Use of spaceborne multispectral microwave radiometry for precipitation remote sensing

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1. Introduction

The use of space-borne microwave radiometers for monitoring precipitation on a global scale has received an increasing attention in the last years, due to the launch at the beginning of 1987 of the Defense Meteorological Satellite Program (DMSP) platform carrying on the Special Sensor Microwave / Imager (SSM/I). A great amount of multi-frequency brightness temperature data has been made available to the microwave remote sensing community [Hollinger et al., 1989]. Unfortunately, the scarcity of in situ meteorological data, concerning cloud systems and precipitation, makes it necessary to tackle the problem through cloud and radiative transfer models. Over the past decades, many studies have been made to delineate modeling frameworks for interpreting microwave observations of precipitating clouds from space [Wilheit et al., 1977, Smith et al., 1992]. The aim is the retrieval of relevant cloud parameters, regarding especially hydrometeors in iced and liquid phases, and the surface rainfall rate [Mugnai et al., 1993].

In this work, the use of SSM/I measurements over the Mediterranean area has allowed us to test the potential of a simulated cloud-radiation dataset, that includes a large number of simulated precipitating clouds and their related brightness temperatures (T_B's). The major feature of this cloud-radiation dataset is the consideration of the correlations among the various hydrological parameters, characterizing the vertical cloud structure. The simulated space-borne T_B's have been computed through a discrete-ordinate radiative transfer, both over sea and land surfaces. The inversion algorithm has been developed with the objective of estimating the vertical distribution of the liquid and iced hydrometeor contents, and the associate surface rain rate. The surface rain-rate retrieval is performed on a pixel-base by means of a maximum likelihood criterion, used to select the most probable cloud structure within the simulated cloud-radiation dataset. A comparison of the retrieval results with the rainfall rates measured by a rain-gauge network during an intense storm detected in September 1992 over Liguria (Italy) has been carried out.

2. Modeling cloud structures and radiative transfer

Modeling the precipitating cloud structures and their related brightness temperatures has allowed us to generate a large cloud-radiation dataset. This is crucial for understanding the microwave radiative transfer properties through precipitating atmospheres and for training the retrieval algorithm.

A threedimensional timedependent cloud mesoscale model, named University of Wisconsin Regional Atmospheric Modeling System (UWRAMS), has been used for generating cloud structures (the primary cloud dataset), explicitly describing the detailed vertical distribution of four species of hydrometeors: cloud drops, rain drops, graupel particles, and ice particles [Smith et al., 1992]. The number of cloud layers has been automatically reduced to at most seven homogeneous layers [Basili et al., 1992b]. Then the primary cloud dataset has been extended by means of a Monte Carlo statistical procedure, based on the use of the correlation matrix of the hydrometeor equivalent water contents [Basili et al., 1992a]. In this way, a dataset of four thousand cloud structures has been statistically generated retaining the physical

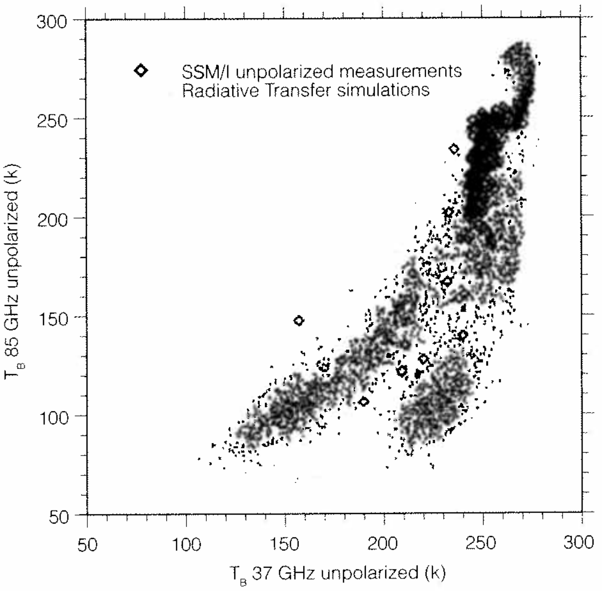

Figure 1 **Simulated dataset of brightness temperatures at 85 and 37 GHz compared to corresponding SSM/I measurements for the Liguria flood event on 27 September 1992.**

and statistical features of the primary cloud model.

In order to associate upwelling brightness temperatures to each structure of the statistically-generated cloud dataset, a radiative transfer scheme based on the discreteordinate method has been used to calculate multi-frequency unpolarized T_B's emerging from a multilayer medium [Basili et al., 1991]. Within each layer, temperature is supposed to be linearly dependent on the height, and the gaseous absorption is determined by means of the Liebe model. The surface background has been modeled as a Lambertian source. The hydrometeors have been supposed spherical and characterized by parametrized exponential sizedistributions. As a result, a cloud-radiation dataset consisting of four thousand cloud structures and the associated T_B's has been generated and considered as a random sample of space-borne microwave radiometer observations of precipitation.

3. Spaceborne microwave signature of precipitation

The SSM/I satellite radiometers provide information on a variety of environmental parameters, including atmospheric water, wind speed, and sea ice. These sensors observe the microwave emission from the Earth at four frequencies, i.e., 19.35, 22.235, 37.0, and 85.5 GHz. The SSM/I orbit is circular, near-polar, and sun-synchronous with an altitude of 860 km and inclination of 98.8°. Dual polarization measurements are taken at 19.35, 37.0, and 85.5 GHz, and only vertical polarization is observed at the 22.235 GHz channel. The spatial resolution of the images depends upon the frequency; specifically, the 3-dB foot print sizes (along-track by cross-track) are 69 x 43 km, 50 x 40 km, 37 x 29 km, and 15 x 13 km for the 19, 22, 37, and 85 GHz channels, respectively.

An intense precipitating cloud system was observed by SSM/I on September 27, 1992 during the DMSP F11 satellite ascending pass over the Italian peninsula at 16:15 UTC. Three areas of low T_B's, are present along the cold front within the convective cloud system. The first one includes part of the Toscana region (central Italy) and the coast of the Tyrrenian Sea close to Rome; the second one, covers a relatively small area of South-Eastern France; the third one, that will be analyzed in this paper, extends from the coast of Liguria, near Genova, to the North-West borders of Italy [Basili et al., 1994]. The areas with the lower T_B's within the cloud system are associated to the most intense cells, in which large ice particles scatter the upwelling radiation, emitted from the lowest cloud and rain layers. In general, scattering from large drops and ice particles is the physical mechanism responsible for the overall appearance of the storm as a cold feature over a warmer continental background. As a result, precipitation signature may be very similar to that of other natural emission sources (like snow cover, sea, lakes, etc.), thus generating a possible confusion when operating an automatic image classification. It must be pointed out that a technique for improving the spatial ground-resolution of the lower-frequency channels (19.35, 22.235 and 37.0 GHz) has been applied to the calibrated T_B's [Farrar and Smith, 1991].

Figure 1 shows the microwave signature at 19, 22, 37, and 85 GHz for the rainfall events over land within the Liguria area as compared to the corresponding simulated T_B's. The low values of T_B's (less than 180 k) at 85 GHz and 37 GHz correspond to the convective cores of the observed storms. Note that 19 and 22 GHz T_B's show a smaller range of values with respect to 37 and 85 GHz T_B's: this depends on the fact that the higher frequency T_B's are strongly modulated by precipitating ice, that exhibits high variability within a convective cloud system.

4. Statistical retrieval of surface rainfall rate

It has been observed that upwelling T_B's at frequencies greater than about 19 GHz are almost insensible to the structure of the lower rain layers and that the variability in the upper part of the cloud causes a large dispersion of the observed T_B's against the rainfall rate [Smith et al., 1992]. These considerations suggested that one should assess a method to identify the gross vertical structure of the precipitating cloud from radiometric measurements and then evaluate the rainfall rate from the retrieved vertical structure by means of a proper fallout model [Mugnai et al., 1993].

In order to describe the retrieval scheme, let the set of hydrometeor vertical profiles be identified by a vector **g**, consisting of equivalent water contents of each hydrometeor category, and the multi-frequency T_B measurement is expressed by vector **t**. Therefore, the surface rain rate is found by searching the most probable cloud structure within the cloud-radiation dataset, i.e. by maximizing the following discriminant function with respect to **g**:

$$d(\boldsymbol{t},\boldsymbol{g}) = \ln[p(\boldsymbol{t} \mid \boldsymbol{g})] + \ln[p(\boldsymbol{g})] - \ln[p(\boldsymbol{t})] \qquad (1)$$

where p(**t** | g) is the probability density function (pdf) of **t** conditioned to g, and p(g) and p(**t**) are the pdf's of g

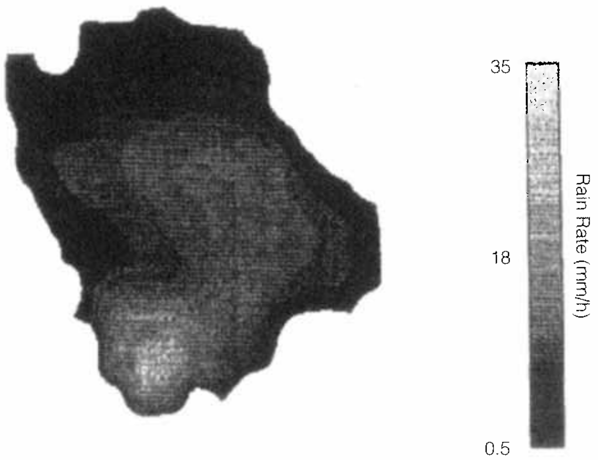

Figure 2 **Raifall-rate contour map derived SSM/I measurements for the Liguria flood event on 27 September 1992.**

and **t**, respectively. equation (1) has been derived by means of the Bayes theorem. Assuming a Gaussian multidimensional joint-distribution of vector **g**, the covariance matrix C_g and the mean vector m are sufficient to describe the statistics of **g**. If **t'** is the T_B vector associated to **g** by the radiative transfer equation, and the errors (**t**-**t'**) are assumed uncorrelated at the different frequency bands with the same variance σ_t^2, by considering that p(**t**) is a common term, it results [Basili et al., 1994b], [Marzano et al., 1994]:

$$d(\boldsymbol{t},\boldsymbol{g}) = -\frac{1}{2\sigma_t^2}(\boldsymbol{t}-\boldsymbol{t}')^T(\boldsymbol{t}-\boldsymbol{t}') - \frac{1}{2}\ln[\det(\boldsymbol{C}_g)] - \frac{1}{2}(\boldsymbol{g}-\boldsymbol{m})^T\boldsymbol{C}_g^{-1}(\boldsymbol{g}-\boldsymbol{m}) \qquad (2)$$

where "T" represents the transpose operator and det(C_g) and C_g^{-1} indicate respectively, the determinant and the inverse matrix of C_g. Once the vector g has been selected, the surface rainfall rate is computed from the retrieved hydrometeor profiles by means of the mentioned fallout model.

For the precipitation event over Liguria, some rainfall measurements from rain-gauges were available and they were used for comparison with satellite rain estimates. Note, however, that comparison of satellite rain rate retrievals with rain-gauge measurements is highly problematic because of the different spatial and temporal integrations. The SSM/I, in particular, provides instantaneous estimations over areas of about 200-220 km^2, while rain-gauge measurements are representative only of the instrument site with one-hour integration time. Moreover, the location of the available rain-gauges was mountainous, and thus characterized by strong and rapid precipitation variations.

Figure 2 shows the rainfall rate map as obtained by applying the maximum likelihood algorithm to the SSM/I image, zoomed for the flush flood event over Liguria. The contour map of rain rate shows a high variability of rainfall rate within the precipitation area with values that can reach even 40 mm/h. The comparison (not shown) of SSM/I derived rain rates with those measured by the rain-gauges present within the SSM/I pixels shows a discrete agreement in the average, even though a discrepancy of the order of 10 mm/h exists for high rain rates [Basili et al., 1994a]. To this regard, note also that possible errors of SSM/I pixel geo-location, that can be of the order of 10 km or more [Hollinger et al., 1989] have not been corrected during the processing.

5. Conclusions

Microwave signature of precipitation as given by a spaceborne multi-frequency radiometer has been shown and discussed. Pre-processing of brightness temperature data are needed when applying retrieval algorithms to satellite brightness temperature images. The use of a simulated cloud-radiation dataset leads to a proper modeling framework for statistical retrieval of precipitation. The maximum likelihood estimation algorithm is able to assimilate the information deduced from the simulated dataset in an effective and efficient way. The potential of the proposed retrieval algorithm has been shown and a preliminary comparison with rain-gauge measurements has given encouraging results.

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