UNIFIED FRAMEWORK FOR PRECIPITATION RETRIEVAL AND ANALYSIS BY MEANS OF MULTISENSOR SATELLITE OBSERVATIONS AND CLOUD MODEL SIMULATIONS: APPLICATION TO H-SAF

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Abstract

The EUMETSAT Satellite Application Facility on Support to Operational Hydrology and Water Management (H-SAF) has been established in mid-2005, to generate products relative to precipitation, soil moisture and snow, and to assess their impact on hydrological applications. The paper deals with the precipitation products generation chain. The precipitation products are derived from MW radiometers such as SSM/I and SMMIS from the DMSP satellites, and AMSU-A, AMSU-B and MHS from MetOp and NOAA; and thereafter blended with SEVIRI images from Meteosat. Other sensors such as AMSR-E from EOS-Aqua, and TMI, PR and LIS from TRMM, are used in support of algorithm development. The products to be generated include: precipitation rate with flag for liquid/solid from MW sensors (SMM/I-SSMIS and AMSU-MHS), precipitation rate from blended LEO/MW and GEO/IR, and accumulated precipitation over 3, 6, 12 and 24 h. Target delivery time is 15 min for MW-derived data, 5 min for MW-IR blended data, and 15 min for accumulated precipitation. The algorithm development is mostly under responsibility of CNR-ISAC, with contributions from other units of the H-SAF consortium. Several H-SAF units contribute to calibration/validation activity. Software integration, pre-operational products generation and distribution after quality control will be under the responsibility of the Italian Meteorological Service.

1. INTRODUCTION - INFORMATION ON H-SAF

The EUMETSAT Satellite Application Facility on Support to Operational Hydrology and Water Management (H-SAF) has been established by the EUMETSAT Council on 3 July 2005 and the kick-off meeting took place on 15 September 2005. H-SAF is supported by 12 EUMETSAT member or cooperating States, sharing work and responsibility as displayed in ***Table 1***. It is noted that Italy acts as "host" as well as leader of precipitation products generation, Austria leads soil moisture with large contribution from ECMWF, Finland leads snow parameters with large contribution from Turkey, and Poland leads the Hydrological validation programme.

No.	Country	Main Unit in the Country	Role
01	Austria	Zentral Anstalt für Meteorologie und Geodynamik	Leader for soil moisture
02	Belgium	Royal Meteorological Institute of Belgium	
03	ECMWF	N/A	Contributor for "core" soil moisture
04	Finland	Ilmatieteen Laitos	Leader for snow parameters
05	France	Météo-France	
06	Germany	Bundesanstalt für Gewässerkunde	
07	Hungary	Hungarian Meteorological Service	
08	Italy	Servizio Meteorologico dell'Aeronautica	Host + Leader for precipitation
09	Poland	Institute of Meteorology and Water Management	Leader for Hydrology
10	Romania	National Institute for Meteorology and Hydrology	
11	Slovakia	Slovakia Hydro-Meteorological Institute	
12	Turkey	Turkish State Meteorological Service	Contributor for "core" snow parameters

Table 1: **Composition of the H-SAF consortium.**

The main objectives of H-SAF are:

a. ***to provide new satellite-derived products*** from existing and future satellites with sufficient time and space resolution to satisfy the needs of operational hydrology; identified products:
  - precipitation (liquid, solid, rate, cumulate);
  - soil moisture (at surface, in the roots region);
  - snow parameters (cover, melting conditions, water equivalent);

b. ***to perform independent validation of the usefulness of the new products*** for fighting against floods, landslides, avalanches, and evaluating water resources; the activity includes:
  - downscaling/upscaling modelling from observed/predicted fields to basin level;
  - fusion of satellite-derived measurements with data from radar and raingauge networks;
  - assessment of the impact of the new satellite-derived products on hydrological applications.

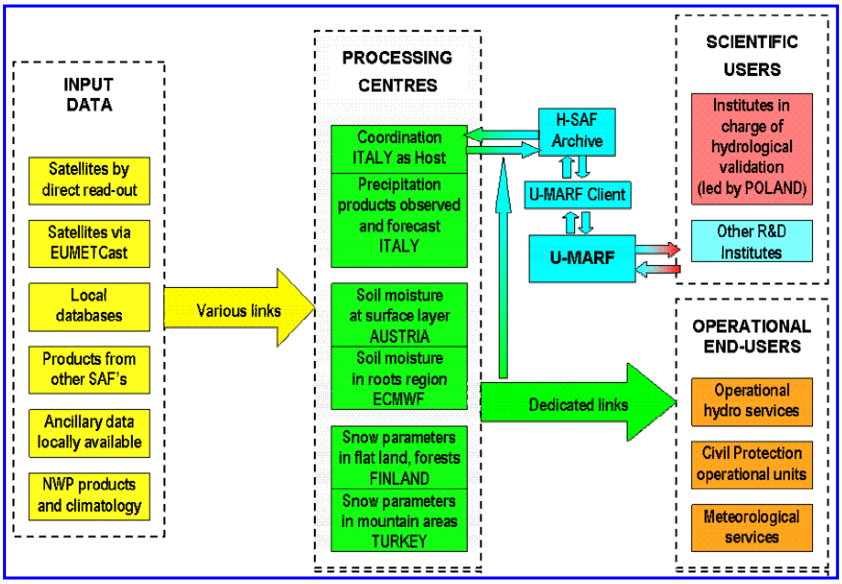

Figure 1: **Conceptual architecture of H-SAF.**

The conceptual architecture of H-SAF is shown in ***Figure 1***. It is noted that Italy has the double role of coordinating the Project, that includes management of the central archive connected to the EUMETSAT U-MARF, and generating the precipitation products (both observed and generated by a NWP model). The soil moisture processing task is shared between Austria, responsible for the product in the surface layer, and ECMWF, responsible for the roots region. The snow products relative to flat areas and forests are generated in Finland, those in mountainous areas in Turkey. Data distribution is performed either through U-MARF, generally for the scientific units responsible of the Hydrological validation programme under Polish leadership (and any other R&D institute), or by direct links with the production centres. Use of EUMETCast is foreseen at an appropriate time. In all data-producing countries, the national meteorological services are responsible of running product generation, whereas the algorithm development and support for software integration are provided by scientific institutes.

Products will be released in a stepwise mode, associated to the development programme as shown in ***Figure 2***. The elements of the stepwise development programme are:

- augmented database of the *a-priori* information needed to support the retrieval algorithm;
- the results of the calibration / validation activities (continuous through the whole project);
- introduction of advanced radiative transfer models or retrieval algorithms;
- availability of new satellites or instruments (a number will come into service during 2006-2010);
- feed back from End-users, particularly from the Hydrological validation programme.

According to plans, Version-1 products should be released about two years after the kick-off meeting, to enable the Hydrological validation programme to start. In advance, prototype products will be distributed at chances to help tools preparation. Version-2 should be released after about 3.5 years, and the final version after 5 years, at end of the Development Phase.

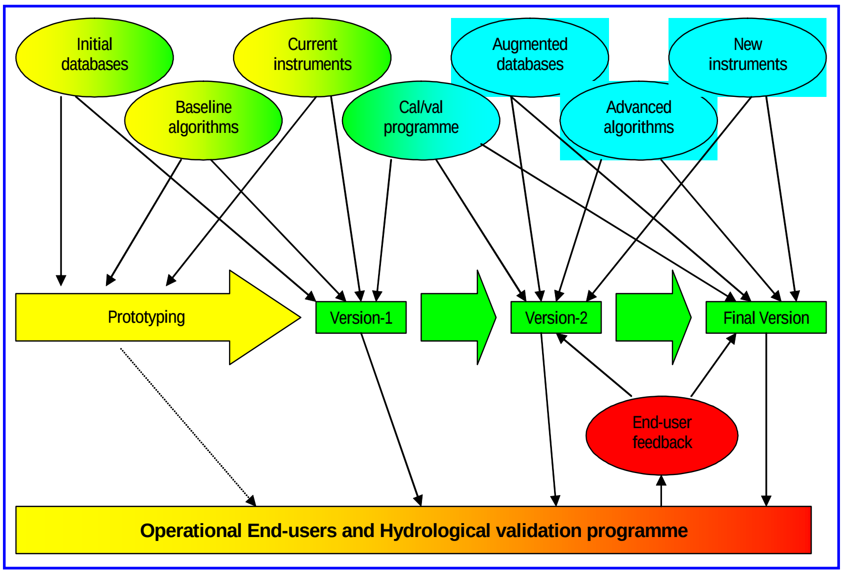

Figure 2: **Stepwise products release.**

2. THE PRECIPITATION PRODUCT GENERATION CHAIN

The precipitation processing chain in Italy aims at generating the products displayed in ***Table 2***. The notation 'OBS' reminds that there will also be computed products from a NWP model.

Code	Product's name	Responsible Unit
PR-OBS-1	Instantaneous precipitation rate at the ground observed in MW, with indication of the phase (liquid or solid)	Italy, ISAC-CNR
PR-OBS-2	Instantaneous precipitation rate at ground observed in MW + IR, with indication of the phase (liquid or solid)	Italy, ISAC-CNR
PR-OBS-3	Accumulated precipitation over 3, 6, 12 and 24 hours, observed in MW and MW + IR	Italy, Italian Met Service

Table 2: **Satellite-derived precipitation products.**

The relationships between satellite data and output products are shown in ***Figure 3***. It is observed that there are four processing chains (yellow-marked), for:

- precipitation rate from conical scanning SSM/I and SSMIS (described in Section 3);
- precipitation rate from cross-nadir scanning AMSU and MHS (described in Section 4);
- precipitation rate by blending MW from LEO and IR from GEO (described in Section 5);
- accumulated precipitation from MW or MW+IR (described in Section 6).

By exploiting both conical scanning SSM/I-SSMIS and cross-nadir scanning AMSU-MHS it will be possible to achieve complete coverage over Europe every ~ 3 h, as shown in ***Figure 4***. In fact, currently there are at least 2 operational DMSP satellites with either SSM/I or SSMIS (in principle 4, but not all in good status) and at least 2 operational NOAA satellites with AMSU-A and AMSU-B or MHS (again, 4 in principle, but some in bad status); then there will be soon MetOp-1, with AMSU-A and MHS. Figure 4 only shows the latest two DMSP satellites, the latest two NOAA satellites, and MetOp-1. Two consecutive orbits are shown, separated by a period of ~ 100 min. Other satellites data to be exploited, but only in support of algorithm development and validation, are: EOS-Aqua, specifically the Advanced Microwave Scanning Radiometer (AMSR-E), and TRMM, specifically the Precipitation Radar (PR), the TRMM Microwave Imager (TMI) and the Lightning Imaging Sensor (LIS). These R&D satellites are not shown in Figure 4.

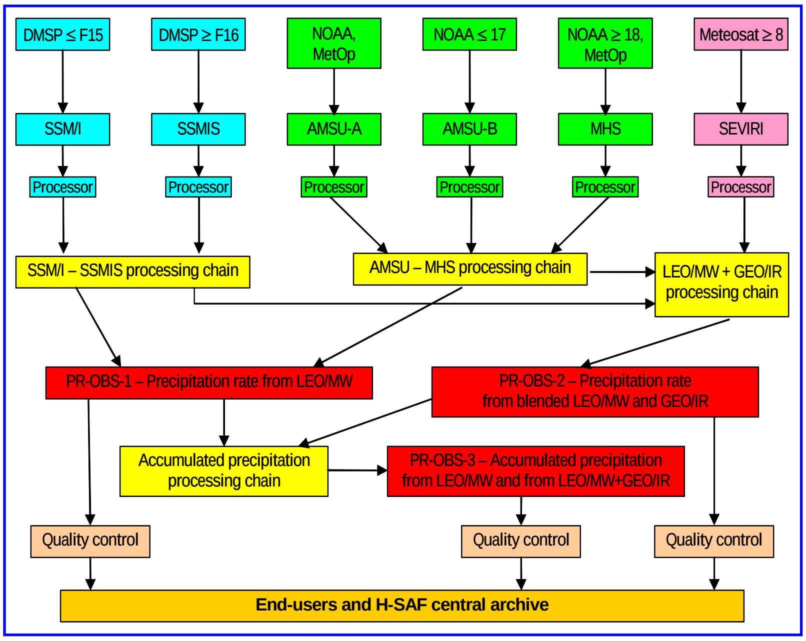

Figure 3: **Precipitation products generation. chain.**

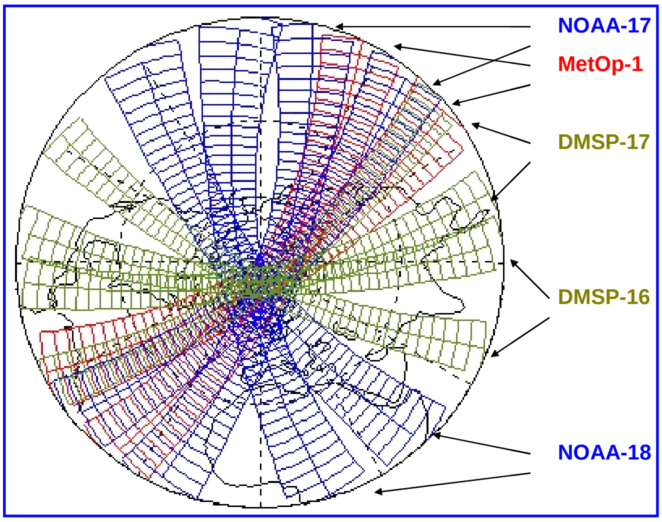

Figure 4: **Coverage from MW radiometers in 3 h.**

3. SSM/I-SSMIS PROCESSING CHAIN

The Special Sensor Microwave / Imager (SSM/I) and the Special Sensor Microwave Imager-Sounder (SSMIS) are the current operational instruments supposed to provide the highest quality precipitation data. This is due to their relatively low frequencies, that include atmospheric windows viewing through the whole troposphere, and the conical scanning mechanism, that provides constant incidence angle (~ 53° from zenith), thus ensuring comparable polarisation conditions (and also constant IFOV size across the scene, though changing with frequency. SSM/I operates with 4 frequencies: 19.35, 22.235, 37.0 and 85.5 GHz; and 7 channels (the three window frequencies have two polarisations, the water-vapour 22 GHz only one). The resolution varies from ~ 13 km at 85.5 GHz to ~ 55 km at 19 GHz. SSMIS operates with 21 frequencies in 24 channels. 7 channels are basically the same as SSM/I; 13 are similar to AMSU-A, in the ~ 54 GHz O_2 band, for temperature profiling; 4 are similar to AMSU-B: a 150 GHz window channels and 3 channels in the ~ 183 GHz H_2O band for water vapour profiling. The purpose of the AMSU-like channels is to acquire self-standing information on the atmospheric vertical structure

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.

Microphysical parameters are conveniently retrieved by Cloud Resolving Models (CRM). The problem 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). Then (***Figure 5***) a Radiative Transfer Model (RTM) converts the CRM output into brightness temperatures at the various instrument channel frequencies. The collection of the processed events constitutes the Cloud-Radiation Database (CRD).

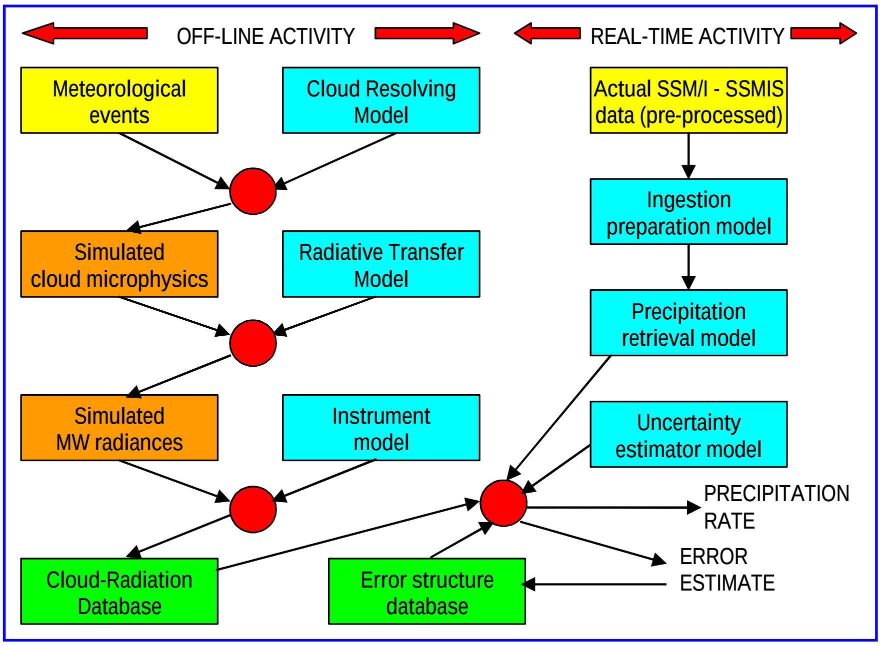

Figure 5: **Flow chart of the SSM/I-SSMIS precipitation rate processing chain.**

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, surface emissivity, preventive classification of the 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 Figure 5, the blue-coloured boxes indicate algorithms/models, yellow boxes observed data, green boxes databases, orange boxes intermediate products. Main highlights are:

- for the Cloud Resolving Model, we adopted the "*University of Wisconsin - Non-hydrostatic Modeling System (UW-NMS)*" (see, e.g., Tripoli 1992);
- the Radiative Transfer Model is a multi-year evolution starting from Roberti et al. 1994;
- the ingestion preparation and the retrieval models are a combination of the "*Goddard Profiling algorithm (G-PROF)*" (see, e.g., Kummerow et al. 1996) and the *Bayesian Algorithm for Microwave Precipitation Retrieval (BAMPR)* (see, e.g., Mugnai et al. 2001).

Figure 6 shows an example of map of precipitation rate at ground retrieved from SSM/I. It is noted that, currently, the use of SMMIS is still in an experimental status, therefore the Version-1 product release will either use SSM/I or the SSM/I-like channels of SSMIS. The use of absorption bands of SSMIS will be introduced with Version-2.

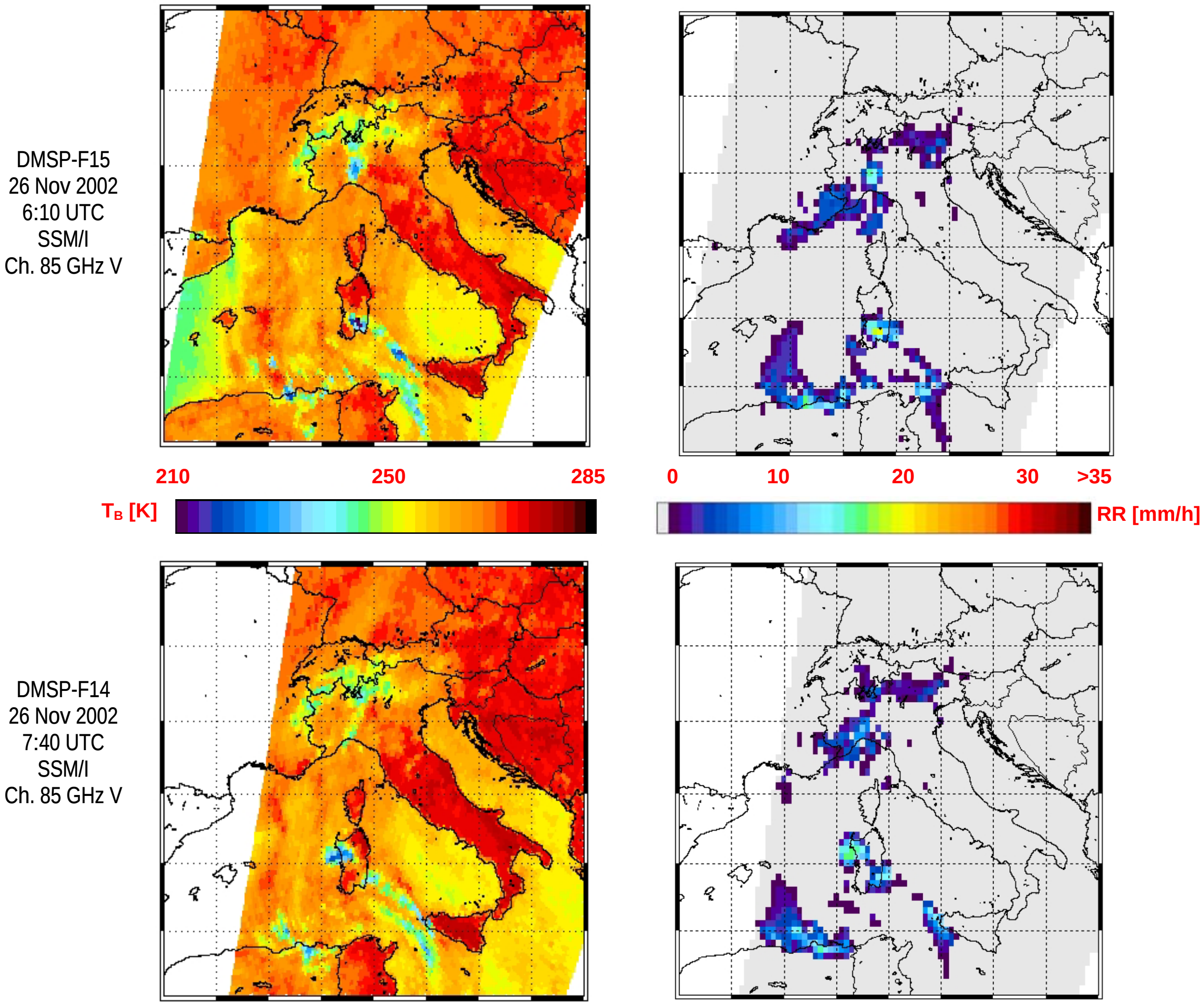

Figure 6: **Example of precipitation retrieval from SSM/I.**

4. THE AMSU-MHS PROCESSING CHAIN

Unlike SSM/I-SSMIS, the Advanced Microwave Sounding Unit (AMSU-A and AMSU-B) and the Microwave Humidity Sounder (MHS) are based on absorption channels:

- AMSU-A has 15 channels, 12 in the 54 GHz O_2 band, two windows (31 and 89 GHz) and one at 23 GHz for water vapour correction; resolution 48 km at the sub-satellite point (s.s.p.);
- AMSU-B has 5 channels, 3 in the 183 GHz H_2O band, and two windows (89 and 150 GHz); resolution 16 km at s.s.p.;
- MHS is very similar to AMSU-B: the 150 GHz channel is moved to 157 GHz and the 183±7 GHz dual-side channel is replaced by the single-side 190 GHz.

AMSU and MHS are not designed for precipitation observation: however they have entered into use for a number of reasons:

- to improve the overall observing cycle (see Figure 4);

- to improve observation over land (e.g., of light precipitation) thanks to the reduced effect of surface emissivity in absorption channels;
- to detect precipitation types closely associated to cloud ice (e.g., snowfall), where high-frequency and strong-absorption channels are more sensitive.

The use of AMSU-MHS places some new problem in respect of SSM/I-SSMIS:
- the resolution changes across scan and, for AMSU-A, that is the most significant for liquid precipitation, degrades from 48 km at s.s.p. to ~ 100 close to end-of-scan;
- the changing zenith angle across-scan implies inhomogeneous effect of polarisation;
- retrieval algorithms for absorption channels (much less directly linked to precipitation) are not as developed as for SSM/I-SSMIS that, incidentally, benefited from the TRMM experience.

The processing scheme for AMSU-MHS is shown in ***Figure 7***. It can be observed that, comparing with the SSM/I-SSMIS processing chain in Figure 5, there is a rather intensive image processing effort in the initial phases, for:
- enhancing the AMSU-A resolution by ‘importing’ high spatial frequency content from the AMSU-B or MHS image;
- reporting the geometric viewing condition to a single zenith angle (currently assumed to be 0°, i.e. vertical viewing).

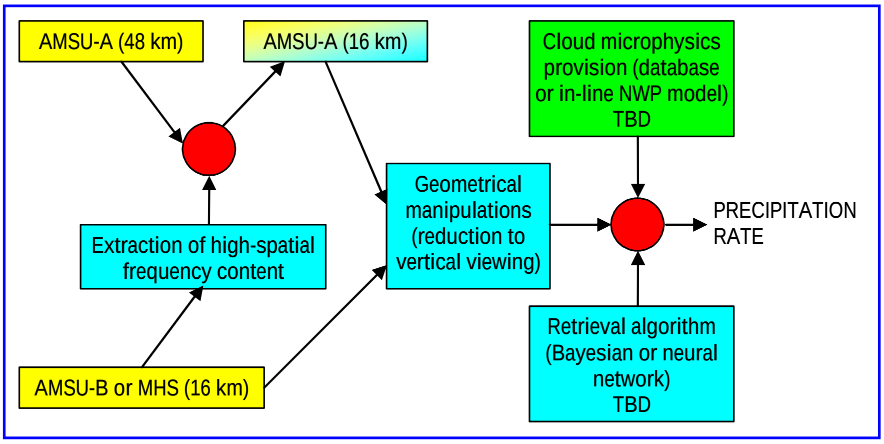

Figure 7: **Flow chart of the AMSU-MHS precipitation rate processing chain.**

It also can be noted that, at this time, the way how to input cloud microphysical information to support retrieval, and the retrieval scheme itself have not yet been selected. It is therefore envisaged that the Version-1 product release will be based on the simple techniques currently used, e.g., at NOAA, whereas the advanced product will be distributed with Version-2. Experiments of AMSU-A resolution enhancement, following, e.g., Chen and Staelin 2002, have already been carried out (Bizzarri et al. 2005). ***Figure 8*** shows an example of results. It can be observed that the AMSU-A enhanced resolution image exhibits most features of the AMSU-B or MHS 16-km resolution image. In turn, the AMSU-B or MHS resolution (16 km at s.s.p. degrading to ~ 30 km at end-of-scan) is similar to the resolution of SSM/I-SSMIS (13 km at 90 GHz, 32 km at 37 GHz).

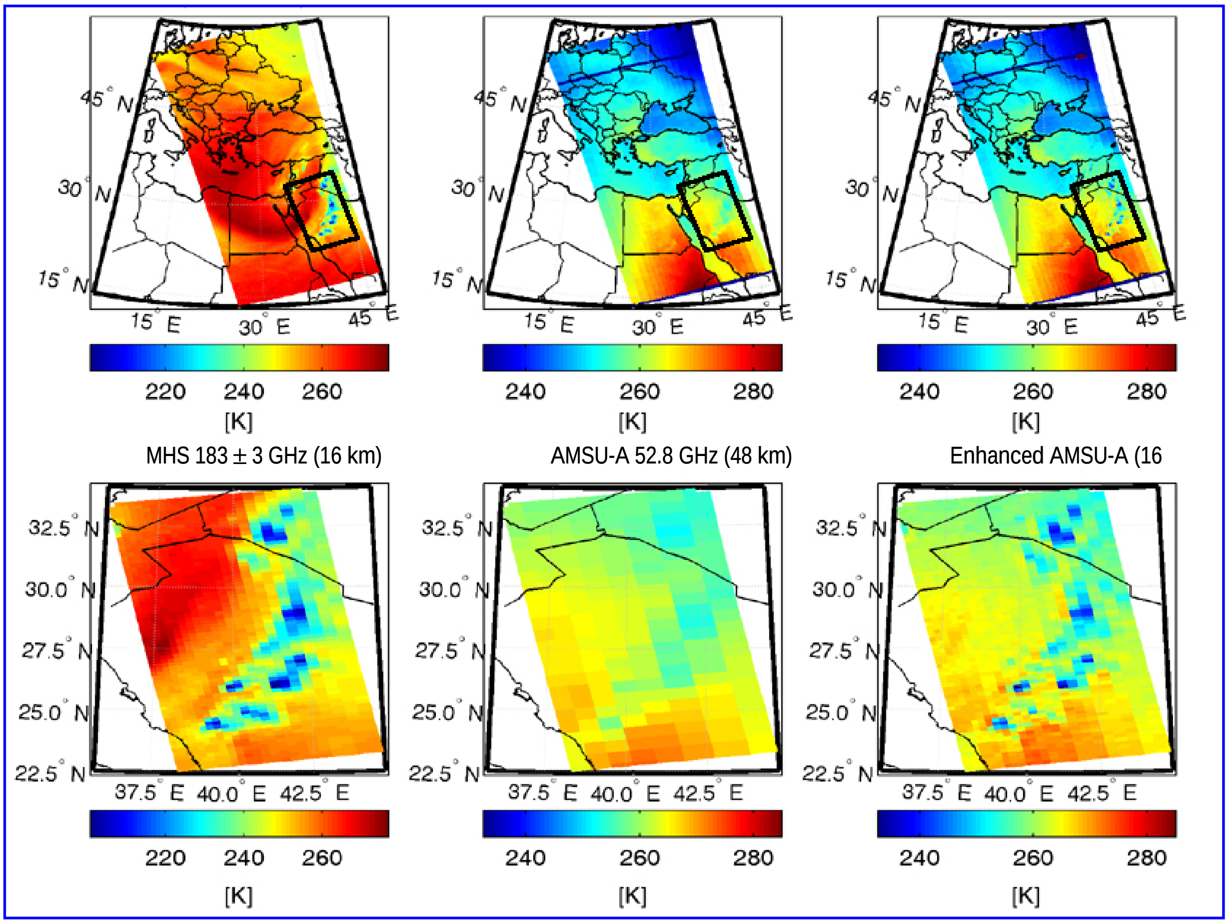

Figure 8: **Example of AMSU-A resolution enhancement. NOAA AMSU-A and MHS, 2 February 2006, 11:11 UTC.**

5. THE BLENDED LEO/MW + GEO/IR PROCESSING CHAIN

In order to comply with the requirement for frequent sampling, and waiting for MW in geostationary orbit, blending (infrequent) accurate measurements from MW in LEO and frequent (inaccurate) measurements from IR in GEO is the current practise. Two techniques are being used: one, "Rapid update", well consolidated, the other one, "Morphing" in a more developmental stage. The *Rapid-update* technique has been conceived by Turk et al. 2000. Precipitation is retrieved from IR radiances by calibration against lookup tables built from space-time coincident precipitation measurements retrieved from MW radiometers. The lookup tables are updated by any new available MW-IR coincident measurements. The *Morphing* technique, introduced by Joyce et al. 2004, makes use of GEO/IR to interpolate in between successive LEO/MW passes, by exploiting the cloud pattern dynamics observed across the GEO/IR image sequences. MW images are simulated as weighed averages between the forward image from the earlier MW pass and the backward image from the successive one. Unlike Rapid-update, that converts IR radiances into rain intensities estimates (a very disputable relationship), Morphing provides retrieval always from LEO/MW.

Both methods will be implemented in H-SAF, as indicated in ***Figure 9***. The Rapid-update product will constitute the most timely possible information on precipitation, though its accuracy is biased towards convective precipitation. The Morphing product is somewhat retro-active, most useful for computing accumulated precipitation. The Rapid-update is operational in several environments, including EUMETSAT (see the MPE, Multi-sensor Precipitation Estimate). We argue that the H-SAF product will have superior quality thanks to the unprecedented quality and amount of MW measurements (from SSM/I-SSMIS and AMSU-MHS) available to update the lookup tables. The Morphing technique is still under development and will be introduced with the Version-2 products release. ***Figure 10*** reports an example of precipitation map obtained by the Rapid-update method, currently still based on the Meteosat-7 imager.

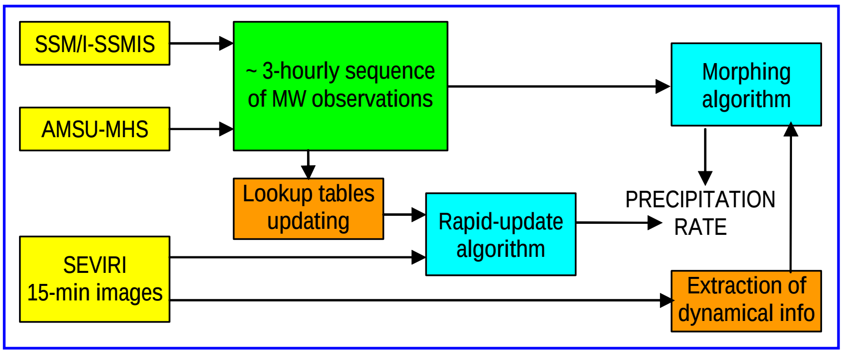

Figure 9: **Flow chart of the LEO/MW-GEO/IR-blending processing chain.**

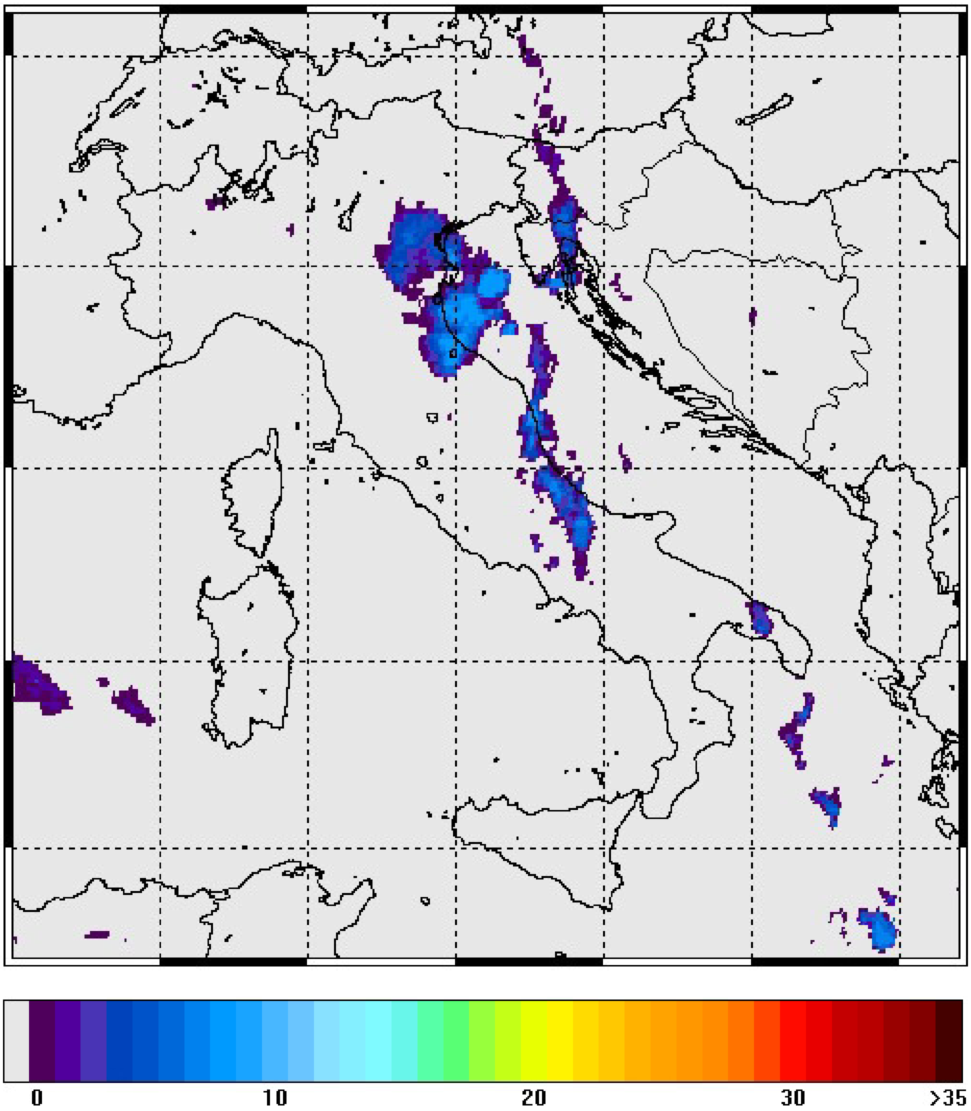

Figure 10: **Surface rain intensity maps in mm/h over the Italian peninsula (November 1999, 17:30 UTC) obtained by means of the Rapid-update technique combining IR brightness temperatures (Meteosat-7) and MW (SSM/I) rain estimates.**

6. THE PROCESSING CHAIN FOR ACCUMULATED PRECIPITATION

Accumulated precipitation will be computed in two different ways:

- only using MW measurements, integrated over the last 24 h, at each new orbital pass of a MW-equipped satellite;
- using the LEO/MW-GEO/IR blended product, initially by Rapid-update, then by Morphing, integrated over the last 3, 6, 12 and 24 h and distributed shortly after each SEVIRI acquisition.

The time integration will weigh the various input data according to their error structure. The product will be developed by the Italian Meteorological Service, and it is not described here.

7. CONCLUSIONS

H-SAF could strongly expand the use of satellites in Hydrology. The Development Phase (2005-2010) will:

- make available new products (precipitation, soil moisture, snow parameters) in a pre-operational fashion;
- progressively improve products quality through a continuous development programme parallel to the pre-operational activity;
- independently assess the benefit of the new products through a hydrological validation programme.

Consequent to:

- demonstrated feasibility and affordability of generating the new products;
- demonstrated cost-effectiveness for application to Hydrology;

a possible Operational Phase could follow in 2010-2015 and later.

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