercomparison activities, such as the First WetNet Precipitation Intercomparison Project (PIP-1) (see Barrett 1994). Soon after it became evident that Bayesian retrieval techniques were best suited for the CRD approach (see Evans et al. 1995; Pierdicca et al. 1996). Nevertheless, it was with the
launch of the Tropical Rainfall Measuring Mission (TRMM) space observatory in November 1997, carrying onboard the TRMM Microwave Imager (TMI) and a Precipitation Radar (PR), that such physically-based Bayesian techniques were fully exploited and showed their potential for retrieving tropical precipitation – in addition to our BAMPR algorithm, we must mention here the Goddard Profiling Algorithm (GPROF) (Kummerow et al. 2001) which is NASA’s official algorithm for TMI retrievals. Thereafter, the optimized algorithms for TMI have been adapted for retrieving precipitation at higher latitudes using SSM/I and SSMIS observations.
4. Examples of PR-OBS-1 products

Fig. 14, Fig. 15 and Fig. 16 show precipitation maps associated to an intensive convective event, to a moderate perturbation and to a light rain situation, respectively.

Fig. 14 - Example of an intensive convective event over Sicily. The strong convective system caused the Messina city flood during the night between 01 and 02 January 2010 - Left: retrieved precipitation [mm/h]; right: brightness temperature in channel 85.5 GHz, H polarisation [K] - Satellite DMSP-F16, SSMIS, day 01/10/2009 18:07 UTC, ascending pass.

Fig. 15 - Example of moderate perturbation over the central Mediterranean region - Left: retrieved precipitation [mm/h]; right: brightness temperature in channel 85.5 GHz, V polarisation [K] - Satellite DMSP-F15, SSM/I, day 15/01/2010 14:22 UTC, ascending pass.
Fig. 16 - Example of high-latitude light rain situation over Northern Britain - Left: retrieved precipitation [mm/h]; right: brightness temperature in channel 85.5 GHz, V polarisation [K] - Satellite DMSP-F16, SSMIS, day 05/04/2010 07:47, descending pass.
References


