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NEFOCAST project for real-time precipitation estimation from Ku satellite links: Preliminary results of the validation field campaign

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Abstract

NEFOCAST is a project funded by the Tuscany Region Government (Italy) that aims at setting up, and demonstrating through field experiments, the concept of a system able to provide precipitation maps in real-time based on the attenuation measurements collected by a dense population of interactive satellite terminals (called SmartLNB, smart Low-Noise Block converter) commercially used as bidirectional modems. The system does not require the set-up of specific precipitation measuring instruments, but uses telecommunication links. An algorithm that converts the SmartLNB raw data into attenuation values, and infers rainfall rate from the total signal attenuation provided by the devices and from the knowledge of the link geometry, has been developed. An experimental campaign will take place in 2018 in Tuscany with the purpose of validating the NEFOCAST estimates, obtained through a dense population of smartLNBs and an X-band dual-polarization weather radar, purposely installed. During a preliminary test phase, performance of the algorithm has been assessed tested by comparing data from individual smartLNBs with tipping bucket rain gauge and a co-located laser disdrometer. This study presents and discusses results obtained during the test phase, focusing on disdrometer evaluation.

1. Introduction

The NEFOCAST project aims at setting up and validating a system able to provide precipitation maps in real-time based on the attenuation measurements collected by a dense population of interactive satellite terminals (called SmartLNBs - smart low-noise block converters), designed to be used as bidirectional modems for commercial interactive TV applications [1]. The system does not require the deployment of specific precipitation measuring devices, rather uses the properties of signals available from commercial telecommunication systems. The attractiveness of this system is due to the possibility of using a huge amount of attenuation measurements from a widespread network of low cost domestic terminals, especially in urban areas, where a very high density of measurements can be achieved. This system can also bring significant additional information if deployed in regions where instruments for measuring precipitation are sparse, but such modems can be made available for commercial services. To obtain rainfall maps, the project has developed [2] a set of algorithms that *i)* convert the SmartLNB raw data into attenuation values, *ii)* infer rainfall rate from the total signal attenuation provided by the devices and from the knowledge of the link geometry, and *iii)* generate rain field maps from the measurements collected by a network of sensors. In 2018, an experimental field campaign will be carried out in Tuscany, with the purpose of validating the NEFOCAST estimates, obtained through a dense population of SmartLNBs (more than 20) purposely installed in schools. Almost half of the SmartLNBs are co-located with a rain gauge. Furthermore, an X-band dual-polarization weather radar installed close to the cluster of experimental SmartLNBs, will scan precipitating clouds. The role of the radar will be to support the validation of the system. This means not only that the radar rainfall estimates will be compared to those provided by the SmartLNB network estimates, but also that the physical assumptions of the NEFOCAST rain retrieval algorithm will be validated so as to improve future releases of the algorithm itself. Before starting the validation phase, the performance of the NEFOCAST rain algorithm has been preliminarily tested (this phase will be referred to as “test phase”) by comparing: *i)* data provided from one SmartLNB installed at the Department of Information Engineering of the University of Pisa (Italy) with a tipping bucket rain gauge installed nearby, and *ii)* data provided from one SmartLNB installed at Institute of Atmospheric Sciences and Climate (ISAC) of CNR in Rome (Italy) with a co-located laser disdrometer. In this study, the NEFOCAST algorithm is presented and the results obtained during the test phase at the Rome site are shown and discussed.

2. The NEFOCAST system

The configuration adopted for NEFOCAST experimentations uses a bidirectional geostationary satellite network: EUTELSAT 10A (EUT 10A) is used for both the return link (RL) and the forward link (FL). The RL operates at a frequency of 14216.6 MHz, with linear horizontal polarization. The RL coverage provided by EUT 10A in the area chosen for experimentation (the region of Tuscany, Italy) has a merit factor of G/T = +4 dB/K, where G is the antenna gain and T is the noise system temperature. Terminals access the RL asynchronously using the Spread Spectrum Aloha technique implemented by the F-SIM protocol [3]. The equivalent isotropic radiated power (EIRP) of the terminals ranges from 15 dBW to 35 dBW, in order to assure signal reliability over the link also in severe channel conditions. The FL is received by the NEFOCAST SmartLNBs in vertical linear polarization at a frequency of 11345.8 MHz. In the area of interest of the project, the satellite EUT 10A provides a nominal emitted EIRP towards the Earth of 48 dBW. The FL is a DVB-S2 modulated signal with modulation and coding QPSK 4/5. Measurements of SmartLNBs power levels on FL and RL are periodically collected by the NEFOCAST service center that interacts with the satellite HUB management system. The main features of the satellite links are summarized in Table 1.

Table 1. Summary of satellite link main parameters

Feature / Item	**Symbol / Name**
Satellite	Eutelsat 10A, 10° East
RL frequency uplink	*14.216 GHz*
RL polarization uplink	*linear horizontal*
RL protocol	F-SIM
FL frequency downlink	*11.345 GHz*
FL polarization downlink	*linear vertical*
FL protocol	DVB-S2

3. Rain retrieval from path attenuation

The approach for obtaining quantitative rainfall estimates at ground from a ground-to satellite link can be described referring to Fig. 1. The figure sketches the approach under the hypothesis of stratiform precipitation. For such kind of precipitation, the effect of vertical air motion is negligible, and ice particles melt in a layer (the melting layer, ML) that starts at the height of the 0° isothermal, at the bottom of which ice particles melt into raindrops. With reference to the symbols in Fig. 1, the total attenuation (dB) along the path d between the cloud top to the smart LNB can be expressed as the sum of the attenuations along the path through rain and that along the melting layer

$$A(d) = A\left(r^{(p)}\right) + A\left(r^{(m)}\right) + A\left(r^{(i)}\right). \qquad (1).$$

At the Ku frequencies used for the FL and RL, the attenuation due to ice particles can be neglected. Attenuation in rainfall can be expressed through power law relations between specific attenuation (k, dB/km) and rain rate (R, mm/h)

$$R = ak^{b} \qquad (2).$$

The ITU-R P.838-3 recommendation lists the coefficients a and b for different frequencies and polarizations. However, using data available from six years of disdrometer measurements collected in Rome, specific relations that are supposed to be optimal and more representative of the climate of the area in which the disdrometer measurements were collected, were derived. The values derived for a and b are 17.910 and 0.836, respectively, for the RL, and 28.140 and 0.798 for the FL. The accuracy of such relations, expressed in terms of normalized standard error, is around 20% [4]. This means that we have a relatively small error (compared to other remote sensing techniques) related to the variability of drop size distribution (DSD). The total path attenuation excess is then referred to the layers with hydrometeors in the liquid phase, whose height (and consequently the path along which attenuation is generated), is determined by the geometry of the satellite link and by the height of the 0°C isothermal. By applying the same rule below the 0°C isothermal, the derivation of the rain rate is straightforward once total attenuation, height of the 0°C isothermal and geometry of the link are known. The 0°C isothermal is obtained by a meteorological model, namely the WRF-ARW model.

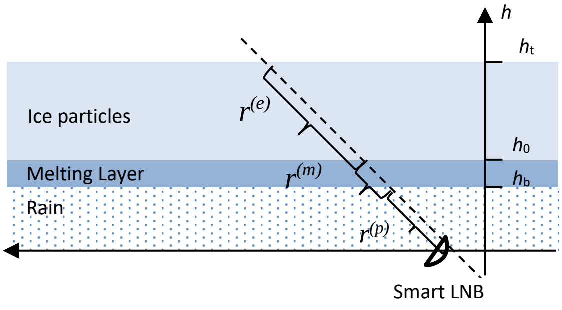

Figure 1. Sketch depicting NEFOCAST precipitation retrieval for stratiform rain

4. Path attenuation estimation

The NEFOCAST rain rate estimation algorithm relies on the availability of the instantaneous value of the ratio E_s/N_0provided by the SmartLNB device, where E_s is the average received energy-per-symbol and N_0 is the one-sided power spectral density of the additive white Gaussian noise. Precipitation along the propagation path causes a reduction of the measured E_s/N_0 values.

Figure 2. Smart LNB and collocated laser disdrometer at CNR-ISAC in Rome

However, even in clear-sky conditions, the received signal is affected by several impairments that determine random amplitude fluctuations which, if not properly tackled, may result in a worse sensitivity of rain detection. Among them we can mention:

1) *Scintillation fading*: This term denotes rapid fluctuations in signal amplitude caused by small-scale irregularities in the tropospheric refractive index. At Ku band, signal fluctuations are within ±0.5 dB. The period of scintillation fades varies from less than 0.1 second to several minutes. These fluctuations are thus much faster than the time dynamics of the rain events and as such can be effectively smoothed out via a proper low-pass filtering.

2) *Orbit fluctuations*: a GEO satellite is subject to many sources of perturbation that make it impossible to maintain it in the same exact position with respect to the Earth. Perturbations are counteracted by means of periodic manoeuvers for correcting the orbit: the residual orbit inclination is typically kept within ±0.15 degrees which, if considered alone, causes an apparent movement of the satellite along an 8-shaped path, causing daily fluctuations which can be effectively tracked by using a Kalman filter [6].

3) *Sun transit*: around equinoxes, the GEO Earth receiving stations are “blinded” by the Sun’s apparent passage behind the satellite. This situation lasts a few minutes per day, during which the Sun interferes with the satellite’s downlink signal.

Reference [6] reports a detailed description of such perturbation of E_s/N_0 and the countermeasures adopted in the NEFOCAST system to identify and mitigate these effects.

5. Validation (test phase)

Precipitation estimation obtained with remote sensing techniques are usually evaluated by comparing remote sensing estimates with measurements at ground and rain gauges are generally used for this purpose. However, to make a meaningful comparison, differences in precipitation sampling mechanisms between the two sensors must be taken into account. In fact, whereas NEFOCAST rain rate estimates have quasi-instantaneous nature, those from raingauges come out from a time derivative of the rain accumulation (that is the actual measurement made by any raingauge). Disdrometers are also used. Their advantage with respect to raingauges for validation is that they attempt to estimate, in a given time interval (1 minute), the drop size distribution. Through such distribution one can estimate bulk parameters, such as rain rate and also (using an e.m. scattering/extinction numerical computation method) the specific attenuation. Some examples of comparison of NEFOCAST rain estimation is provided for some rainy days in November 2017 with data collected in Rome at the Institute of Atmospheric Sciences by a co-located disdrometer (a Thies Clima laser disdrometer owned by the Environmental Protection Agency of the Piedmont Region, Italy) and a SmartLNB (Figure 2).

Figure 3 (top panel) shows examples of E_s/N_0 measurement collected by SmartLNB in Rome in 12 hours on 9 november 2017. The rainfall rate derived from the SmartLNB and the measurement of the co-located disdrometer are compared in the bottom panel. In spite of the E_s/N_0 fluctuations, two clear dips are visible, the largest one being of ~1 dB. Looking at the bottom panel, it is possible to notice that the disdrometer registered three peaks of precipitation. The first in time is masked by the fluctuations of the smartLNB signal levels and the SmartLNB does not detect it. Instead, the other two peaks are detected and correctly co-located in time by the SamrtLNB. As far as the second peak is concerned, there is also a good agreement in the maximum value of rain rate.

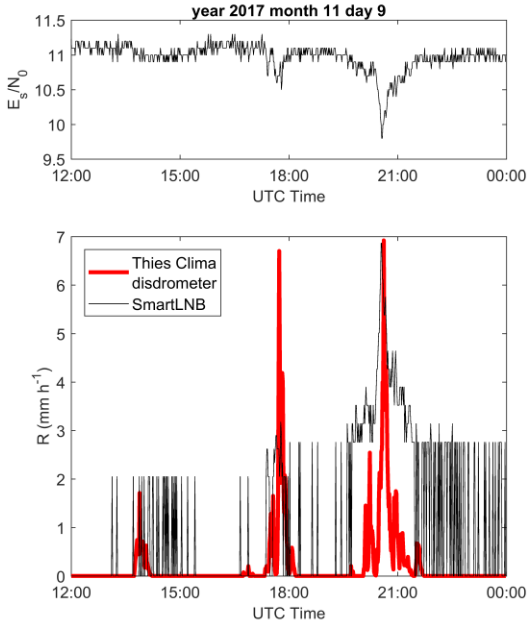

Figure 3. Smart LNB and collocated laser disdrometer at CNR-ISAC in Rome (November 9, 2017)

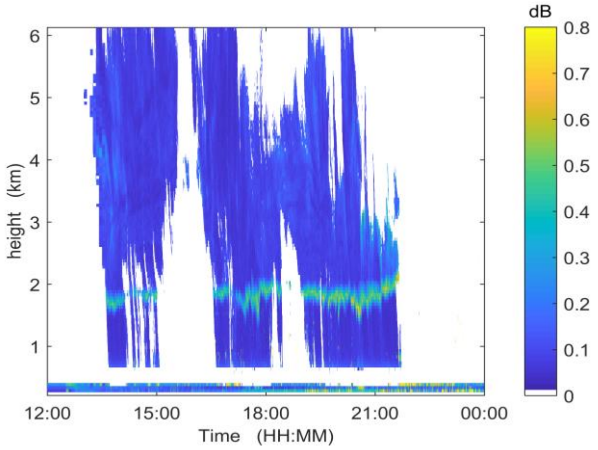

Figure 4. Standard deviation of differential reflectivity highlighting the melting layer signature. (November 9, 2017). Height is referred to the Sea level. Data are not computed below 500 meters.

Furthermore, at ISAC-CNR, data from the dual-polarization C-band weather radar Polar 55C [7] are available. Measurements shown in Figure 4 were collected with antenna aligned with the Earth-space link. In particular, shown is standard deviation of differential reflectivity that gives a well defined signature of the melting layer [8]. The layer of larger values defines the bottom of the melting layer. A certain variability of height and width of such layer is evident and determines the layers of the precipitating cloud that contributes to the total path attenuation (eq. 1).

6. Acknowledgments

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