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# ROXI: a small compact vertically-pointing X-band radar Doppler for atmospheric profiling

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**Abstract**—ROXI is a compact transportable X-band radar designed to provide long-term measurements of reflectivity and Doppler (velocity and spectra) in rainy situation. It was initially thought to perform studies on ice microphysics to address uncertainties in the retrieval of rain from satellite remote-sensing instruments.

Since its deployment in Q4 2016, ROXI has been deployed in various field campaigns during which a rich dataset was acquired. In the present short paper, we present a number of possible applications of such a versatile system.

**Keywords**—Radar, X-Band, precipitation, ice microphysics

## I. INTRODUCTION

Rain retrieval from microwave measurements onboard satellite instruments requires a good knowledge of the microphysical properties of clouds and precipitations. In ice phase, crystals can have many shapes and densities and those properties will impact directly their signatures in the measured brightness temperatures.

In order to improve our understanding of the measured signal, long term measurements are necessary in complement to dedicated airborne campaign with dedicated in-situ probes.

The ROXI system was designed with this objective in mind and will provide a full vertical profile of measured reflectivity and Doppler. The latter consists in both velocity and full spectrum in each radar bin.

The radar was deployed in various locations over the years (see Table 1). In between campaigns, it is operated in [Palaiseau SIRTA](#) or at LATMOS in Guyancourt and goes through constant improvement.

The present paper gives a brief description of the system and its philosophy and will show a number of applications before presenting future developments.

Part II will present the main characteristics of the ROXI and its modes of operation, while part III shows various application examples, from comparisons with other radars (Météo-France, W-band BASTA), to comparisons with fuzzy logic particles classification with the Météo-France radar at Trappes and also the exploitation of the full Doppler spectra to help identification of the ice particles. A brief mention of a more recent application on bird detection is also presented. Finally, part IV will present some conclusions and perspectives.

TABLE I. LIST OF THE OF ROXI DEPLOYMENTS.

Location	Period	Objectives
SIRTA [1], Palaiseau, France	2016-2017	Microphysics, first tests
Corsica, France	Summer and Falls 2018	<a href="#">EXAEDRE</a> campaign, atmospheric electricity
La Chaux-de-Fond, Switzerland	Winter 2020-2021	ICE-Genesis campaign [2], ice microphysics and icing
Paris Downtown, France	2022-2023	H2C campaign, PBL development
SIRTA, Palaiseau, France	July 2024-present	Microphysics, attenuation of satellite-to-ground link at Ku-band.

## II. PRINCIPLE AND CHARACTERISTICS

### A. General design

ROXI is a low-power (70 W peak power) transportable X-band (9.42 or 9.48 GHz) radar designed to provide long-term vertical profiles of reflectivity and Doppler (velocity and spectra) in rainy situations. It is designed around a System-on-Chip (SoC) which includes a CPU and a FPGA (currently on a ZC706 Evaluation Kit card from Zinq/Xilinx). The FPGA handles full control of the radar while the CPU is in charge of

data formatting and transfer to a control PC via a standard internet link.

The 1.2 m offset antenna is tilted by  $21.5^\circ$  to avoid the filling of the main reflector with water or snow (Fig. 1). Its 3dB aperture is  $1.9^\circ$ . A dual polarization-capable horn is set atop although only one way is currently used.

The system is made of four sub-systems:

- a Power Unit (PU) that hosts all the power sources,
- an Electronic Unit (EU) hosting the ZC706 (c) card with the SoC and the ADC/DAC card.
- a radio frequency Unit (RFU) hosting the various filters and switches of both the transmitter and the receiver part of the radar.
- a 70 Watt solid-state power amplifier.

The FPGA is in charge of generating the pulse, handling all the clocks, triggering the power amplifier and controlling both the receiver and the transmitter switches. The first switch is meant to protect the receiver from the emitted pulse, the second one is meant to protect the receiver from the residual noise coming from the transmitter during reception.

The FPGA is also in charge of performing various tasks during the signal reception and notably data stream packaging and pulse-pair processing. The data are then passed to the CPU which will send the packets to the control computer through a standard FTP protocol via RJ45.

The system was designed to be very versatile and has been used in two main configuration so far. The first one, which will not be detailed here is meant to measure planetary boundary layer turbulence (CURIE mode). The second one, purpose of the present paper is meant to study ice microphysics (ROXI mode).

The FPGA can be reconfigured on-the-fly at any moment to change the mode of operation and even interleave different modes since it is controlling the whole system's clocks.



Fig. 1. ROXI deployed in Corsica during the EXAEDRE campaign. The antenna system sits atop the radar container itself. The system is connected to a control PC via a RJ45 cable and is powered through a standard 220 V power plug.

### B. Operating configuration

So far, the most common configuration that has been used during the various field campaigns is the following:

- 666.67 ns pulses for a 100 m resolution
- 128 radar bins along each ray, from 100 m to 12.8 km
- 8 coherent integrations are performed in the FPGA to reduce data flow

Because the time series of I and Q are stored, further integration can be performed in post processing. The most common configuration is to compute up to  $4096 \times 8$  individual pulses which gives a ray every 2.79 s. In that configuration, the ambiguous Doppler velocity is  $\pm 11.73$  m/s.

In the configuration described above, the radar produces 120 Go of data per day.

Nominal sensitivity at 1 km is about -21/-18 dBZ (depending on the number of integrations) which allows us to get a good sensitivity for light precipitations and ice clouds aloft if they have enough ice and snow content.

During the ICE-Genesis field campaign a 50 m (333.34 ns pulse) resolution with 128 bins and 16 coherent integrations was tested since the radar range needed was below 6 km in Winter in Switzerland and the Doppler velocities for iced precipitation were expected to remain within  $\pm 6$  m/s.

## III. APPLICATIONS EXAMPLES

### A. Comparison and complementarity with W-Band

BASTA is a small FMCW W-band Doppler radar developed at LATMOS [3]. While ROXI wavelength ( $\lambda \sim 3.16$  cm) implies mostly Rayleigh scattering on the rain drops and ice particles, BASTA (at  $\lambda \sim 3.16$  mm) is almost exclusively in Mie scattering regime. This difference in the scattering regimes makes the two radars complementary with each other. They can be used together for intercalibration as proposed in [4].

Fig. 2 provide an example of an active convective cell passing over both radars at the same time on June 10<sup>th</sup> 2018. The much more sensitive W-band ( $\sim 35$  dBZ at 1 km) provides a very detailed view of the higher part of the forward anvil and of the low-level clouds between 16:00 and 16:30 UTC. However, the BASTA signal is dramatically attenuated during the most intense cell between 16:30 and 16:45 UTC. This attenuation arises both from propagation through the rain and from the thin layer of water deposited on the radome.

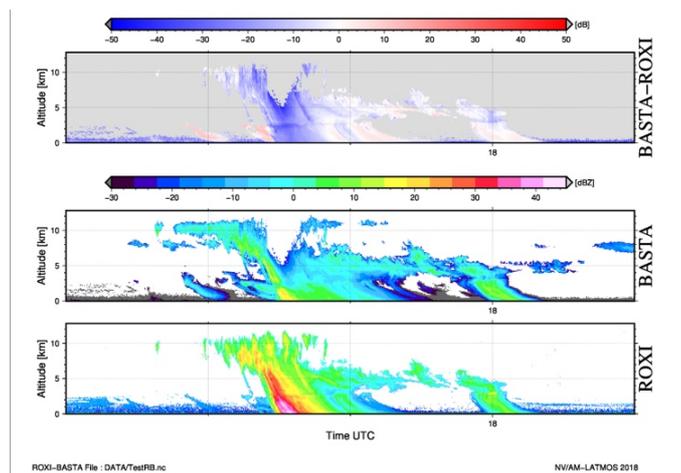


Fig. 2. Reflectivity factor (dBZ) of an isolated thunderstorm cell passing over Guyancourt on June, 10th 2018 and seen simultaneously by BASTA (middle) and ROXI (bottom). The top panel is the reflectivity

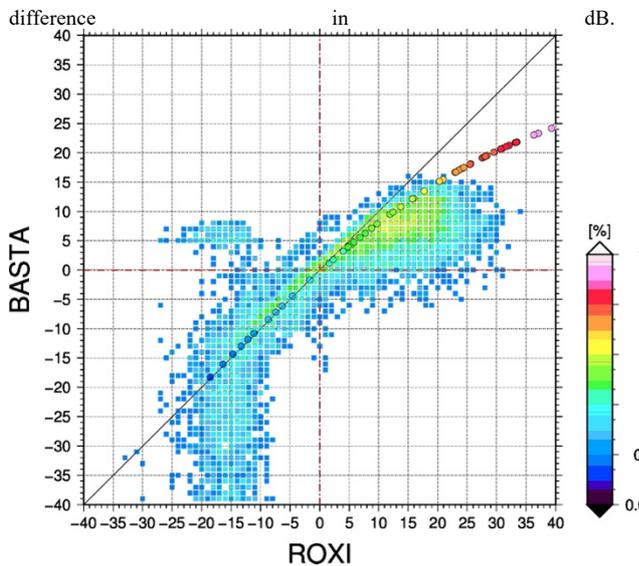


Fig. 3. 2D-histogram of ROXI and BASTA reflectivity over a series of situations observed simultaneously by both radars.

Fig. 3 shows the density histogram of the reflectivity of the two radars on a series of events keeping only the part below the melting layer. The line of dots is the simulated reflectivity with a simple Marshall-Palmer DSD. Between  $-25$  dBZ and  $-10$  dBZ on the x-axis, the higher sensitivity of BASTA is apparent. When the reflectivity reaches the sensitivity of ROXI around  $-18$  dBZ, the two radars are in Rayleigh scattering regime so their reflectivity are on the  $x=y$  line. As the reflectivity increases along the x-axis, BASTA starts increasingly to reach Mie scattering and the two radars start to show different reflectivity. The histogram departs slightly from the theoretical curves because of attenuation in the BASTA signal which is not accounted for in the simulation.

### B. Particles type comparisons with Météo-France radar

A Météo-France operational C-band polarimetric radar is located in Trappes near Paris and a fuzzy-logic algorithm inspired by [5] was used to classify particle types on 22<sup>nd</sup> of December 2016. At the time, a large stratiform frontal system was passing over the Paris area and ROXI was deployed some 22 km in the azimuth  $112.5^\circ$  (red line on Fig. 4) from the C-Band, at SIRTA (Palaiseau, France).

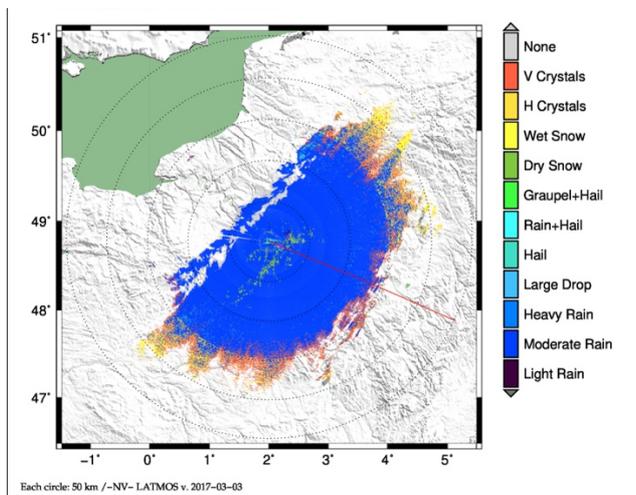


Fig. 4. Particles classification from C-Band Météo-France radar on 22nd December 2016 at 04:49 UTC ( $0.4^\circ$  elevation). The red line is the vertical cross section shown on Fig. 5

Fig. 4 shows a large area of stratiform precipitation from a frontal rainband, classified as “Moderate Rain” which is in agreement with the ROXI measurements of a 2 km-thick rain layer with reflectivities varying between 10 and 20 dBZ (Fig. 6). Within the 50 km radius, some spots are classified as Dry Snow. Three of these Dry Snow “columns” can be seen on Fig. 5 at 15, 20-23 and 27-28 km from the radar.

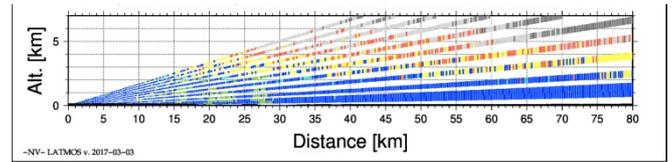


Fig. 5. Vertical cross-section from Trappes C-band radar at azimuth  $112.5^\circ$  passing over the SIRTA site where ROXI is operating. Color code is the same as Fig. 4. The vertical cross-section is a combination of all the PPLs produced over a full exploration sequence of 15 minutes.

At the time of the C-band radar observation, ROXI does show (Fig. 6) in this exact region a series of four columnar structures occurring between 04:45 and 05:00 UTC and extending vertically from the ground slightly above the melting layer (3 km). The increase in both vertical Doppler velocity and reflectivity in these columns make it unlikely that these columns are made of Dry Snow and so were most likely improperly classified as such. The increase in reflectivity in the melting layer at the top of these columns is a clear signature of denser particles melting. We can assume that in this case the particles should have been classified as a mixture of Graupel and Hail.

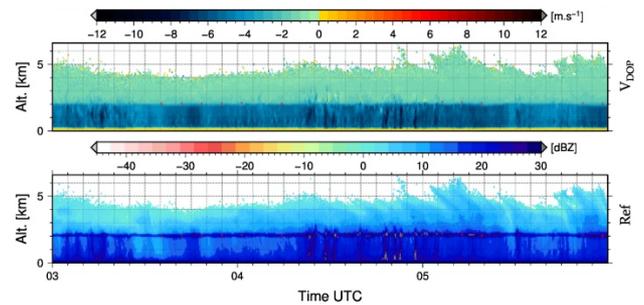


Fig. 6. Doppler velocity (top) and reflectivity (bottom) time-altitude cross-sections from ROXI on December 22<sup>nd</sup>, 2016. The matching time with Fig. 4 and 5 is the interval between 04:45 UTC and 05:00.

### C. Doppler spectra

One important information when studying the DSD and PSD properties is to access Doppler spectra which are directly connected to the terminal fall velocity distribution of the particles and drops [6]. ROXI produces temporal series of I and Q which allows us to compute spectra through FFT processing at any chosen resolution. The following example is taken from a rain system that passed over Paris (France) on August 25<sup>th</sup> 2020 during the H2C Summer field campaign.

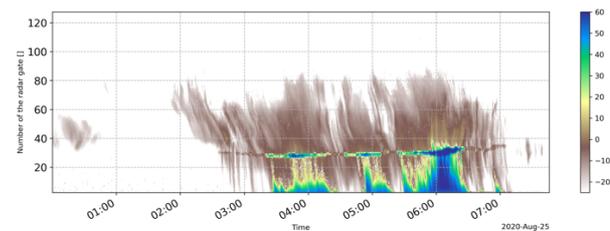


Fig. 7. Reflectivity factor measured by ROXI on the early hours of August, 25th 2020 in Paris downtown.

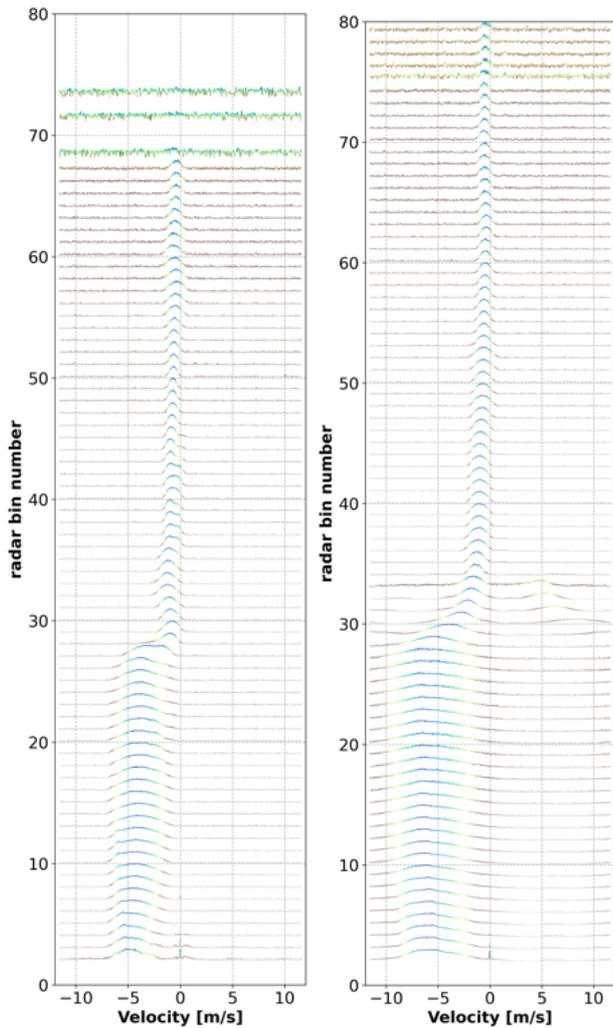


Fig. 8. Two spectra taken respectively at 03:06:28 (left) and 06:12:53 UTC (right), computed from data collected over Paris on August 25<sup>th</sup>, 2020. For each spectra profile 20 radar rays were averaged to smooth out the noise and enhance the useful part of the spectra. Only the first 80 radar bins are represented for readability and negative velocities are downward. The colors are just used to emphasize the useful part of the spectrum.

Fig. 7 shows the corresponding reflectivity factor. This weak system passed during the morning hours and exhibited a succession of slightly more convective cells embedded in mostly stratiform precipitation.

Fig. 8 shows two spectra computed respectively by averaging 21 spectra taken from radar rays at 03:06:18 and 06:12:53 UTC. The radar bins are 100 m and the melting layer can be found around bin 30 (3 km). From bin 50 and up, the spectra associated with the ice phase are not very different, the 06:12 ones being slightly larger. Between bin 40 and bin 50, the 03:06 spectrum exhibits a double mode type of spectrum that can be interpreted as the likely presence of two type of iced particles, one slightly denser than the other.

In the melting layer (bin 30 to 35), the 06:12 spectrum shows two maximum, one centered around -2 m/s corresponding to melting ice and another one at +5 m/s likely associated with a small updraft that carries the lightest particles upward.

Below bin 30, in the liquid phase, the 06:12 spectrum is much broader than the 03:06 one denoting a more turbulent environment associated with much larger drops (higher reflectivity factor).

#### D. Bird detection

On a more anecdotal side, ROXI has been used for bird detection in Paris. There is an important aspect related to bird detection during bird migration which happen mostly at night. Operational radars from the Météo-France network offer an almost complete coverage of the French territory. They could allow an opportunistic tracking of bird migration (direction, density of birds and eventually type of birds) [7, 8]. Various attempts have been made over the years but the difficulty is the validation. ROXI can offer an easy-to-deploy platform to detect and quantify birds to compare with retrieval from meteorological radars.

Fig. 9 was computed by manually selecting echoes of a few dBZ during a clear-air summer day. The echoes were isolated and standing out over the background noise and at an altitude compatible with birds in flight. In theory, the frequency of the wing beating, as seen from below could give an indication on the type of bird and be extracted from the spectrum. As such, we could assume that the orange, blue and red curves of Fig. 9 are from the same kind of species because the spectra look alike, even if the orange one is shifted with respect to the two others. The green spectrum shows a very different pattern which could indicate either a larger flock flying in a more random pattern or a signal of a completely different nature. At the time of the measurement, birds were not the main objective of the field campaign and no visual validation was performed.

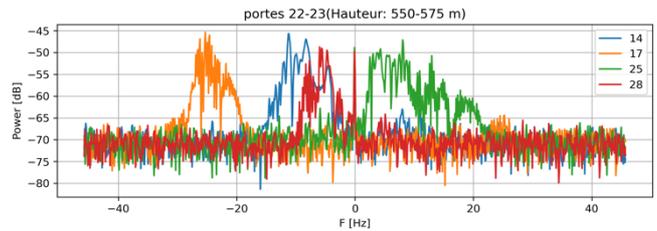


Fig. 9. Power spectrum extracted from a clear-air day (July 05<sup>th</sup>, 2022) when various flock of pigeons flew over the radar at height comprised between 550 and 575 m. Each colored curve corresponds to a different occurrence taken randomly throughout the day. The numbers associated with the colors are just the number order of each echo and have no particular meaning.

#### IV. CONCLUSION

The present paper offered a brief description of a small compact Doppler X-band radar system that was initially developed for ice microphysics studies: ROXI. A few examples of application were presented, showing how such a versatile system can be used for many more topics than its initial goal.

The system is entirely controlled by a SoC with both a FPGA and a CPU on the microchip. The FPGA does most of the work while the CPU is only used to facilitate the data transfer between an external control PC and the radar. Since everything is synchronized on the FPGA clocks, it is extremely easy to modify on-the-fly the radar configuration and even interleave modes.

The next step in developing ROXI will be to include an encoded pulse (chirp) with a frequency ramp that will also be generated through the FPGA via a Voltage Controlled Oscillator.

A new application envisioned for the future is to fly ROXI with BASTA under a stratospheric balloon (Stratospheric Open Balloon). This balloon would be launched from the new CNES (*Centre National d'Études Spatiales*) site in Brazil

during the 2026 or 2027 campaign. This would allow us to fly over deep Amazonian convection with unprecedented spatial and temporal resolution in order to study the vertical structure of such deep continental systems that cannot easily be investigated with conventional airborne system.

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