3rd URSI AT-AP-RASC, Gran Canaria, 29 May – 3 June 2022

Multi-Satellite Rain Sensing: Design Criteria and Implementation Issues

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Abstract

In this paper, we propose a novel opportunistic multi-satellite sensor system which overcomes the limitations of the conventional single-satellite solutions of the literature. The considerable robustness to the possible unavailability of some satellites, besides being well suited for powerful 2D reconstruction techniques of the rain field, makes it an appealing solution for experimental tests within national and EU-funded research projects.

1. Introduction

Sensing techniques based on the measurement of the attenuation induced by rain on microwave signals, either satellite downlinks [1] or terrestrial commercial links [2], are receiving a growing interest for rain rate estimation. The following appealing features, indeed, come up:

- "green" approach, i.e., no need to generate any signal (as in weather radars, instead), and therefore no additional electromagnetic (EM) radiation in the environment and low-power operations;
- no installation and maintenance costs, as in a network of rain sensors such as the customary tipping bucket rain-gauges (TBRGs), due to the opportunistic use of already available microwave signals, e.g., the backhaul-links (BLs) of cellular networks or the slanted paths in direct-to-home (DTH) TV broadcasting from geostationary (GEO) satellites, as depicted in Fig. 1;
- good accuracy in comparison with conventional rain measurement instruments: disdrometers, rain gauges and weather radars [3];
- collection of high spatial resolution rainfall data and accurate rainfall map reconstruction [4] for sparsely gauged or completely ungauged regions, but characterized by a large number of consumer satellite receivers or wireless networks with a dense mesh of microwave BLs.

From a conceptual standpoint, rain sensing based on measurements of microwave links attenuation exploits the following popular power law [5]

$$\frac{A[\mathrm{dB}]}{L[\mathrm{km}]} = \gamma[\mathrm{dB/km}] = a\,(R[\mathrm{mm/h}])^b \qquad (1),$$

where $A[\mathrm{dB}]$ and $L[\mathrm{km}]$ are the attenuation and the length or the "wet" radio path, respectively, $\gamma[\mathrm{dB/km}]$ is the relevant specific attenuation, $R[\mathrm{mm/h}]$ is the rain rate (assumed constant on the path L), and a, b are frequency- and polarization-dependent empirical coefficients.

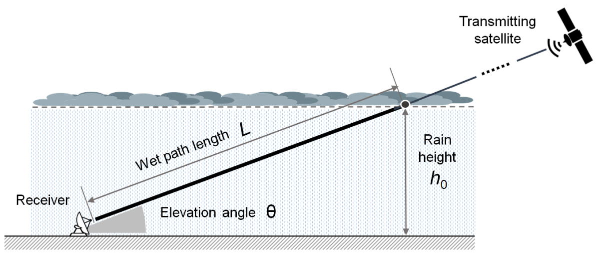

Figure 1. Geometry of a slanted satellite link through rain.

Additionally, satellite-based rain sensing systems [1], which typically exploit GEO satellites for direct TV broadcasting, enable the following advantages:

- no need for authorization to access network data owned by the operators, as the satellite downlink signal can be freely acquired and processed;
- deployment of additional receiving terminals with minimal technical requirement, in purposely selected locations to fill the coverage gaps of eithe satellite- or BL-based opportunistic networks;
- possibility of using inexpensive commercial-grade devices for domestic satellite reception.

In the case of satellite-based rain sensing, more complex relationships derived from (1) can be adopted to take into account for the layered structure of the troposphere, which is crossed by the slanted radio paths [6].
The contribution of this paper consists in presenting and discussing features and implementation issues of a novel multi-satellite receive arrangement for rain sensing.

2. Single-Satellite Rain Sensing

Most of the satellite-based opportunistic rain sensing systems proposed in the literature rely on a single-satellite receiver ([1] and the references therein). The single-satellite rain sensor (SSRS), however, exhibits some drawbacks:

- depending on one provider only, the satellite signal might be modified or even switched off without any adequate forewarning;
- the spatialization process, i.e., the reconstruction of the 2D precipitation field is less accurate when all the sensing receivers are aimed at the same satellite through parallel slanted paths, as in the case of already installed receivers for DTH TV reception, also called as set top boxes (STBs);
- the satellite could experience orbit perturbations affecting the quality of the received signal.

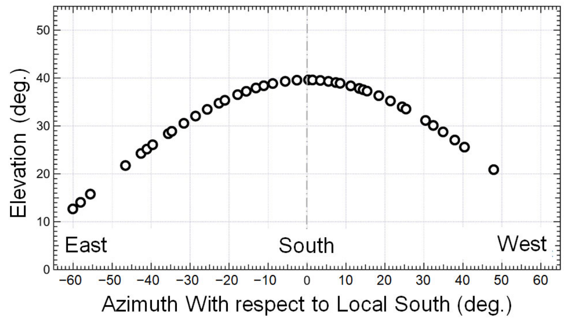

Figure 2. GEO arc in Pisa, Italy (10.4147°E, 43.7117°N)

Figure 3. The Wave-Frontier T90 dual reflector toroidal antenna (left). A close up view of the multiple LNBs (right).

3. Multi-Satellite Rain Sensing

3.1 The GEO Arc

At any receive site there are several satellites in line-of-sight (LOS) on the GEO arc (i.e., the Clarke Belt as seen in the sky from Earth) having a footprint covering that location. So, many GEO satellites are visible at different angles, whose signals can be received for rain estimate along different directions. For instance, assuming Pisa, Italy (10.4147°E, 43.7117°N), as the receive location (see Fig. 2), there are approximately 40 satellites for DTH TV broadcasting in the Ku band, lying on the GEO arc from 70.5°E to 37.5°W, with at least one beam covering the city [1]. A multi-satellite experimental setup for rain monitoring can be found in [7].

3.2 Multi-Beam Antenna

The implementation of a multi-satellite rain sensor (MSRS) based on a motorized dish is costly and impractical, since the dish should be continuously moved and sequentially aimed at all the desired satellites. A cheaper and more practical solution consists in resorting to a commercial-grade multi-beam antenna for DTH, such as the Wave-Frontier T90 dual reflector toroidal antenna ([8], Sub-Section 4.4), which can allocate up to 16 low-noise block converters (LNBs) spanning over an arc range of 40° (Fig. 3). The ground projection of the slanted paths for this multi-satellite receive antenna has a fan-shaped pattern (Fig. 4, left). The MSRS is a very appealing solution, which effectively tackles all the issues shown by the SSRS:

- it is less sensitive w.r.t. possible unavailability of some satellites;
- tomographic techniques can be proficiently used for the 2D reconstruction of the precipitation field [9], as shown in Fig. 4 (right), for latitude 43.7117°N and rain height 2700 m.

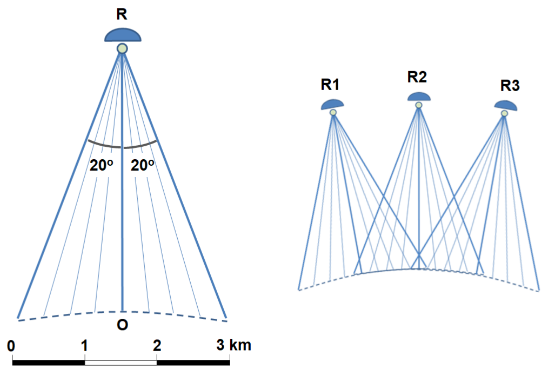

Figure 4. The fan-shaped pattern generated by the ground projection of the slanted paths for multi-satellite receive antennas (left). Pattern superposition for 2D tomographic reconstruction of the precipitation field (right).

3.3 SmartLNB

3.3.1 Outline of the Device

In [5], [6], the satellite receiver used as SSRS is an innovative low-cost, small-size, low-power two-way device named SmartLNB which includes both a DVB-S2 receiver and a return link (i.e., ground-to-satellite) transmitter. The return link employs the Spread Spectrum Aloha as modulation/medium access technique, implemented by the Fixed Interactive Multi-media Services (F-SIM) protocol, and can carry user-generated contents (e.g., for interactive TV services) or local sensor data, plus information about the status of the device, including the readings of received signal strength, or signal-to-noise ratio (SNR).

3.3.2 Sensitivity Issues

If the received SNR falls below a given minimum operation level (also called sensitivity), the outage condition occurs, i.e., synchronization is lost and data detection fails. The SmartLNB during outage also does not provide the readings of received signal strength, or SNR. Then, the sensitivity sets the maximum tolerable rain-induced signal attenuation and therefore the associated maximum rain rate that can be measured. From the results in [6] (see Fig. 12), the sensitivity of the SmartLNB is 5 dB and the range of the rain rate measurement turns out to be < 25 mm/h, which is definitely too low for practical applications. Unfortunately, commercial-grade receivers for DTH (STBs), including the SmartLNB, implement proprietary algorithms for SNR estimation, and so any type of modification are prevented.

3.3.3 Data Logging Issues
Signal strength, or SNR, measurements produced by a number of satellite-based receivers must be collected in a service centre via a proper data return channel. By using the SmartLNB as receiver, measured data can be effectively transmitted via the F-SIM return channel towards the satellite, which in its turn relays them down to the service centre. This solution requires, however, a subscription fee for each SmartLNB and a properly enabled satellite. Unfortunately, only a small number of satellites support F-SIM return link. Hence global coverage is not available. As a consequence, the SmartLNB turns out to be unsuited for the MSRS case and data logging shall be performed via some conventional technology, either wired (Ethernet or ADSL) or wireless (Wi-Fi or 4/5G network).

3.4 Multi-Satellite Receiver Requirements

In the development of the MSRS, the most demanding task is the implementation of the receiver, which calls for the following features:

- the sequential tuning of all the LNBs of the multi-beam antenna is required through the open standard Digital Satellite Equipment Control (DiSEqC) switch [10];
- for each satellite, a reliable measure of the received signal strength, or SNR, has to be provided over a wide range to detect deep attenuations and to estimate the related rain rate up to high values, as in Section 3.3.2;
- in order to allow real time tracking of the precipitation, the measures for every satellite shall be carried out at a rate not lower than one reading per minute (this means that, with 16 LNBs, each satellite signal can be monitored for no more than 3.75 seconds);
- the measures from received signal shall be made available for data logging, as discussed in Section 3.3.3.

Unfortunately, such a device does not exist in the market and therefore a proper engineering effort is required, as outlined in Section 3.5.

3.5 Multi-Satellite Receiver Solutions

Different approaches can be pursued for implementing the MSRS.

3.5.1 Low-Cost Linux-Based Satellite TV Receivers
The first solution we analyzed is based on the use of Linux-based commercial satellite TV receivers. These devices are quite cheap and could be an all-in-one solution for the multi-satellite receiver.

<u>Pros</u> Custom code run possibility; simple architecture (acts as a router plus a data logger); support for DiSEqC switch available.

<u>Cons</u> LinuxDVB APIs for signal monitoring lack of adequate documentation; reported measurements not reliable.

3.5.2 Software-Defined Radio
An alternative approach we investigated is the use of Software-Defined Radio (SDR) cards to decode the signal. This requires the external implementation of the LNB power supply and DiSEqC control.

<u>Pros</u> Full control on the receiver side; flexibility and re-programmability; high-end boards very accurate.

<u>Cons</u> Need for an external DiSEqC switch; low-cost SDR not accurate enough; high-end board expensive.

3.5.3 Satellite Router
Another COTS option taken into account consisted in using DVB-IP satellite routers (Forsway ODIN F50).

<u>Pros</u> Support from manufacturer available.

<u>Cons</u> Limited range of measurement (due to chipset limitations); support for DiSEqC 1.0 only (it allows switching for at most 4 satellite sources).

3.5.4 Professional USB Card
The last tested COTS device is an USB card based on the same RF front-end as the SmartLNB: STV6111+STV0910 from ST Microelectronics (STM).

<u>Pros</u> Based on STM chipset, with limited support from manufacturer available.

<u>Cons</u> Limited range of measurement; firmware modification required (the manufacturer does not provide support to this respect).

3.5.5 Modified SmartLNB
With the support from a manufacturer, the following modifications have been implemented in the SmartLNB device: *i*) DiSEqC control added (software/firmware modification); *ii*) DiSEqC output connected to the "External LNB" socket to the SmartLNB; *iii*) received signal processed using the embedded SmartLNB demodulator (hardware/software/firmware modification). Hereafter, this new arrangement will be addressed as "Modified SmartLNB" (MSmartLNB).

<u>Pros</u> Full support from manufacturer available; re-use of existing hardware.

<u>Cons</u> High development costs; external data logger/router required.

4. Experimental Results

An test campaign was recently carried out in Pisa, Italy (10.4315°E, 43.6865°N), using a MSRS-based system featuring: *i*) a Wave-Frontier T90 multi-beam antenna equipped with commercial-grade LNBs; *ii*) a DiSEqC switch connecting the LNBs to the receiver unit; *iii*) a receiver consisting of a MSmartLNB. Figure 5 depicts two sample records of the E_s/N_0 ratio, i.e., the average RF energy per modulation symbol (E_s) and the one-sided power spectral density of the channel noise (N_0) obtained from the Eutelsat 10A at 10°E, and Astra 3B at 23.5°E, satellites. Figure 6 presents the MSRS' estimates of the cumulated rain, obtained by the processing the records of Fig. 5 with the algorithm described in [6]. The measures provided by a nearby conventional TBRG are also reported (red curve) for the sake of comparison.

5. Conclusions

This paper addresses the opportunistic satellite-based rain rate estimation by proposing and discussing the implementation issues of a novel multi-satellite sensor system, the MSRS, which skips the main drawbacks of the conventional single-satellite solutions proposed so far in the literature. Besides being slightly affected by possible unavailability of some satellites, indeed, its fan-shaped pattern is well suited to powerful tomographic techniques for the rain field 2D reconstruction. In view of its appealing features, *i*) the proposed MSRS is currently deployed in agricultural environments in Tuscany (Italy) for experimental tests within the INSIDERAIN project (http://www.insiderain.it), and *ii*) it stands for a competitive solution for weather monitoring within the H2020 SCORE project (https://score-eu-project.eu), whose aims are to increase the climate resilience of European coastal cities.

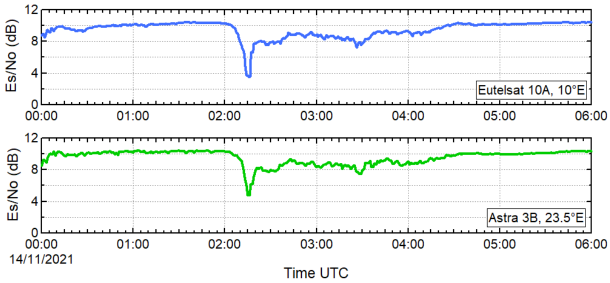

Figure 5. Sample records of E_s/N_0 measured in Pisa, Italy, from a MSRS with a MSmartLNB receiver: Eutelsat 10A at 10°E (top); Astra 3B at 23.5°E (bottom).

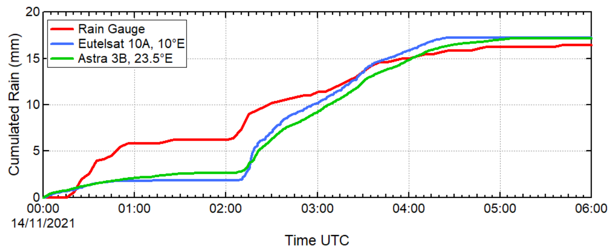

Figure 6. Cumulated rain provided by a MSRS and a TBRG in Pisa, Italy.

6. Acknowledgements

This work was partially supported by the INSIDERAIN (INStruments for Intelligent De-tection and Estimation of Rain for Agricultural INnovation) project funded by Tuscan Region (Italy), Decreto n. 21885, 18 December 2020, and by the SCORE (Smart Control of the Climate Resilience in European Coastal Cities) project funded by European Commission's H2020 research and innovation programme under grant agreement No. 101003534.

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