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Exploiting satellite Ka and Ku links for the real-time estimation of rain intensity

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Abstract

In this paper we describe a statistical and a physically based approaches to retrieve 2D rainfall fields exploiting the attenuation measurements made along satellite links at K_a and K_u bands, in the framework of the research project NEFOCAST. The retrieval algorithms, the main results obtained so far, and the on going test campaign are presented and discussed.

1. Introduction

Precipitation, along with other causes, can produce floods and trigger landslides, which cause annually loss of lives and damages. Particularly prone to flash-floods are cities and small catchment basins. A specific class of rain events are characterized by a high water volume concentrated in a relatively short time period. The detection of this kind of phenomena is a challenging issue for conventional meteorological observational networks based on rain gauges and weather radars. Rain gauges, usually referred to as ground truth, although prone to measurements errors especially in the presence of wind, for both very light or very intense precipitation, perform a pointwise measurement. Density of rain gauge networks is highly variable, with some regions having a quite dense coverage while others have few or no gauges at all. On the other hand, ground based weather radars provide seamless measurements and can have a high spatial resolution (less than 1 km, although not constant along the radar range) and a temporal resolution that ranges usually between 5 and 10 min. Radar quantitative precipitation estimation (QPE) are indirect measurements and can be subjected to a variety of potential errors; furthermore, error in precipitation estimation is not spatially uniform [1]. Since the cost for purchase and maintenance of a weather radar system can be very high, radar networks are built in order to minimize the number of them in the system. Therefore, some areas can result not adequately monitored by weather radar. This is especially likely in regions with complex orography for which the selection of an optimal site for the installation of the radar is critical depending on several aspects, related to both technical, scientific, and regulatory issues.

In the last few decades, in order to overcome these problems and to improve rain retrieval from remote sensors complementing the traditional techniques, the possibility of retrieving rain rate (R) from attenuation measurements available from "signal of opportunity" such as microwave links used in telecommunications have been explored. The latter can be either satellite links ([2] among others) or point-to-point radio links such as the one used for mobile communications ([3] and [4] among others). These techniques allow the implementation of low cost systems able to provide 2D estimates of rainfall that can be used as independent measurement systems especially in regions where conventional measurements are lacking or to improve the quality of measurements in critical area, eventually exploiting synergy with conventional measurement systems.
In this framework the research project named NEFOCAST [5] has the aim of providing rain retrievals from attenuation measurements made along a population of interactive satellite terminals, called smartLNBs [6]. The project aims at demonstrating the rain retrieval concepts and validating it through point-wise ground measurements and radar dual polarization measurements.
In order to develop a rain retrieval procedure from path attenuation measurements, and predict its performance, the body of knowledge related to the planning of satellite telecommunication systems (also incorporated in ITU recommendation) has been first exploited (section 2). Dependency of relations used by such methods on the variability of precipitation in the area of interest has been established by physically based microphysical and electromagnetic models applied to long term disdrometer measurements (section 3). In the following of the paper, the two approaches will be illustrated and discussed.

2. Statistical model for rain retrieval

In the scenario envisaged in the NEFOCAST project, reliable predictions of rainfall rate from measurements of radio signal attenuation received from satellites in K_u and K_a bands are of the outmost importance. Due to the attenuation it introduces on the received signal in terrestrial or satellite radio links above 10 GHz, rain is known to be a potentially severe degradation factor for the link performance. Among the methods proposed for evaluating (and counteracting) rain attenuation in satellite or terrestrial links, ITU-R and Crane [7] are the most popular ones. In detail, these methods allow to estimate the attenuation experienced by a radio link in the presence of rain with a given intensity (also referred to as *direct* problem). Conversely, in the NEFOCAST project we focus on the *inverse* problem, i.e. to recover rain intensity starting from signal attenuation, which is far less pursued in the literature. In both cases, the solution of the problem requires not only knowledge of link's geometry (i.e., terminal and satellite coordinates) and radio parameters (i.e., carrier frequency and polarization), but also of meteorological information, such as the statistics of the rain intensity and notably the current height of the 0°C isotherm, which is strongly correlated to the height of the space volume affected by the liquid precipitation. In [8], [9] rainfall rate estimates are obtained from measurements of satellite signal attenuation and compared with the corresponding data generated by radar sensors. Moreover, [10] discusses a technique for rainfall rate estimation using satellite links for internet services.

The approach pursued in NEFOCAST for the estimation of rain intensity from attenuation measurements requires that the SmartLNB operates nominally with a wide link margin [5], allowing correct terminal operation even in the presence of severe rain attenuation. This margin is usually guaranteed for DVB and internet satellite services, which are intentionally designed so as to provide the intended QoS even in significantly hostile propagation conditions.

The two most popular techniques for the solution of the direct problem are taken into account, one elaborated by ITU-R [11], and the other known as the global Crane method [7]. For both techniques, it is found that in a wide range of rain intensity values there exists a one-to-one relationship between the rainfall rate (in mm/h) and the corresponding attenuation value (in dB), and hence the relationship between the two variables can be easily reversed, either numerically or analytically. Furthermore, while for the Crane algorithm the height of the 0°C isotherm stems univoquely from the initial assumption on the rain intensity, the ITU-R approach envisages a few variants in the choice of this parameter and provides then a greater number of degrees of freedom for the adaptation of the algorithm to a real situation. Figure 1 plots the key relationship of the inverse problem which maps the measured signal attenuation into the estimated rain intensity, for both the techniques mentioned above and the scenario specified in the figure labels and caption.

The accuracy of the inverse algorithm for rainfall rate estimation can be improved by exploiting more reliable information about the actual height of the 0°C isotherm. Specifically, we can use the database available from the re-analysis of global dataset MERRA (Modern-Era Retrospective Analysis for Research and Applications) [12] which provides, over very long periods of time, experimental data relevant to the 0°C isotherm height. For instance, Figure 2 shows the daily sequence of the 0°C isotherm height values over a period of 35 years (1980 - 2015) measured over the city of Florence. As seen from the figure, the plot has a pseudo-periodic behavior, as the parameter being represented depends on the seasonal variability of climatic conditions. Figure 3 shows, for each day of the year, the 0°C isotherm height obtained averaging the values of Figure 2 for the same day of 35 consecutive years. Further, the red curve shows the same results after low-pass filtering (smoothing) of the data, while the upper and lower curves are obtained by taking the smoothed average plus or minus the standard deviation calculated from the above mentioned values. With respect to standard models such ITU-R, where a mean annual value is employed for the 0°C isotherm height, it is expected that the data from the MERRA database will give a great improvement in the accuracy of the rainfall rate estimation. Alternatively, the inverse algorithm can also resort to short term predictions of the 0°C isotherm height provided by meteograms based upon the Weather Research and Forecasting (WRF) model.

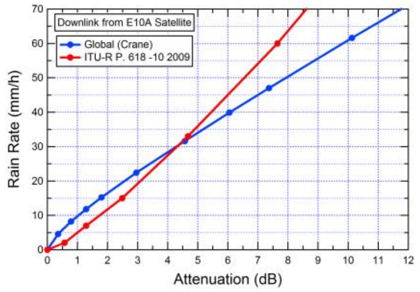

Figure 1: K_u downlink rain attenuation vs. rainfall rate with ITU-R and Crane algorithms. Ground terminal in Florence.

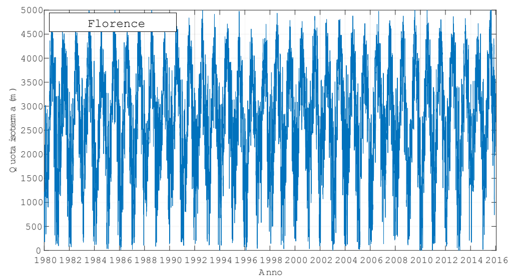

Figure 2: 0°C isotherm height vs. time over a 35-year period, in Florence (Lat 43°47'14" N, Lon 11°14'59" E).

3. R-k parametrizations from ground based DSD

Rain intensity from path attenuation can be obtained by deriving the specific attenuation (k, in dB/km) from the path integrated attenuation (A in dB) provided by satellite receiver, and then in converting k into rainfall rate (R, mm/h) using an appropriate relationship (algorithm) of the form $R = ak^b$. The coefficients of this R-k relation, depend on raindrop size distribution (DSD) variability, in fact the two variables can be expressed as

$$R = 6\pi 10^{-4} \int_0^\infty N(D) D^3 v_t(D) dD \qquad (1)$$

$$k = C_k \int_0^\infty \sigma_E(p, D, \lambda, T, h) N(D) dD \qquad (2)$$

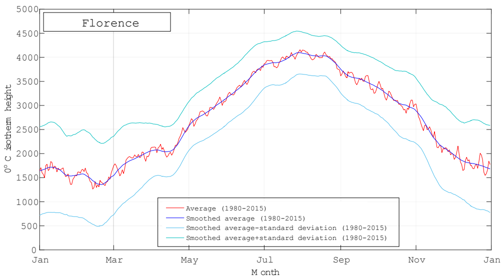

Figure 3: Height of the 0°C isotherm represented over a 1-year period, measured over the city of Florence (Lat 43°47'14" N, Lon 11°14'59" E), averaged over 35 years, with and without smoothing (red and blue, respectively). The upper and lower curves represent the smoothed average +/- std. deviation, respectively.

where $N(D)$ is the DSD, D is the equivolumetric drop diameter, v_t is the terminal fall velocity, σ_E is the extinction cross section for the polarization p, λ is the wave length, T is the environmental temperature, h is the type of hydrometeor and $C_k = 4.343\ 10^{-3}$ is a constant. The set of DSDs used to obtain the coefficients of the *R*-*k* relation can be both theoretical (typically having gamma distribution, although the use of gamma DSD can determine an error in simulating radar measurement [13]) or long-term disdrometer measurements. The use of measured DSDs is supposed to produce algorithms that are adequately representative of the climate of the region in which the disdrometer measurements are collected. In this study we used a long-term dataset of 1 minute DSD measured by an OTT Parsivel disdrometer (P1) installed on the roof of the main building of the Institute of Atmospheric Sciences and Climate (ISAC) of the CNR in Rome (Italy) for more than 6 years (2010-2016) that can be consider as representative of the climate of the region target of NEFOCAST project [14]. To remove the spurious drops due to splashing or wind effect from the raw disdrometer data, the filter criterion of [15] was adopted. The obtained datasets consist of 85207 1-min DSD. Knowing the DSD the corresponding values of R and k can be computed through equations (1) and (2). The extinction cross section (σ_E) has been obtained through an electromagnetic simulation based on the T-matrix algorithm [16], for which the following assumptions were used: T equal to 20°C, shape model of [17], and Gaussian canting angle distribution with 0° mean and standard deviation of 7.5°. The geostationary satellite EUTELSAT 10A (K_u band at 11345.833 MHz and horizontal polarization) was used in the forward down link, while EUTELSAT's geostationary satellite KA-SAT (K_a band at 29.74 GHz and Right-Hand Circular Polarization) was used in the return up link. Finally, a nonlinear regression is established between the obtained rainfall rates and specific attenuations to determine optimal coefficients of the *R*-*k* relations for the K_a and K_u frequencies:

$$R = 5.46\, k_{Ka}^{0.98} \qquad (3)$$

$$R = 25.30\, k_{Ku}^{0.78} \qquad (4)$$

Furthermore, in order to provide some information regarding the goodness of the obtained algorithms, for each of the two relations the values of the Normalized Mean Absolute Error (NMAE), Normalized Bias (NB), Root Mean Square Error (RMSE), and correlation coefficient (cc) between the disdrometer based rain rate and the one obtained applying the relation (3) or (4) to the disdrometer measured specific attenuation (2), have been provided (Table 1). The scatterplots between the latter variables are shown in Figure 4, where the R obtained from ITU relations versus the measured R are also plotted. NB is an index of the systematic error, negative values means that the *R*-*k* relation slightly underestimates the rainfall rate with respect to disdrometer measured values. This statement is particularly valid for high rain rates (*R*>75 mm/h) and for the downlink in K_u band. Since RMSE is a measure of the accuracy of the proposed algorithm, the value for K_a band close to zero indicates a very good performance, while the value for K_u band is a bit higher, probably due to the deviation for high rain rates (Figure 4b). NMAE indicates that rain estimates obtained from specific attenuation at K_a band are almost immune to the DSD variability, whereas a variability of 21.7% has been established for the K_u link. Values of obtained relations have some agreements with ITU-R global formulas that, however, do not provide values of the error related to DSD variability.

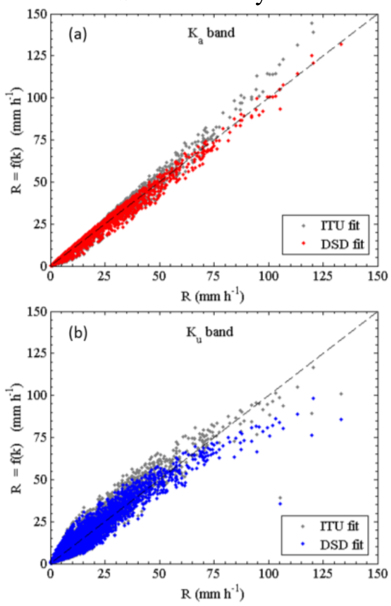

Figure 4: scatterplot between DSD based R and estimated R for K_a (a) and K_u (b) bands computed using ITU relations (grey dots) and DSD based relations (3) and (4).

4. Conclusions

In this paper both statistical and physical models to retrieve R from measurements on satellite K_a and K_u links have been discussed. Based on the results exposed above, an algorithm for reconstructing rain field is defined and under implementation within the NEFOCAST project. A validation experiment has been planned in Tuscany (Italy) where a network of SmartLNBs is being deployed. The experiment will involve meteorological measurements from operation networks with purposely deployed instruments, such as a dense rain gauge network and a dual-polarization radar. The precipitation fields estimated from measurements of satellite link attenuation will be compared with those obtained from rain gauges and weather radar. Such data will help to assess and improve the performance of the rain retrieval based on path attenuation measurements and to optimize it for regional climatology (such as seasonal values of the 0°C isotherm height or DSD variability in the test area) and to specific characteristics of precipitating clouds. The experimental campaign is currently on going and results will be available soon.

Table 1: Statistics indices NMAE, NB, RMSE, and cc between measured and estimated rain rates.

	NMAE	NB	RMSE	cc
$R = \alpha\, k_{Ka}^{\beta}$	8.5%	-2.9%	0.443	0.996
$R = \alpha\, k_{Ku}^{\beta}$	21.7%	-4.3%	1.186	0.970

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