A VERIFICATION STUDY OVER EUROPE OF AMSU-A/MHS AND SSMIS PASSIVE MICROWAVE PRECIPITATION RETRIEVALS

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Abstract

Global monitoring of the precipitation requires the full exploitation of all overpasses of present and future satellites carrying cross-track and conically scanning passive microwave (PMW) radiometers. Therefore, it is essential to achieve consistency and accuracy of passive microwave precipitation retrievals from the different sensors orbiting around the globe. Within the EUMETSAT H-SAF program (Satellite Application Facility on Support to Operational Hydrology and Water Management, http://hsaf.meteoam.it) we have developed two different passive microwave precipitation retrieval algorithms, one based on a physically-based Bayesian approach for conically scanning radiometers (i.e., SSMIS), and the other one based on Neural Network approach for cross-track scanning radiometers (i.e., AMSU-A/MHS). The two algorithms are based on the same physical foundation, i.e., same cloud-radiation model simulations to be used as *a priori* information in the Bayesian solver and as training dataset in the neural network approach. They also use similar procedures for screening of non-precipitating pixels, identification of frozen background surface, presence of snowfall, and determination of a pixel based quality index of the surface precipitation retrievals. These procedures are calibrated according to the different characteristics of the radiometers used. The two algorithms use dynamical/meteorological/environmental variables as ancillary information to characterize the observed event, and mitigate the ambiguity of the rainfall rates at the ground associated to any given set of measured multichannel brightness temperatures.
A verification study of the latest versions of the two algorithms has been carried out, where the PMW rainfall estimates are compared against radar observations and raingauge network measurements for several precipitation events in Europe, characterized by different environmental, meteorological, dynamical conditions, and by different precipitation regimes. In this paper we present the main results of this study, discussing strengths and potentials of the two algorithms in relation to the different characteristics of the observed events. In addition we describe the efforts made to achieve consistency of the retrievals from close in time overpasses of the cross-track and conically scanning radiometers for the same event, foreseeing potential improvements in nowcasting and/or hydrological applications.

1. INTRODUCTION

The steadily improving quality and capabilities of operational and research satellite data for hydrological remote sensing is essential to respond to the need of global and reliable information on available water resources, as recognized by international bodies and organizations. The improving performances of hydrological models and the hydrological components of weather and climate prediction models, as well as the improving techniques for assimilating hydrological observations into prediction models, particularly satellite retrieval observations, must be associated to the improvement of satellite based retrieval techniques of products essential to hydrological applications.

On July 3, 2005, the EUMETSAT council established the Satellite Application Facility on support to Operational Hydrology and Water Management (H-SAF) designed to deliver satellite products of hydrological interest (precipitation, soil moisture and snow parameters) mainly over the European and Mediterranean region to research and operations users worldwide (http://hsaf.meteoam.it). Mugnai et al. (2013a) provide a detailed description of the H-SAF project, its goal, the consortium structure, the objectives and perspectives, and of the activity foreseen for the future. The H-SAF ground validation network for precipitation measurements is extensive. It includes approximately 4,575 raingauges distributed throughout seven countries and an 81-site C-band and Ka-band radar network distributed over Western and Eastern Europe. Puca et al. (2013) provide a detailed description of the H-SAF Precipitation Product Ground Validation (PPGV) program.

The precipitation products in H-SAF are based on data with different space and time resolutions, derived from sensors installed on European and U.S. satellites. Mugnai et al. (2013a) provide details about the currently available precipitation products and their future development exploiting the new cloud and precipitation monitoring capabilities of Meteosat Third Generation (MTG) and the GPM. In the present paper we focus on the two passive microwave (PMW) precipitation retrieval algorithms used for the two operational instantaneous PMW precipitation products in H-SAF. These two algorithms have undergone through significant changes and improvements throughout the years in order to achieve consistency of precipitation retrievals from close-in-time cross-track and conically scanning radiometer overpasses of the same event. These two PMW products are the basis for the other H-SAF MW/IR combined products which rely on the accuracy and the consistency of the retrievals, provided that a sufficient number of MW overpasses per day are available.

This paper illustrates the results of a study carried out to verify and test the improved capabilities of the new versions of the H-SAF PMW precipitation retrieval algorithms, optimized for the European and Mediterranean basin areas. The PMW rainfall estimates obtained from cross-track and conically scanning radiometers are compared against the H-SAF radar observations and raingauge network measurements for 20 precipitation events in Europe, selected among the H-SAF PPGV dataset. The selected events are characterized by different conditions, and by different precipitation regimes in order to evaluate the strengths and weaknesses of the two algorithms in relation to the different characteristics of the precipitation events. Issues related to the false detection of light precipitation in certain atmospheric and background surface conditions, as well as the detection of snowfall, have been adequately addressed in the new version of the algorithms. Moreover, the algorithms show improved detection capability and precipitation retrievals of heavy precipitation areas. The consistency of the retrievals from close in time overpasses of the cross-track and conically scanning radiometers for the same event is evidenced during the discussion.

2. DESCRIPTION OF PRECIPITATION RETRIEVAL ALGORITHMS: CDRD AND PNPR

The current H-SAF operational precipitation product from PMW conically scanning radiometers (identified as H01) is a physically-based Bayesian precipitation retrieval algorithm funded on a new methodology called Cloud Dynamics and Radiation Database (CDRD). A thorough presentation of the CDRD methodology, attributes and performance is provided by a series of recent publications: Sanò et al. (2013a), Casella et al. (2013), Smith et al. (2013) and Mugnai et al. (2013b). CDRD is an evolution of the more conventional Cloud Radiation Database (CRD) methodology [e.g., Smith et al. (1994), Panegrossi et al. (1998)].

The current CDRD algorithm used within H-SAF is optimized for Europe and the Mediterranean basin (it will be soon extended for use on the full MSG disk). It is based on a large database of simulations of 60 precipitating events over the European/Mediterranean area. The 60 simulations were produced using the Cloud Resolving Model (CRM) Non-hydrostatic Modeling System (NMS) (Tripoli, 1992) coupled to a Radiative Transfer Model (RTM) that relates CRM environments to expected top-of-atmosphere satellite-view PMW brightness temperatures (TBs). The improvements of the CDRD methodology over the CRD one consist in combining meteorological parameter constraints derived from synthetic dynamical-thermodynamical-hydrological (DTH) variables, together with hydrometeor microphysical profiles and multispectral PMW TB vectors into a database used as a-priori knowledge of the Bayesian retrieval algorithm. See Casella et al. (2013) for a detailed discussion of the CDRD algorithm's CRM and RTM and Smith et al. (2013) for the analysis used to select an optimal set of meteorological variables used in the current CDRD algorithm.

The CDRD has been designed for application to a variety of conically scanning PMW radiometers flying on current and future satellites, however, within H-SAF it is presently applied to the Special Sensor Microwave Imager and Sounder (SSMIS) flying on board the DMSP (U.S. Defense Department) satellites, and it is used for the operational H-SAF product H01. In its latest version (ver.

1.7) it makes use of thermo-dynamical information obtained from analysis and forecast data produced by the ECMWF model. It provides instantaneous precipitation rate, with indication of phase, at 13.2 x 15.5 km^2 resolution (corresponding to the SSMIS high frequency channel IFOV), consistent with the SSMIS high-frequency window channel resolution.

The current H-SAF precipitation product from PMW cross-track scanning radiometers AMSU-A and MHS (or AMSU-B) (on board U.S. NOAA-18 and NOAA-19 and European MetOp-A and MetOp–B satellites) is based on an Artificial Neural Network (ANN) approach. The algorithm, originally based on Surussavadee and Staelin (2008), has been recently newly created in order to optimize the product for the European/Mediterranean Basin area. The algorithm is referred to as Passive-microwave Neural-network Precipitation Retrieval (PNPR) and it is described in detail in Sanò et al. (2013b) and Mugnai et al. (2013b). It is based on a new optimal three-layer ANN, trained using the same 60 CRM simulations and the same RTM as in the CDRD algorithm. Moreover, as pointed out in Section 2.1, the two algorithms use the same precipitation screening methodology the same surface identification scheme, and the same phase flag and quality index determination methodologies described in the next section (Section 2.3). The PNPR algorithm is used for the current operational H-SAF product H02 (ver. 2.4).

The simulated satellite TB vectors are consistent with the AMSU-A and MHS channel frequencies and view-angle dependent IFOV sizes along the scan. A variable sensor resolution (VSR), defined according to the nominal resolution of MHS (varying from 16 x 16 km^2 / circular at nadir to 26 x 52 km^2 / oval at scan edge), has been chosen as the PNPR product spatial resolution. As input data, the algorithm incorporates TBs measured by the AMSU-A and MHS radiometers and various additional channel-derived variables (see Sanò et al, 2013b, for details). In order to reduce ambiguity, other geophysical/geographical inputs (i.e., latitude, terrain height, surface type, season) guide the algorithm towards the solution. The pixel number along the scan is an additional input parameter, needed to determine the degree to which limb smearing has to be reduced, an effect produced by the changing atmospheric path length along the scan. The ANN itself performs this limb correction. The algorithm uses a unique ANN that retrieves the surface precipitation rate for all types of surface backgrounds represented in its database, i.e., land, ocean, ice, snow or coast. A procedure for correcting damaged MetOp-A radiometric channels has been also introduced.

For the seek of consistency between PMW H-SAF precipitation products deriving from cross-track and conically scanning radiometers the same screening algorithm and the same specially tailored surface identification procedures (also frozen/snowy background surface) are used in the CDRD and PNPR (see Mugnai et al., 2013b). The procedures used to determine both the phase and the quality index are similar in the CDRD and PNPR algorithms. The quality flag summarizes the product quality and reliability and provides the end-users with a simple and immediate criterion for the evaluation of the products towards a correct selection and application of the precipitation estimates with respect to the analyzed scenario. This index is derived from the “Percentage of Confidence Index” (PCI), evaluated on the base of four different criteria: 1) Quality of input data (sensor used, horizontal resolution, presence of corrupted channels); 2) Background surface; 3) Event type; 4) Retrieval performance (i.e., the Bayesian variance of the retrieval in CDRD, viewing zenith angle across the scan for PNPR). The phase flag is based on the studies on snow and ice detection (see Mugnai et al., 2013b for details). It is evaluated only for pixels flagged as precipitating after the screening procedure and it is not available for pixels where coast is present in the background surface.

3. CASE STUDIES AND GROUND BASED VALIDATION DATASET

A verification study of the latest versions of H01 and H02 has been carried out by selecting 19 case studies from the H-SAF PPGV team reports for the period 2009-2011. The case studies are listed in Table 1, and they represent different typologies of precipitation events characterized by various meteorological and seasonal conditions occurred in 6 of the 7 countries participating to the H-SAF PPGV team.

Ground-based data of the different National radar and raingauge networks have been kindly provided by the H-SAF PPGV team members of each country. Germany, Hungary, Italy, and Poland provided both radar and raingauge data, while for Slovakia only radar data were available. The detailed description of these events is available at the H-SAF web site (http://hsaf.meteoam.it).

In this study we have chosen to use the raingauge data with an integration time of 1 h (see Porcù et al., 2013) and we have applied a procedure called raingauge density test, i.e., at least two raingauge stations needed to be located within a radiometer IFOV in order to be considered in the validation. Based on these criteria it has become evident that the raingauge data from most national networks were too sparse, and for some case studies very few satellite IFOVs passed the raingauge density test. Therefore, we have limited the use of raingauge data to the case studies in Germany and Italy. Radar data were used for all case studies. All data have been averaged to the horizontal resolution of the satellite product, and the raingauges have been integrated for one hour around the time of the satellite overpass, while radar data have been taken at the time closest to the satellite overpasses available for each case study.

Case study code	Date	Region	Description
IT1	20/10/2011	Italy	Rome Flood
IT2	25/10/2011	Italy	Cinque Terre Flood
IT3	4/11/2011	Italy	Genoa flood
IT4	03-04/02/2012	Italy	Snowfall
IT5	10-11/02/2012	Italy	Snowfall
IT6	21-22/12/2009	Italy	Snowfall
HU1	10/9/2010	Hungary	Convective Event
HU2	23/6/2011	Hungary	Convective Event
HU3	30/7/2011	Hungary	Convective Event
HU4	1/12/2009	Hungary	Stratiform Event
HU5	17/9/2009	Hungary	Stratiform Event
HU6	10/2/2009	Hungary	Snowfall
PO1	11/5/2009	Poland	Convective Event
PO2	23/6/2009	Poland	Convective Event
SK1	7/6/2011	Slovakia	Orographic Precipitation
SK2	23/12/2009	Slovakia	Melting snow on frozen soil
GE1	7/8/2010	Germany	Convective Event
GE2	3/6/2010	Germany	Convective Event
GE3	05-06/12/2010	Germany	Frontal winter Event

***Table 1*: List of precipitation events used for the verification study.**

Before proceeding with the analysis of the results of the study, it is worth noticing, that the use of ground-based radar or raingauges for validation of satellite based precipitation rate estimates is troublesome. Radar data are in principle more suitable for comparison with precipitation estimates from polar satellites because of the almost instantaneous nature of the measurements over an extended area. However, radars do not measure directly the precipitation, have a different observation geometry and spatial resolution than satellites, are subject to attenuation (increasing with the distance from the radar) and beam blocking (caused by local topography) affecting the retrieval, and the radar networks suffer from the lack of inter-calibration leading to significant differences in rainfall estimates obtained from different instruments. On the other side, raingauges provide the only available direct measurement of precipitation. However, there are issues to be considered: 1) raingauge measurements are local and integrated in time; 2) the density of the raingauge stations within each satellite IFOV critically affects the results of a qualitative and quantitative comparison. For snowfall case studies, because of additional issues such as large uncertainty associated to satellite and radar snowfall retrieval and the limited availability of heated raingauges data in most cases, only radar data were considered and only precipitation patterns were verified, with no quantitative comparisons.

4. RESULTS

Each case study of Table 1 was separately analyzed, considering all available overpasses from the DMSP F16, F17 and F18 satellites for H01 (ver. 1.7), using the CDRD algorithm, and from NOAA-18, NOAA-19, and MetOp-A for H02 (ver. 2.4) using the PNPR algorithm. In this section the results are shown for some of the case studies listed in Table 1). For comparison, the retrievals obtained with the previous operational versions of the H-SAF H01 (ver. 1.4) and H02 (ver. 2.3) have been also used in the analysis.

Figure 1 shows the results for the PNPR algorithm for the flood producing storm occurred in Rome, Italy on October 20, 2011 (IT1 in Table 1). Extremely heavy precipitation occurred over short periods of time; the maximum recorded precipitation was approximately 200 mm accumulated in 6 hours in Rome. The flood producing cell that hit the city of Rome is very well identified by the PNPR, as well as another intense precipitation area in Northeastern Italy. The retrieval agrees well with the precipitation pattern and intensity given by the raingauges (Fig. 1a, top-right panel) and to a less extent with the radar estimates (not shown), very likely affected by attenuation and beam-blocking effects. There is a minor disagreement in other regions, but overall both the pattern and the intensity of the precipitation is well estimated by the new version of H02. Compared to the old version of the algorithm (last rows of panels) there is an improved detection of intense precipitation areas. It is worth noting the added value of the retrieval due to the information about the phase of precipitation and the quality index (or PCI) (second row of panels). Similar results were obtained for the CDRD, with an improved detection of the convective areas and better agreement with the raingauge measurements with respect to the old version of the algorithm (not shown).

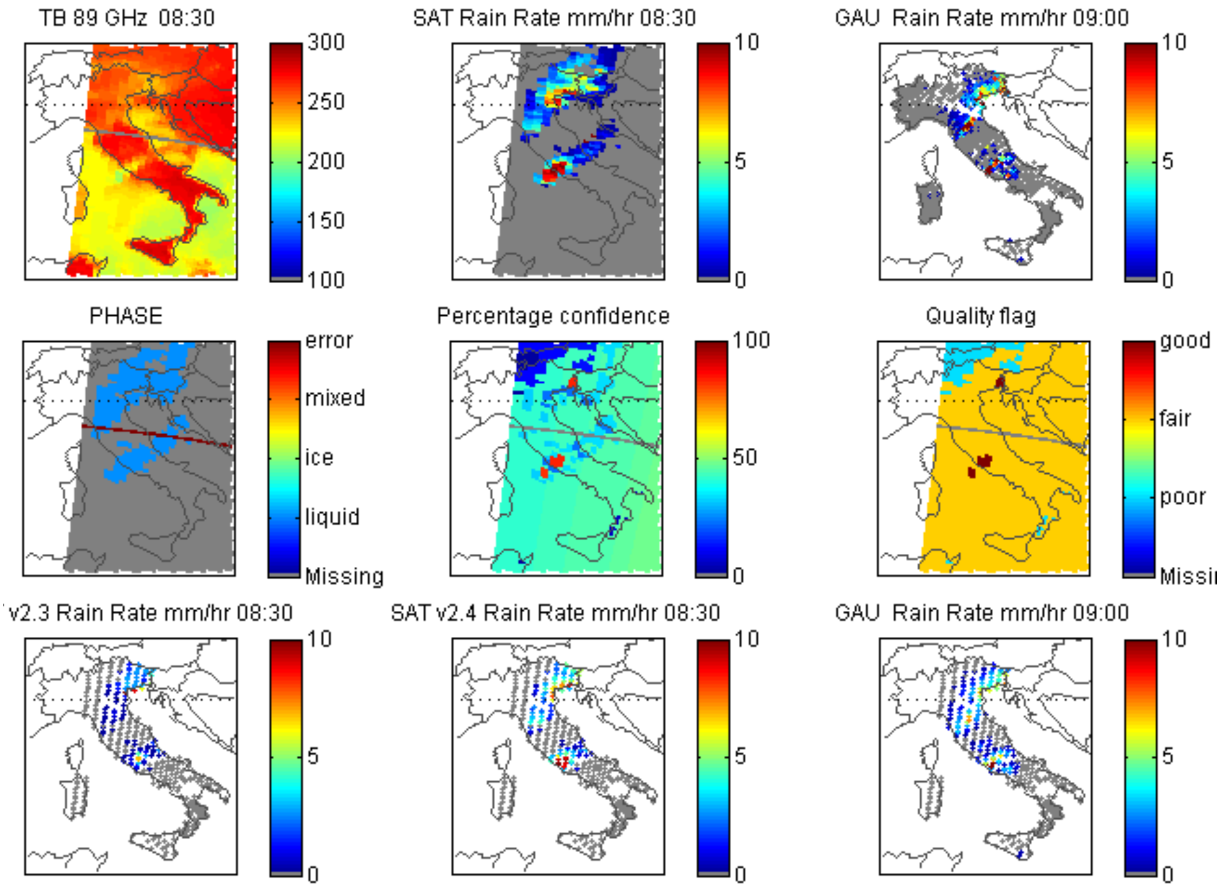

***Figure 1*: Results for PNPR and flash flood case study IT1 20/10/2011 08:30 UTC. Top row from left to right: TB at 89 GHz, PNPR (H02 ver. 2.4) surface precipitation rate; hourly precipitation from gauges. Second row: Phase flag, PCI, quality index. Bottom row: precipitation rate from old version (H02 ver. 2.3) and new version (H02 ver. 2.4), hourly precipitation from gauges (spatially averaged).**

For other convective cases, such as the other flood events in Italy, or the convective events in Poland and Hungary, better agreement with the ground-based precipitation estimates is found with the new versions of the PNPR, which is able to identify very well the most intense areas of convective precipitation, and to solve the underestimation of the precipitation rate in these areas evidenced in the old version of the algorithm. Similar results were obtained with the CDRD algorithm, but an overestimation of the precipitation in the convective areas was evidenced in some cases. For the orographic precipitation case in Slovakia (SK1 in Table 1) in spite of a good correlation between the satellite and the radar estimates, there was overestimation of the CDRD and PNPR precipitation retrievals.

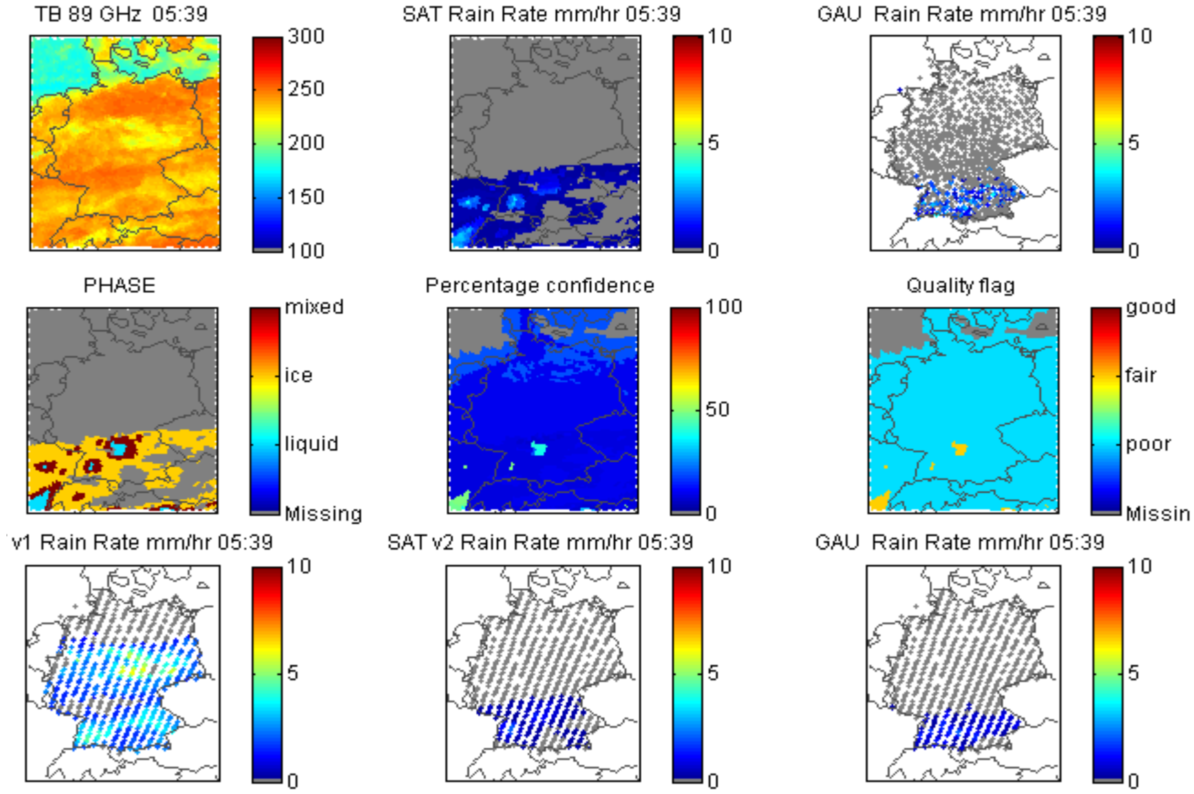

***Figure 2*: Same as Fig. 1 but for CDRD and for winter front case study GE03 06/12/2010 05:39 UTC. In the last row results from the old version (H01 ver. 1.4) and the new version (H01 ver. 1.7) are compared to the gauges.**

The results of CDRD for a winter front in Germany occurred on December 6, 2010 are shown in Fig. 2. For this case study (as for the other Germany case studies) radar and raingauge networks show very good agreement of the precipitation pattern and rate estimates. In Fig. 2 the comparison with the hourly precipitation from gauges show that the new version of H01 (ver.1.7) improves singificantly with respect to its previous version (last row of panels). The performance of the screening of non-precipitating pixel in snow covered background conditions and/or in cold environmental situations has significantly improved, and the precipitation pattern, associated to its phase, obtained from H01 (ver. 1.7) depicts very well the actual situation. Also for this case, the additional information of the phase flag and quality flag (low values for solid precipitation) allows a better evaluation of the algorithm retrieval accuracy. For this case study also the PNPR (not shown) has shown a good agreement in terms of precipitation pattern and rate estimates, confirming the presence of snowfall in agreement with the observations.

Similar results were obtained for a stratiform light rain event in Hungary (HU4 in Table 1). Also in this case that the CDRD algorithm performs very well even in the detection of light rain solving the problems of overestimation of the old version, and showing a precipitation pattern very similar to the radar. For the same case study the PNPR algorithm has evidenced some problems in the identification of the correct precipitation pattern and an overestimation of the retrieved rain rate. Similar results were obtained for the winter case in Slovakia (SK2 in Table 1) characterized by the presence of meting snow over frozen soil, a situation where PMW precipitation retrieval is very problematic.

Figure 3 shows the results obtained with the PNPR algorithm for the snowfall event in Italy occurred on February 3, 2012 (IT4 in Table 1). The precipitation is associated to the solid or mixed phase flag in Central Italy, in accordance with the observations for that day, and a low PCI (poor quality index), which add a very important peace of information to the retrieval. In fact, winter cases with snowfall present the most unfavorable conditions for PMW precipitation retrieval. In addition, the validation of snowfall retrieval is made difficult because of the scarce reliability of ground-based measurements in snowfall conditions, i.e., the absence of heated raingauges, and/or use of Z-R relationships in operational radars not optimized for snowfall. Problems related to calibration of the different radars available in Central Italy are quite evident, with large differences in the snowfall rate estimates (top-right panel). Very similar results were obtained for the CDRD algorithm (not shown).

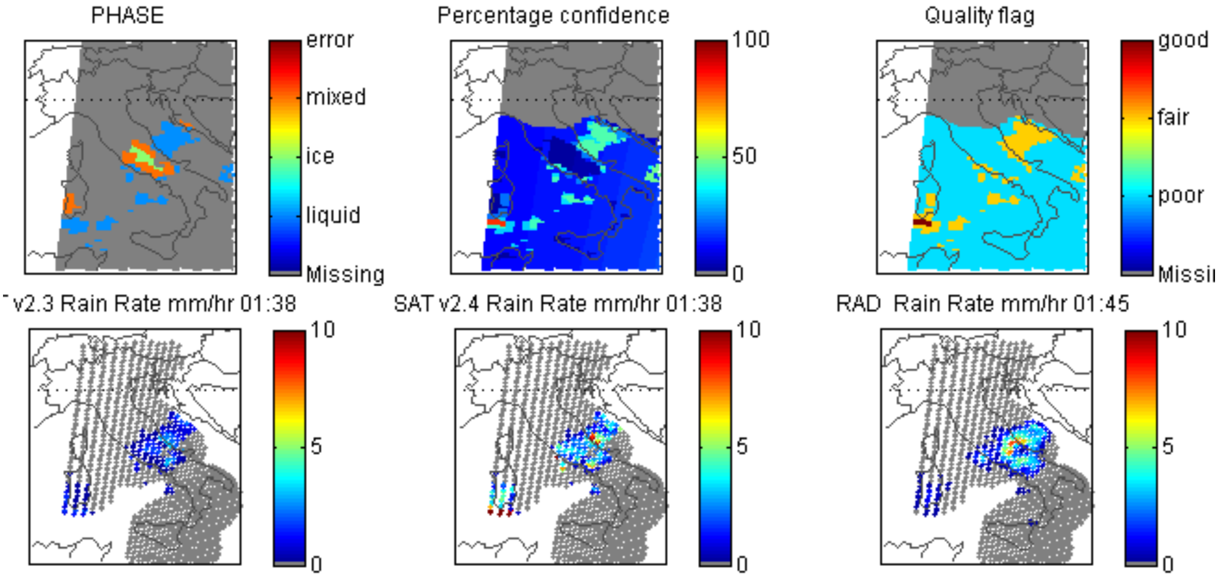

***Figure 3*: Results for PNPR and snowfall case study IT4 03/02/10 at 1:38 UTC. First row: Phase flag, PCI, quality index. Bottom row: precipitation rate from old version (H02 ver. 2.3) and new version (H02 ver. 2.4), precipitation rate from radar (spatially averaged).**

The last important result of this section consists of Table 2, providing the statistical scores and the continuous statistics for all the case studies (except for the snowfall cases). For each case study we have used all reliable ground-based data available, i.e., raingauges over Italy, both radar and raingauges over Germany, and radars over Hungary, Poland and Slovakia.

	H01		**H02**	
	v1.4	**v1.7**	**V2.3**	**V2.4**
NUM	9409	8849	9710	9676
ME	0.15	-0.08	-1.03	-0.59
SD	2.56	2.37	2.68	2.22
RMSE	2.55	2.37	1.99	1.97
FSE%	174.19	161.84	123.32	121.78
CC	0.36	0.39	0.51	0.50
POD	0.70	0.70	0.68	0.68
FAR	0.61	0.52	0.50	0.48
CSI	0.33	0.40	0.41	0.42

***Table 2*: Statistics for all case studies listed in Table 1 (except snowfall cases).**

From the results shown, it is evident the improvement between the old and the new versions of both algorithms. This is confirmed by the lower values of ME, SD, RMSE and FSE% and by the reduction of the FAR respect to the same POD value (and the consequent lower value of CSI). It is worth noting that RMSE and FSE% are lower for H02 than for H01. This can be related to the higher resolution of H01 (roughly 15 km) compared to H02, which, besides providing a more detailed structure of the precipitation, is more affected by geo-location errors in the comparison with ground-based data.

4. CONCLUSIONS

One of the main objectives in developing the CDRD and the PNPR algorithm, and in releasing the new versions of H-SAF operational products H01 and H02, was to achieve better accuracy of precipitation retrievals in the European and Mediterranean basin area and better consistency (both in terms of precipitation pattern and in terms of quantitative estimates) from close in time cross-track scanning and conically scanning radiometer overpasses of the same event. This achievement is crucial in order to be able to use all available overpasses for precipitation monitoring, for ingestion of *all* passive microwave products in the generation of combined MW/IR techniques, and for optimal use of satellite-based precipitation products for hydrological applications. From the results of this study it is evident that we have achieved significant improvements in the consistency of the precipitation patterns obtained with the two algorithms, also for critical situations, such as in presence of light precipitation in coastal areas and over ocean, and detection of precipitation areas over snow covered background surfaces. In most cases improvements were also achieved in the identification of convective areas and heavy precipitation areas, in the screening of the precipitation, the detection and estimates for light rain, also in cold environmental conditions, and detection of solid vs. liquid precipitation. Some criticisms are still evident for very cold/dry environmental conditions with snowy/frozen background surface. It is worth noting that the new versions of the algorithms, besides having better statistics, provide also the percent of confidence index (or quality flag) associated to the retrieval in each pixel, and are able to detect the presence of critical environmental and/or background surface conditions for the reliability of the products. This information is very useful in operational or nowcasting applications, both in meteorology and in hydrology, since it provides the user a quick view of the uncertainty of the precipitation estimates in the different areas. Further and constant improvement and development of the PNPR and CDRD algorithms will lead soon to the extension of the H-SAF products to the MSG full-disk area, and to the full exploitation of the satellite constellation (including the core satellite) of the upcoming Global Precipitation Measurement (GPM) mission.

REFERENCES

Casella D., et al., (2013) Transitioning From CRD to CDRD in Bayesian Retrieval of Rainfall From Satellite Passive Microwave Measurements: Part 2. Overcoming Database Profile Selection Ambiguity by Consideration of Meteorological Control on Microphysics, IEEE Trans. Geosci. Remote Sens,, **51**, no. 7, pp.4650-4671.

Mugnai et al. (2013a): Precipitation products from the hydrology SAF, Nat. Hazards Earth Syst. Sci., **13**, 1959–1981.

Mugnai, A. et al. (2013b) CDRD and PNPR satellite passive microwave precipitation retrieval algorithms: EuroTRMM/EURAINSAT origins and H- SAF operations, Nat. Hazards Earth Syst. Sci., **13**, 887–912, doi:10.5194/nhess-13-887-2013

Panegrossi G. et al. (1998) Use of cloud model microphysics for passive microwave-Based precipitation retrieval: significance of consistency between model and measurement manifolds. J. Atmos. Sci., **55**, 1644–1673.

Puca, S., et al. (2013) The validation service of the Hydrological SAF geostationary and polar satellite precipitation products, Nat. Hazards Earth Syst. Sci., submitted.

Sanò, P. et al. (2013a): Transitioning From CRD to CDRD in Bayesian Retrieval of Rainfall From Satellite Passive Microwave Measurements: Part 1. Algorithm Description and Testing, IEEE Trans. Geosci. Remote Sens, **51**, no. 7, pp. 4119-4143..

Sanò et al. (2013b), The Passive microwave Neural network Precipitation Retrieval algorithm (PNPR) for AMSU/MHS observations: description and application to European case studies, Proc. 2013 Joint EUMETSAT/AMS Meteor. Satellite Conference.

Smith, E.A., et al. (1994) Design of an inversion-based precipitation profile retrieval algorithm using an explicit cloud model for initial guess microphysics, Meteorol. Atmos. Phys., **54**, 53-78.

Smith, E.A., et al. (2013): Transitioning from CRD to CDRD in Bayesian retrieval of rainfall from satellite passive microwave measurements: Part 3 – Identification of optimal meteorological tags, Nat. Hazards Earth Syst. Sci., **13**, 1185–1208, doi:10.5194/nhess-13-1185- 2013.

Surussavadee C. and D. H. Staelin, (2008) Global millimeter-wave precipitation retrievals trained with a cloud-resolving numerical weather prediction model, Part I: Retrieval design, IEEE Trans. Geosci. Remote Sens, **46**, pp. 99-108 .

Tripoli G. J., (1992) A Nonhydrostatic Mesoscale Model Designate to Simulate Scale Interaction," Mon. Weather Rev., **120**, pp. 1342-1359.

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