

PRECIPITATION MEASUREMENTS FROM SPACE

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ABSTRACT

Measuring precipitation from space is a long standing issue of meteorology, hydrology and climatology. Since the launch of the first meteorological satellites in the 60s several visible/infrared/microwave techniques for “inferring”, rather than “measuring” rainfall intensity from space were conceived, but seldom reached operational application. Algorithms have greatly evolved and now offer an acceptable quality level when products are averaged over suitable time and space scales. Daily, monthly and yearly products have become important inputs for climate studies, but their quality significantly lowers when the algorithms are applied to estimate instantaneous rainrates.

More recent methods go back to the basic physical principles of precipitation formation and evolution. The re-examination of the physical content of the algorithms is driven by new insights on precipitation formation mechanisms now available together with new observational tools from space and from the ground.

The current status of precipitation measurements from space will be addressed with an eye on what is available for applications such as those of telecommunications. The focus will be on advanced algorithms, satellite missions, activities and efforts of international organizations, including generation of high resolution precipitation products for propagation applications.

1. RECENT METHODS

Methods have tried to exploit visible (VIS), infrared (IR), near infrared (NIR), water vapour (WV), passive microwave (PMW), and radar data. A complete review of satellite rainfall estimation methods is out of the scope of the present paper. The reader will find reviews and comparisons, among others, in the articles by Adler et al. (2001, global products), Kidd (2001, climate), Levizzani et al. (2001, 2002, generic), and Petty (1995, over land methods). A state-of-the-art collection of papers on the advances in the field is now in press (Levizzani et al. 2007). We will here concentrate on the most recent methods, i.e. 1) PMW physical-statistical methods, and 2) combined algorithms for global products.

1.1 Passive microwave methods

At PMW frequencies precipitation particles are the main source of attenuation of the upwelling radiation and thus

PMW techniques are physically more direct than those based on VIS/IR radiation. The emission of radiation from atmospheric particles results in an increase of the received signal while at the same time the scattering due to hydrometeors reduces the radiation stream. Type and size of the detected hydrometeors depend upon the frequency of the upwelling radiation. Scattering and emission happen at the same time with radiation undergoing multiple transformations within the cloud column in the sensor's field of view. At different frequencies the radiometers observe different parts of the rain column and this principle is behind the choice of observing channels.

Precipitation drops strongly interact with MW radiation and are detected by radiometers without the IR strong biases. The biggest disadvantage is the poor spatial and temporal resolution, the first due to diffraction, which limits the ground resolution for a given satellite MW antenna, and the latter to the fact that MW sensors are consequently only mounted on polar orbiters. The matter is further complicated by the different radiative characteristics of sea and land surfaces underneath. While the sea surface has a relatively homogeneous emissivity, land surfaces have a high and variable emissivity, close to that of precipitation, and low polarization. The emissivity depends upon the characteristics of the surface including vegetation and moisture content. Rainfall over land will increase the upwelling radiation stream but at the same time will absorb radiation introducing considerable difficulties in the identification of rain areas. Scattering is thus the key to the PMW rainfall estimation techniques over land.

Several approaches have been developed in time from relatively simple threshold-based algorithms to the most recent and complex physical-statistical techniques. Some of these rather simple threshold methods were used also to produce global estimates such as that of the National Oceanic and Atmospheric Administration (NOAA), which has just recently been reconsidered trying to lower the existing biases (McCollum and Ferraro 2003). Products are available at <http://www.orbit.nesdis.noaa.gov/corp/scsb/mspps/main.html>

PMW frequencies have always shown an obvious tendency to perform better for convective precipitation while stratiform rain or, more generally, low rainrates are poorly detected. An example is shown in Fig. 1 where the same precipitation system is simultaneously

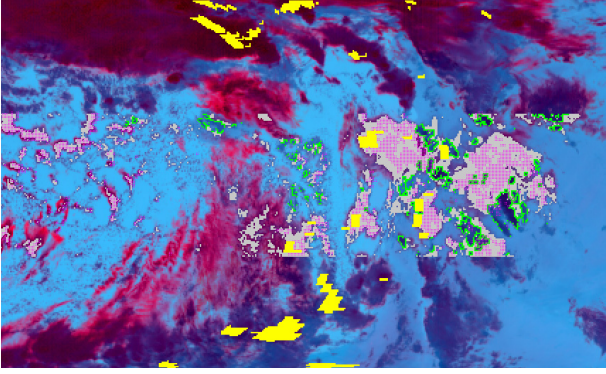


Figure 1. Rainfall as estimated by the various TRMM sensors over East Mediterranean. The scene is depicted in false colors as seen by VIRS. The central narrow strip is where rainfall is estimated by a VIS/IR method (gray) and by the PR (pink). The conical scanning of the TMI is in yellow. (courtesy of D. Rosenfeld)

scanned by three sensors on board the Tropical Rainfall Measuring Mission (TRMM): Visible and InfraRed Scanner (VIRS, visible/infrared), TRMM Microwave Imager (TMI, PMW), and Precipitation Radar (PR). While the VIS/IR method overestimates by including low-temperature, non-precipitating high clouds, its performance in rain area detection is not far from that of the PR. The PMW algorithm based on TMI data, however, is grossly underestimating since it only detects precipitation from cumulonimbus clouds. Low stratiform rainrates go completely undetected.

More complex methods were developed with the aim of tying cloud microphysical profiles and rainrate at the ground. The Goddard Profiling Algorithm (GPROF, Kummerow et al. 2001) aims to retrieve the instantaneous rainfall and the rainfall vertical structure using the response functions for different channels peaking at different depths within the raining column. However, more independent variables are present within raining clouds than there are channels in the observing system and thus the solution requires additional assumptions or constraints. Radiative transfer calculations are used to determine a brightness temperature vector, \mathbf{Tb} , given a vertical distribution of hydrometeors represented by \mathbf{R} . An inversion procedure is needed to find the hydrometeor profile, \mathbf{R} , given a vector \mathbf{Tb} . The GPROF retrieval method is Bayesian and the probability of a particular profile \mathbf{R} , given \mathbf{Tb} , can be written as:

$$\Pr(\mathbf{R} | \mathbf{Tb}) = \Pr(\mathbf{R}) \times \Pr(\mathbf{Tb} | \mathbf{R}) \quad (1)$$

where $\Pr(\mathbf{R})$ is the probability with which a certain profile \mathbf{R} will be observed and $\Pr(\mathbf{Tb} | \mathbf{R})$ is the probability of observing the brightness temperature vector, \mathbf{Tb} , given a particular rain profile \mathbf{R} . The first term on the right hand side of Eq. (1) is derived using

cloud-resolving models (CRM). The strength of the algorithm is based on the accuracy and number of profiles contained in the dataset. Other authors have proposed analogous approaches and published additional results on cloud-radiation databases (CRD) (e.g., Di Michele et al. 2003, 2005). However, note that the complexity of the 3-D structure of precipitating systems is very high and a certain degree of uncertainty remains on which profile in the CRD is to be attributed to the PMW observational profile linked to a rainrate at the ground.

Finally, the problem of low rainrates and stratiform rainfall is a serious one and most algorithms perform very poorly under these conditions. The melting layer inclusion in the PMW inversion methods for the generation of adequate CRDs was addressed by Bauer (2001) who was also among the few attempting to tackle the problem of modeling stratiform rainfall in the PMW (Bauer et al. 2000). The problem is still under investigation and represents an important topic for future observations using the new active sensors as mentioned later in this paper.

1.2 Global products

Global precipitation products are of the maximum interest for telecommunication applications. Naturally, gridded products find adequate use in meteorology and climatology for the assimilation in global models as well as for their verification.

The Global Precipitation Climatology Project (GPCP, <http://cics.umd.edu/~yin/GPCP/>) offers a number of daily, pentad, monthly and yearly products from a variety of algorithms using VIS/IR and PMW. A user-friendly and complete series of these products is to be found also at <http://precip.gsfc.nasa.gov/> (see also Adler et al. 2003).

Applications in telecommunications as well as for civil protection and meteorological use, however, require instantaneous products, which are by far the most affected by errors and biases.

Global products are generally derived using as many sensors as possible in order to ensure the best space-time coverage. One of the first global products is that by Turk et al. (2000) conceived at the Naval Research Laboratory (NRL). The algorithm is a blended technique that uses the NOAA PMW algorithm to estimate rainfall upon the passage of a PMW sensor and builds a look-up-table (LUT) linking these rainrates to the IR brightness temperature data of the closest geostationary image. The “calibration” of IR temperatures in terms of rainfall is then used for estimating rainrates from all geostationary IR images until the next PMW sensor overpass when another LUT is built. An example of global precipitation product on 30 July 2006 is shown in Fig. 2.

The same concept of probability matching between IR temperatures and PMW-derived rainrates has been

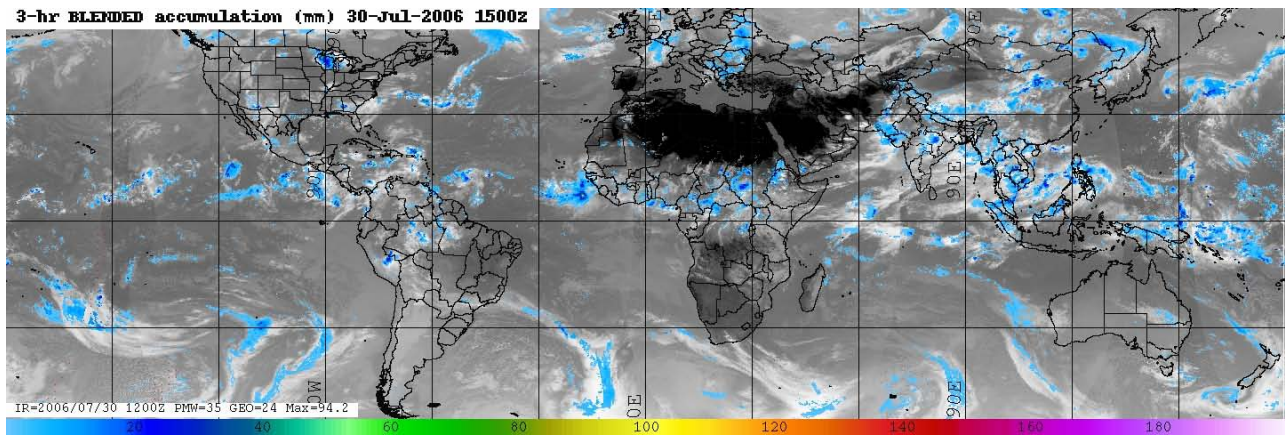


Figure 2. Global 3-hourly cumulated precipitation (mm) on 30 July 2006, 1500 UTC as derived using the NRL blended PMW/IR algorithm. (courtesy of Naval Research Laboratory, http://www.nrlmry.navy.mil/sat_products.html)

applied to produce the Microwave/Infrared Rainfall algorithm (MIRA) (Todd et al. 2001) at high spatial and temporal resolution. A similar algorithm that uses a linear relationship between geostationary IR and polar orbiting PMW data is the Microwave/Infrared Rain Rate Algorithm (MIRRA) (Miller et al. 2001), whose tests have indicated low biases and good performances also at daily and monthly scales.

Multispectral data for the identification of raining clouds are applied by the GOES Multispectral Rainfall Algorithm (GMSRA) (Ba and Gruber 2001). The method uses NIR channels of geostationary sensors to estimate the effective radius of cloud particles at cloud top. Using the finding of Rosenfeld and Lensky (1998) that raining clouds are identified by the 15 μm radius threshold and applying a 230 K threshold at nighttime, rain areas are thus delimited using an objective cloud microphysical signature at cloud top. The calibration was done using radar data at the ground.

A totally novel concept of using PMW and IR was recently introduced by Joyce et al. (2004) with their Climate Prediction Center morphing method (CMORPH), which uses motion vectors derived from half-hourly interval geostationary satellite IR imagery to propagate the relatively high quality precipitation estimates derived from PMW data. The shape and intensity of the precipitation features are morphed during the time between PMW sensor scans by means of a time-weighted linear interpolation. The result are spatially and temporally complete PMW-derived precipitation analyses, independent of the IR temperature field. CMORPH showed substantial improvements over both simple averaging of the PMW estimates and over the above mentioned blended techniques. The technique does not solve the problems of PMW rain estimation but certainly represent a step forward for global products by eliminating a possible source of errors of blended methods, i.e. the LUT production and its validity in time.

2. COMBINING CLOUD PHYSICS, MODELLING, RADAR AND PMW

The advent of TRMM in 1997 and its long lifetime in space has opened up the perspective of using spaceborne radar for estimating precipitation. For the first time algorithms were conceived and products made available on a regular basis for the tropical belt (see for example Haddad et al. 1997, Iguchi et al. 2000). Since then several studies were conducted to compare PMW and radar precipitation estimates and assess their relative performances. As is easily understood, both ways of estimating rainrates have their strengths and weaknesses and neither one is completely winning. However, the PR in space has provided an unambiguous tool for cloud structure analysis, which helps considerably while verifying the algorithms' performances.

It soon appeared that the combined use of all passive and active instruments is the way forward, as for example shown by Grecu et al. (2004). The field is still very much experimental but it appears that perspectives are encouraging.

The precipitation community is moving along the same data fusion path in exploiting cloud microphysics as seen from multispectral VIS/NIR/IR measurements now available on geostationary satellites. An excellent perspective on the great potential of using cloud microphysical identification for satellite rainfall estimation is given by Rosenfeld and Woodley (2003). The concept is based on the original findings of Rosenfeld and Lensky (1998) and has significantly evolved considering cloud microstructure all around the world. The necessity of introducing a cloud microstructure identification in PMW estimation algorithms is also supported by the study of Rosenfeld and Ulbrich (2003) who used radar observations to connect raindrop size distributions (RSDS) to radar R-Z (rainfall-reflectivity) relationships from the point of view of rain forming mechanisms. Cloud

microstructure which determines maritime and continental cloud masses, cloud dynamics which is behind convective and stratiform cloud classification, and also orographic effects are demonstrated to introduce systematic differences in rainrate estimations. R for a given Z is greater by a factor of more than 3 for rainfall from maritime compared to extremely continental clouds, a factor of 1.5–2 greater R for stratiform compared to maritime convective clouds, and up to a factor of 10 greater R for the same Z in orographic precipitation.

3. INTERNATIONAL EFFORTS

International activities concentrate on the improvement of algorithms, especially combined, multisensor algorithms, the calibration and validation of existing products, and the preparation of upcoming satellite missions.

The International Precipitation Working Group (IPWG), in particular, was established to organize efforts of the community worldwide. It is active since 2001 and is co-sponsored by the Coordination Group for Meteorological Satellites (CGMS) and the World Meteorological Organization (WMO). Its web site is accessible at <http://www.isac.cnr.it/~ipwg/>. The IPWG has launched several activities that are of interest for the overall user community:

- Validation is now being conducted on a routine basis over Australia, Europe and the USA, and data are available on the web site.

- The PMW modelling efforts for the retrieval of snowfall are another important chapter since precipitation estimates up to now have completely disregarded solid precipitation.
- Global products are now available at coarse resolution and this is the reason why IPWG is sponsoring an activity called Proposed Evaluation of High Resolution Precipitation Products (PEHRPP). The generation of these products will be particularly interesting for the telecommunication community.

New missions are planned that will involve participation from several countries in a combined effort for the best possible space-time coverage and the observation of cloud microphysics. The most important of these plans concerns the Global Precipitation Measurement (GPM) mission (<http://gpm.gsfc.nasa.gov/>), a constellation of satellites with a main spacecraft hosting a dual-frequency precipitation radar and an advanced PMW radiometer. The constellation will then consist of a large number of smaller satellites boarding PMW radiometers, which will be calibrated against data from the mother ship. It is foreseen that a global coverage of precipitation estimates every 3 hours will be reached.

Another important effort focuses on the completion of another constellation, the so-called A-train (Stephens et al. 2002), whose most important component for precipitation studies is CloudSat that flies the first spaceborne millimeter wavelength radar. The unique feature of this radar lies in its ability to observe most of

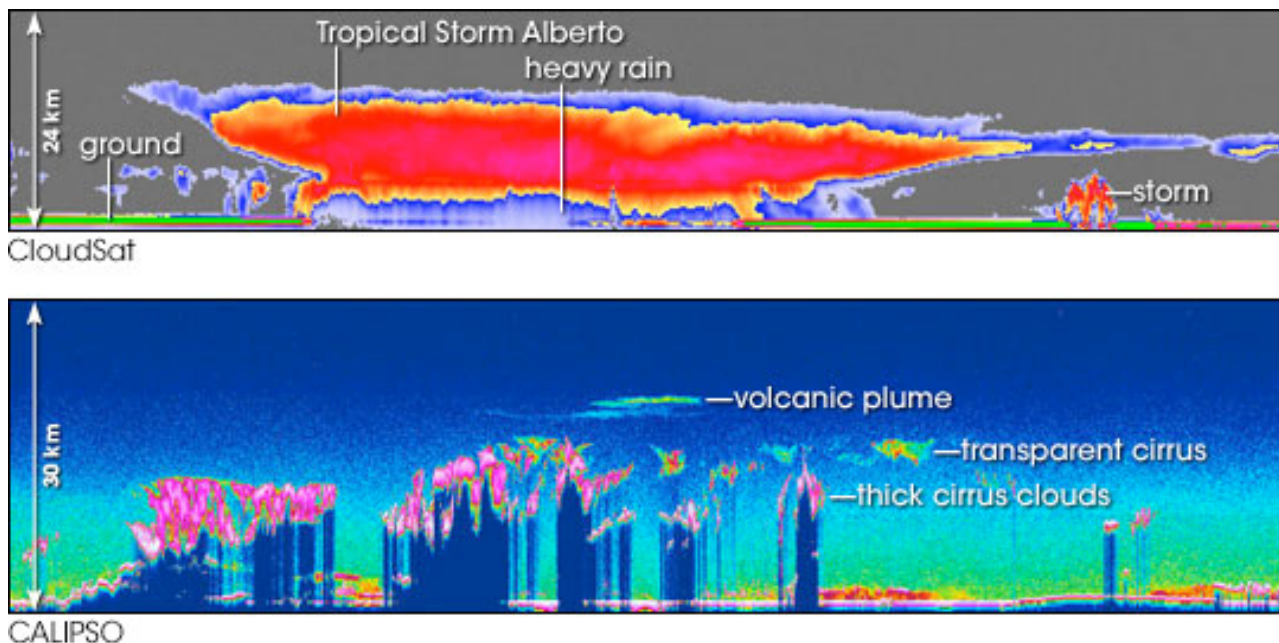


Figure 3. The top image is a vertical cross-section of Tropical Storm Alberto, the first named storm of the 2006 Atlantic Hurricane season, captured by the CloudSat radar on 12 June, 2006. The bottom image is a vertical cross-section of the atmosphere from the lidar on CALIPSO northeast from a location near the southwest coast of Australia, across Indonesia and the Pacific Ocean, and over part of Japan on 7 June, 2006. (courtesy of NASA Earth Observatory, <http://earthobservatory.nasa.gov/>)

