LoRa based remote expendable radiosonde network for environmental observations

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***Abstract*—The aim of the work is to design and develop a remote radiosonde cluster network and receiver station based on LoRa radio communication protocol. The designed remote sensing unit, radiosonde, should be light (less then 20 gr) and expendable as much as possible. The radiosonde tracks variations of physical and chemical quantities in the surrounding environmental ambient. Primary target of this this new kind of radiosonde is to obtain Lagrangian statistics of turbulence fluctuations inside warm clouds, clear-air and cloud-clear-air mixing regions. However, the application of the sensor network is not limited and can be extended to other contexts, such as environmental monitoring over urban and industrial areas. The radiosonde is made of the radioprobe attached to a biodegradable balloon filled with a mixture of helium and air. The system is able to float inside and around clouds for a time span of the order of a few hours and measure fluctuations of air temperature, pressure, humidity position, velocity and acceleration along its own trajectory. In this manner, the system can provide a multi-point endoscopic view of the flow by following the air parcels in passive way.**

***Index Terms*—radiosonde, LoRa, remote sensor, sensor network, cloud, atmosphere**

I. INTRODUCTION

In the past decades, the rise of interest in the Lagrangian statistics of turbulence has promoted the rapid development of Lagrangian measurement techniques. These techniques are mainly laboratory based and involve seeding the flow with tracer particles and tracking their motion [1]. Recent developments in remote sensing and MEMS (Microelectromechanical systems) sensors have made it possible to track Lagrangian fluctuations in the atmosphere via in-field measurement techniques, which have been the focus of interest from the beginning [2]. The primary purpose of such an in-field technique is to be able to remotely measure real fluctuations over a large range of scales (from a few meters to hundreds of kilometers [3]) inside the atmospheric flow (e.g., warm clouds) for a few hours. This method can be implemented through an *expandable radiosonde cluster* that is designed as a remote sensor network. LoRa is a relatively new proprietary wireless technology that allows long-range communication distances while consuming very little power.

Due to the required criteria of the passive floating radiosondes for long range and extensive time-span, LoRa communication technology has been adopted. LoRa is a chirp spread spectrum (CSS) modulation technique, which encodes information in linearly increasing chirps [4]–[6]. Even if LoRa was originally developed for the Internet of things (IoT), however, it underwent enormous growth, widely used in range of applications [6] because of its ability to scale up to hundreds of sensor nodes within a wide coverage area. In the present work, we intend to produce an in-field cloud Lagrangian dataset by means of a passive floating cluster of radiosondes inside atmospheric flow. To this end, a special focus is devoted to the development of a new method to track Lagrangian fluctuations by means of a newly designed, prototyped, and tested light expendable radiosonde that is able to float inside clouds for a time span of the order of a few hours. The developed probes use the LoRa radio communication protocol to send real-time variations of measured quantities inside clouds to ground receiver stations. Each radiosonde includes various sets of sensors, such as pressure, humidity, temperature, Inertial Measurement Unit (IMU), and Global navigation satellite system (GNSS) sensors. The IMU allows for measurements from a 3-axis accelerometer, gyroscope, and magnetometer, while the GNSS sensor can provide position, velocity, and timestamp information. The generated Lagrangian fluctuation dataset is required to reduce the fragmentation of results and knowledge in this field. By providing more accurate data obtained by radiosondes, we try to reduce the ambiguities and limitations of climate simulation models and weather prediction.

Preliminary in-field experiments were carried out with a single and multiple radiosondes in different environments. Sensor readings are validated by comparison with reference values provided by INRIM (the Italian National Institute of Metrology Research) traceable instrumentation, the vertical atmospheric profiling system of ARPA-Piedmont (the Regional Agency for Environmental Protection), and nearby meteorological stations at OAvdA (the Astronomical Observatory of the Autonomous Region of Aosta Valley).

The following Section 2 discusses the previous and related works. In Section 3, we describe the sensor network and methodology. Then, in Section 4, we describe preliminary in-field campaigns and the results obtained. At the end, it is concluded with future work, acknowledgements, and references.

II. Related works

Remote sensing based Lagrangian instruments have been used to study large regions of both the atmosphere and ocean [7]. One of the early experiments was the EOLE experiment in the southern hemisphere stratosphere [8], where they used a special-purpose navigation satellite for tracking their radiosondes with constant-volume balloons in global-scale. However, nowadays, with the help of low-cost and small-sized GNSS sensors, it is possible to perform much more accurate observations for understanding smaller-scale local dynamics, such as clouds. Radiosondes are mostly launched as a single or pairs of probes either vertically upwards for atmospheric profiling or dropped vertically down from an aircraft/UAV (Unmanned aerial vehicle) [9]. They usually do not consider working with multiple radiosondes at a time that can ascend to the target altitude, stay there, and send simultaneous measurements to the ground stations.

In our previous works, we discussed the first in-field experiments with a single radiosonde [4]. In addition to this, the previous works focused on the design of a radiosonde PCB board, sensor selection, environmental chamber tests [4] and a feasibility analysis of the WSN network with P2P LoRa communication on the basis of the star topology [10]. One of the important characteristics of each radiosonde is its ability to float in the inner layers of the atmospheric isopycnic surfaces. This is achieved by attaching a radiosonde electronic board to a non-elastic, small, and lightweight (biodegradable) balloon. The balloon material selection, together with its processing techniques and polymer coatings, was studied [11], in order to achieve essential experimental features such as helium permeability, hydrophobicity, and resistance to ambient variations. However, it has not been fully possible to perform in-field experiments with multiple radiosondes and a set of ground stations in wide areas. The present work mainly points out the demonstration of the experimental method with a **cluster of radiosondes** for simultaneous multi-point and multi-parameter measurements inside clouds.

III. Methodology

To analyze a variation in the rate of diffusion with distance and time, Richardson [2] suggested using a set of "marked molecules" and following their motion after their release. In practice, the "marked molecules" could be replaced by balloons, for those values of relative distance, which are many times the diameter of a balloon [2]. The proposed measurement system uses helium-filled biodegradable balloons to lift a payload (an electronic board with sensors, battery, and others) and act as "marked air parcels" within the atmospheric flow (cloud, clear air, polluted air, etc.). Figure 1 describes the in-field measurement setup, which includes a set of sensor nodes, receiver stations, and a post-processing machine. The receiver stations act as LoRa gateways and are connected via a serial communication port to the processing machine. The application server is responsible for receiving data from hardware ports, analyzing it, and storing it in local storage. The obtained measurements from the radiosonde cluster can

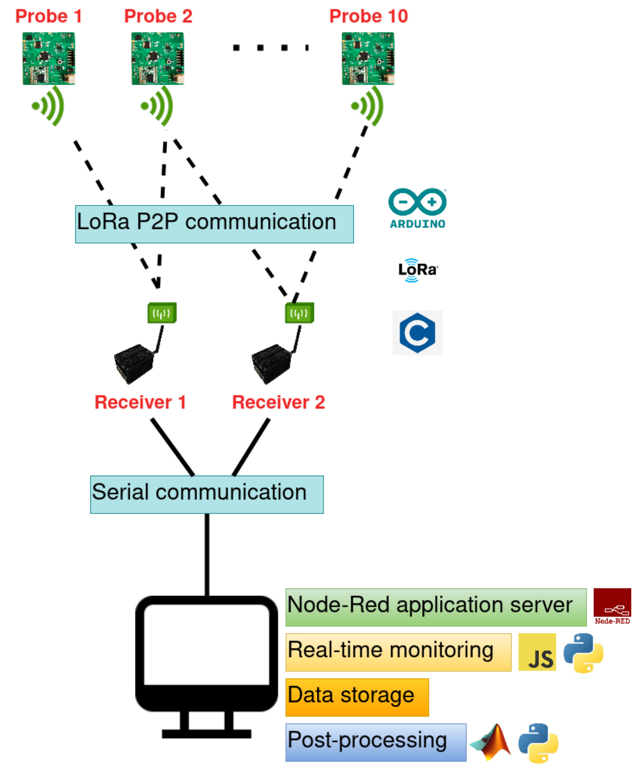


Fig. 1: In-field measurement system setup with a cluster of radiosondes. For simplicity, probes (radiosondes) are shown only as transmitters. However, in practice they comprise a biodegradable balloon and electronic board.

be visualized in real-time with the built-in functionality of the Node-RED application server or via Python scripts. A post-processing toolbox was also developed to filter raw data readings, remove biases, and perform complex analysis such as turbulent diffusion, dispersion, power fluctuation spectra, or Lagrangian correlation.

A. Radio transmission system

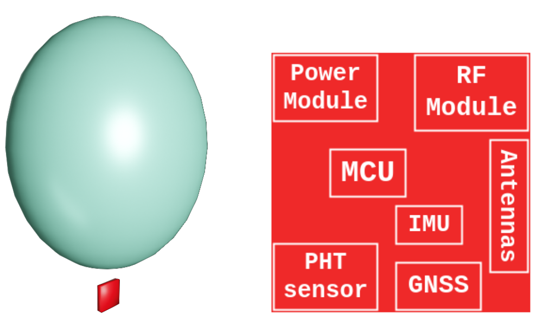
In most cases, LoRa based WSNs are designed on top of the LoRaWAN (LoRa Wide Area Network) infrastructure. However, in this work LoRa protocol is used to create an ad-hoc private network and adapt the technology in the working scenario. The network is organized as a star topology from each receiver station towards transmitters (sensor nodes). Each sensor node is connected via a P2P direct communication channel to the receiver. To this end, the commercial off-the-shelf LoRa-based transceiver module RFM95 from HopeRF was used [4], [12] in both sides of the P2P link. This module allows power-transmission ranges within 5 dBm (3.16 mW) to 20 dBm (100 mW), although according to the regulations released by the European Telecommunications Standards Institute (ETSI), the maximum power allowed in the European area is 14 dBm (25.12 mW) [13]. The following Table I describes the configuration parameters of the P2P communication link between each radiosonde and a receiver station. In order to minimize the computational burden on the transmitter and receiver sides, acknowledgement (ACK) messages and cyclic redundancy checks (CRC) were disabled in the configuration.

TABLE I: Configuration parameters of LoRa P2P communication.

Parameter	Value
Frequency channel	865.2 MHz
Bandwidth	250 KHz
Spreading factor	10
Coding rate	4/5
ACK	OFF
CRC	OFF
Power	10 dBm

B. Radiosonde - sensor node

The first prototype of the radiosonde was designed based on the Arduino framework [4]. It helped speed up the phases of system development: prototyping, component selection, hardware design, and firmware development. Figure 2 presents the assembled radiosonde (biodegradable balloon and sensor board) on the left and a logical diagram of the board units on the right. The board consists of a microcontroller unit (MCU) for data processing and control, GNSS and IMU sensors for positioning, and pressure, humidity, and temperature (PHT) sensors for measuring environmental parameters. Furthermore, it includes a power module for battery connection, a radio module, and antennas for data transmission. The current version of the radiosonde weighs 17.5 grams: 7 grams for the electronic board, 8 grams for the battery, and 2.5 grams for connecting parts. The weight of the biodegradable balloon with a radius of 20 centimeters is 12.5 grams and can lift the radiosonde board up to an altitude of 1725 meters. With the help of its small size and low weight, each radiosonde inside the cluster can follow air flow without disturbing the surrounding flow itself.



(a) (b)

Fig. 2: (a) Balloon-borne radiosonde. (b) Building units of the electronic board of the radiosonde: microcontroller, radio module, power module, antennas, GNSS, IMU and PHT sensors.

IV. Results and Discussion

During the development of the sensor network, we have carried out a set of important in-field experiments with different setups (see Table II). Tests were started by comparing the sensor network with respect to traditional environmental measurement systems. The traditional systems are either fixed stations or vertical profiling radiosondes. The validation experiments were performed at the campus of INRIM, the automatic radiosonde launching side of Arpa-Piemonte at Levaldigi Airport, and the Astrophysical Observatory (OAvdA) at Nus, Aosta. A list of experiments is given in Table II in chronological order. The above-mentioned validation experiments helped us validate the system and perform a free launch experiment with 10 radiosondes in OAvdA on November 3, 2022, at an initial altitude of 1700 meters. The first dual launch experiment

TABLE II: In-field measurement campaigns during the development of the sensor network and measurement system.

Date	**Description**	**Place**	**Coverage**
June 9, 2021	Dual launch experiment with Vaisala RS-41 SG probe in collaboration with Arpa-Piemonte	Levaldigi Airport, Cuneo, Italy	vertical profiling, up to 13 km
July 20, 2021	Radiosonde configuration testing with 2 sample configurations	INRIM, Turin, Italy	short-range setup, up to 100 m
Sep 29, 2021	Sensor network test with multiple tethered radiosondes in test environment	INRIM, Turin, Italy	short-range controlled setup, 100-200 m
Feb 10, 2022	Sensor network test with multiple tethered radiosondes in operating environment	OAvdA, Nus, Aosta, Italy	short-range controlled setup, up to 100 m
Nov 3, 2022	The first free launch experiment with 10 radiosonde network	OAvdA, Nus, Aosta, Italy	long-range freely floating setup, up to 9 km

at Levaldigi airport (Cuneo, June 9, 2021) allowed us to determine and verify radio communication coverage. We were able to receive data packets with an average 4 second interval (see Figure 3) up to a 13 km distance. In the next field test at INRIM (Turin, July 20, 2021), it was performed to identify the proper assembly setup for the radiosonde out of two configurations: (i) the radiosonde electronic board is inside the balloon; (ii) the radiosonde board is attached to the balloon from outside. As a result we selected the second configuration like in the Figure 2a. The next two experiments at INRIM and OAvdA served as preparation for the last free launch experiment. In the following subsection, results are shown from the last experiment with a cluster of radiosondes.

A. In-field experiment with a radiosonde cluster network

The Figure 4 shows the setup process of the latest experiment, which was carried out in Valle d'Aosta, Osservatorio Saint Barthelemy, on November 3, 2022. The experiment was arranged with a cluster network of 10 freely floating

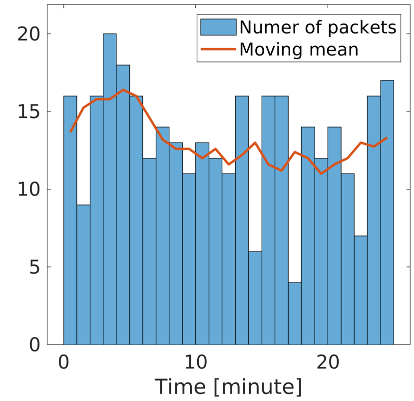
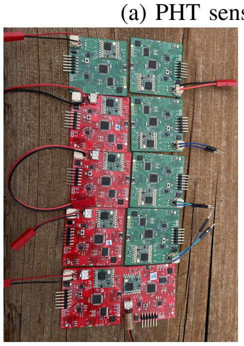


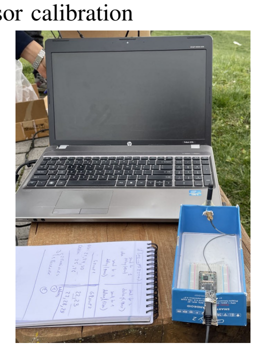
Fig. 3: Number of packets received in each minute during the experiment at Levaldigi Airport (Cuneo, Italy) on Kune 9, 2021.

radiosondes as follows: (i) Each radiosonde electronic board attached to the biodegradable balloon; (ii) Ground stations (2 pcs.); (iii) Sony HDV cameras for stereo vision analysis (2 pcs.); (iv) INRIM reference instrumentation for temperature pre-launch calibration.

Figure 5 shows the trajectory of the launched radiosondes

(a) PHT sensor calibration

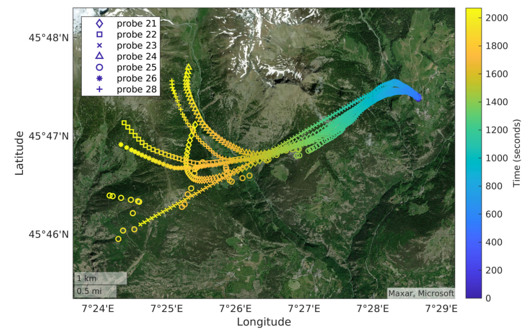




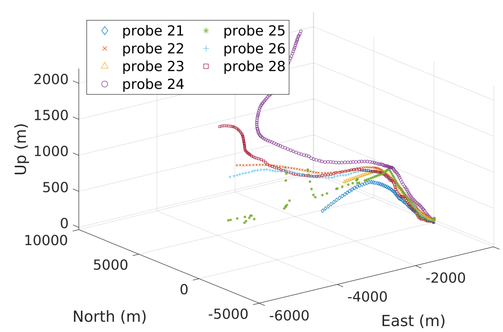
(b) Radioprobes (c) receiver station

Fig. 4: Experiment setup at the OAVdA, Saint-Barthelemy, Aosta, Italy on February 10, 2022.

inside a cluster network during the experiment. In panel a, trajectories are given in terms of global reference frame coordinates, longitude, and latitude. The colorbar indicates the free flight duration starting from the initial launch timestamp (at 14:15, November 3, 2022). The panel b shows the trajectories of the radiosonde cluster, which were converted from the global coordinate frame into the NED (North, East, Up) local experiment frame. The initial launch position was used as the origin of the local experiment frame during the conversion (reference position: latitude = 45.78994, longitude = 7.47764, and altitude = 1700 meters). During the free launch, the radiosonde reached up to an altitude of 3500 meters and up to 9000 meters in terms of distance (Figure 5b). During the setup, two stereo cameras recorded the pre-launch preparation and launch phases of the experiment. The camera dataset was used to perform stereo vision analysis and validate accurate relative positioning among radiosondes. However, for the sake of brevity, the results of the relative positioning analysis will be presented in future works.



(a)



(b)

Fig. 5: Trajectory of the radiosondes during the in-field experiment at the OAVdA, Saint-Barthelemy, Aosta, Italy, on February 10, 2022. (a) Trajectory with respect to the global geo-positional reference frame (b) Trajectory with respect to the local NED (north, east, and up) experiment frame Radiosondes were identified with labels from 21 to 28.

During this in-field observation, it was possible to determine a quantitative representation of the fluctuation spectra. In particular, Figures 6 and 7 illustrate the raw measurements and post-processed fluctuation spectra for carrier flow velocity, acceleration magnitude, humidity, and temperature in a time span of the order of 1 hour. The sounding or dropping of

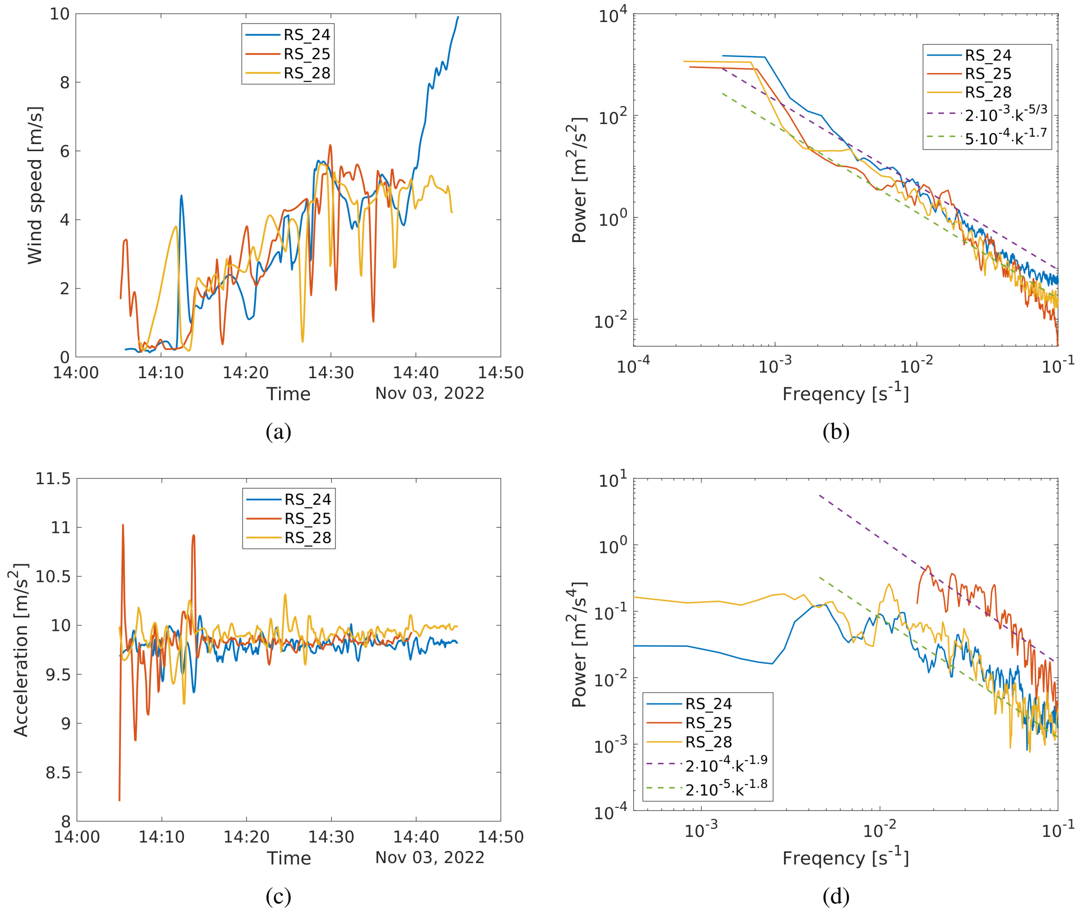


Fig. 6: Wind speed and acceleration measurements from a set of radiosondes during the in-field experiment at the OAVdA, Saint-Barthelemy, Aosta, Italy, on February 10, 2022. (a, c) Wind speed and magnitude of 3D acceleration measurements from 3 freely floating radiosondes. (b, d) The power spectrum of wind speed and magnitude of the 3D acceleration readings of 3 radiosondes. Two trend lines (violet and green) are provided for comparison.

a single radioprobe spans vertically a large portion of the atmosphere without necessarily meeting a cloud. If the cloud is met, residency time inside the cloud is limited to a few minutes. In our case, the observation was carried out for 45 minutes at multiple points in an inner stratum of the atmospheric boundary layer. These multi-point measurements help us to understand the local dynamics (on a small scale) of the air-water vapor-water droplet multi-phase systems in a general manner.

V. Conclusion and Future Works

The proposed radiosonde cluster and measurement technique help us perform multi-point observations over a wide range of scales with the help of an ad-hoc remote sensor network. In this way, it is possible to acquire Lagrangian fluctuations inside warm clouds. The generated dataset can be used to study complex physical processes such as turbulent diffusion (originally suggested by Richardson (1926), [2]), dispersion, and spectral analysis of fluctuations.

The final goal is to design and develop a biodegradable radiosonde board and balloon to a greater extent. Furthermore, we aim to use energy harvesting to minimize electronic waste due to the battery. Currently, aside from the biodegradable balloon, we were able to reduce the size and weight (17.5 grams) of the electronic board by 50% while designing the second version (8.5 grams) of the radiosonde. In addition to this, computing capabilities and low-power features were improved. In any case, the weight of the both radiosonde versions are much lighter than that of conventional radiosondes (50 - 200 grams). The optimized version of the radiosonde was developed within the MIGRE-POC (Proof of Concept) project, funded by the Links Foundation. The new version of the board will be validated in the following in-field campaigns.

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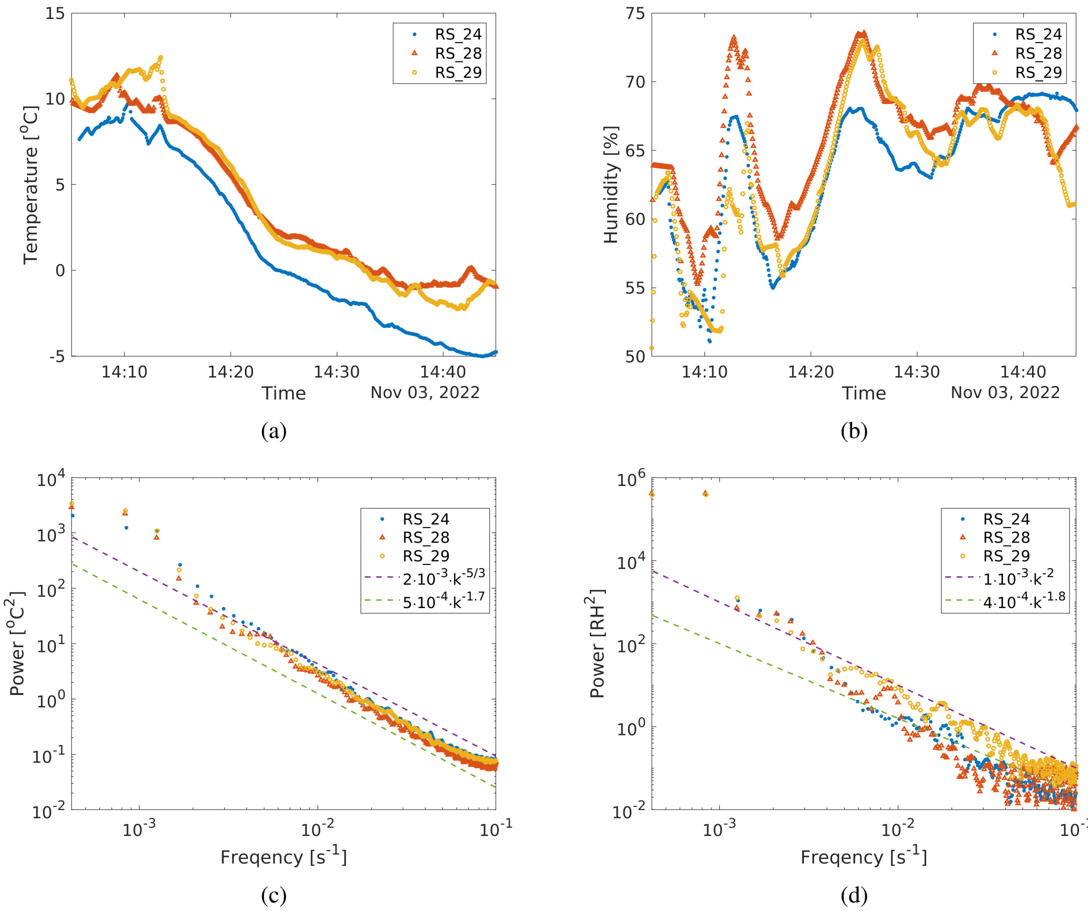

Fig. 7: Temperature and humidity from a set of radiosondes during the in-field experiment at the OAVdA, Saint-Barthelemy, Aosta, Italy, on February 10, 2022. (a, c) Raw temperature and humidity readings from 3 freely floating radiosondes. (b, d) The power spectrum of temperature and humidity readings of 3 radiosondes. Two trend lines (violet and green) are provided for comparison.

dation for the project MIGRE-POC. We would like to thank to *L'Osservatorio Astronomico della Regione Autonoma Valle d'Aosta*, Luca Tommassone and *ARPA, Piemonte* for hosting us during in-field experiment campaigns.

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