H2020COMPLETE-MIGRE radiosonde sensor readings from all 2020-2022 in-field measurements

December 23, 2022

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Contents

1 Timeline of all in-field experiments

20/10/2020 - Drone and INRiM experiment

- Drone experiment
- INRiM probes are used to validate PHT sensors
- Drone trajectory data is used to validate trajectory of the radioprobe
- Results are used to publish MPDI sensors paper
- GW from radioprobe, UAV_logs from Drone and INRiM

09/11/2020 - Experiment with Balloon

- First experiment with biodegraable balloon with helium inside
- Radioprobe was fixed inside the balloon pocket

26/11/2020 - Experiment with Phone

- In order to validate the positioning data we have used this experiment
- Drone experiment was noisy, we decided to check the positioning in 2D

09/06/2021 - Levaldigi Airport experiment with ARPA Piemonte, 2nd launch

- This experiment was to verify the correct functionoing of the positioning sensors
- Moreover we aim to identify the biases of the PHT sensors

20/07/2021 - Experiment with 2 balloons in INRIM, 1st launch

- 2 radiosondes are tested two check two different configurations
- 1st configuration: radioprobe is inside the balloon
- 2nd configuration: radioprobe is outside the balloon

29/09/2021 - Experiment in INRIM with 5 ballons, 2nd launch

- We tested 5 radiosondes with 2 ground stations
- The first test of multiple (¿2) radiosondes with previously selected configuration
- Datasets will be used for relative positioning analysis

10/02/2022 - Experiment in Valle d'Aosta, Osservatorio Saint Barthelemy with 5 tethered ballons

- We tested 5 radiosondes with 2 ground stations
- We used 2 cameras for stereo vision analysis
- Camera dataset will be used to validate positioning sensors

03/11/2022 - Experiment in Valle d'Aosta, Osservatorio Saint Barthelemy with 10 balloons

- We tested 10 radiosondes with 2 ground stations
- Radiosondes are released to the atmosphere
- We used 2 cameras for stereo vision analysis
- Camera dataset will be used to validate positioning sensors
- Reference PHT readings/ calibration from INRIM, Chiara and Andrea

In the following sections we present results from all in-field experiments in reverse date order.

2 Experiment at the Osservatorio Astrofisico St. Barthelemy, Valle d'Aosta, Nov 3, 2022

Objective

Our intention is to test entire radiosonde system with 10 radioprobes, that are launched freely into the atmosphere.

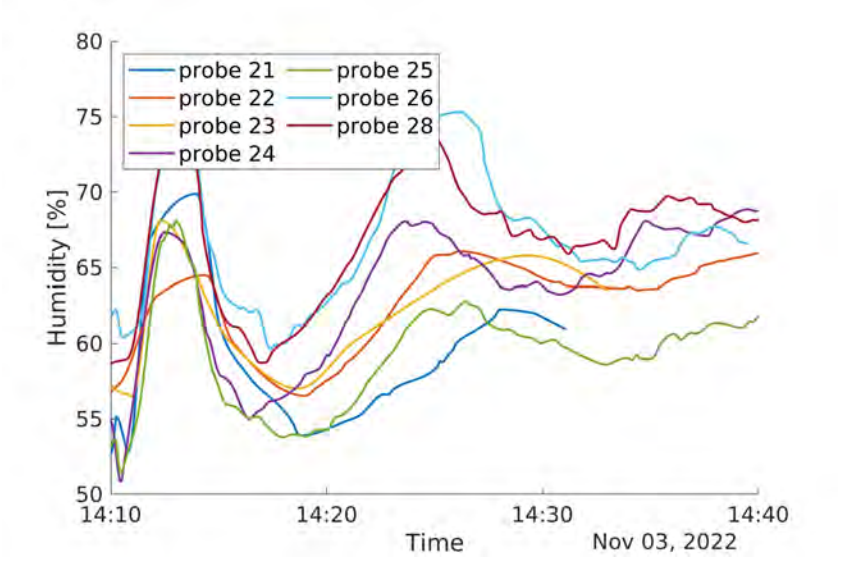
Experiment setup

- 10 radiosondes, all balloons are filled with helium..
- 2 ground stations were ready to receive packets from all radiosondes, both receivers were connected to pc to store and analyze coming packets in real-time.
- We used 2 Sony HDV cameras to capture radiosonde movement during the experiment.
- Calibration instrumentation from INRIM, to validate PHT (pressure, humidity and temperature) sensor readings.

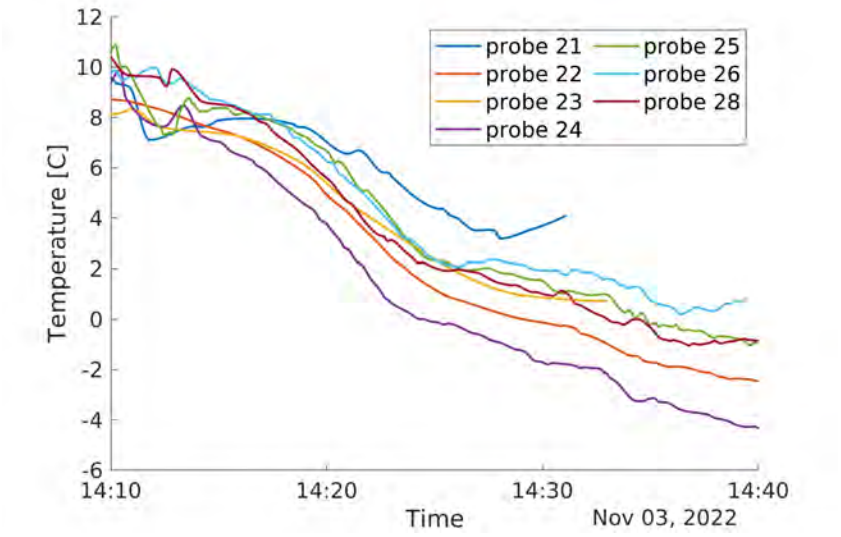
2.1 Pressure, humidity and temperature readings

2.2 IMU dataset

2.3 GNSS (GPS) dataset



(a)



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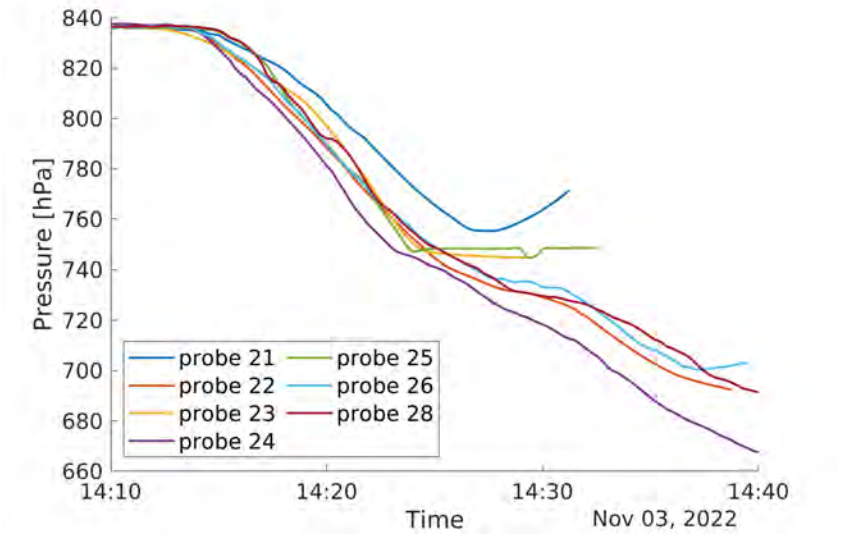
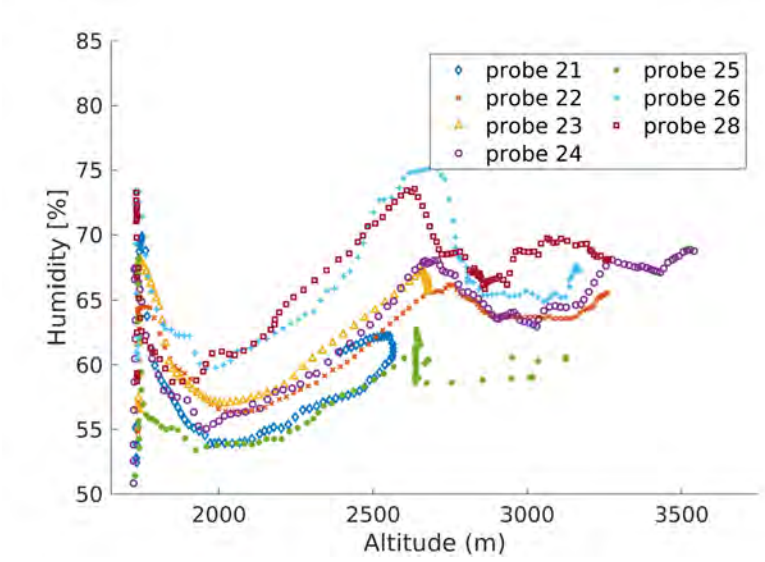
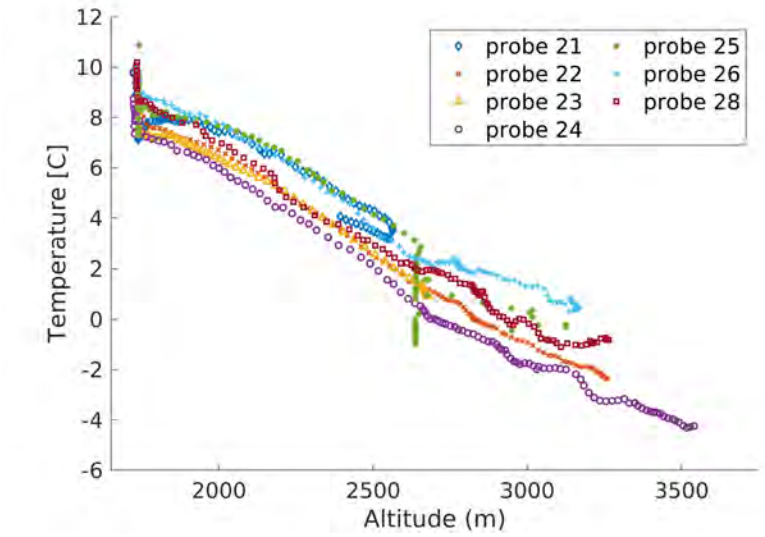


(c)

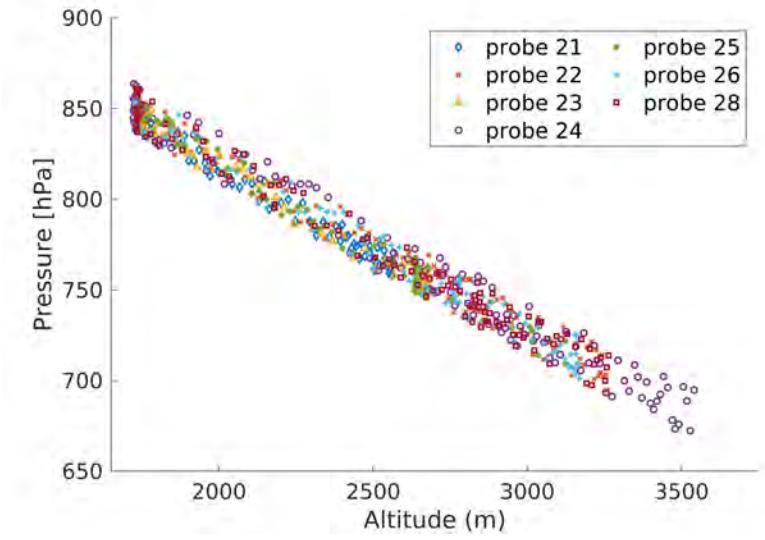
Figure 1: Raw humidity (a), temperature (b) and pressure (c) with respect to time axis.



(a)

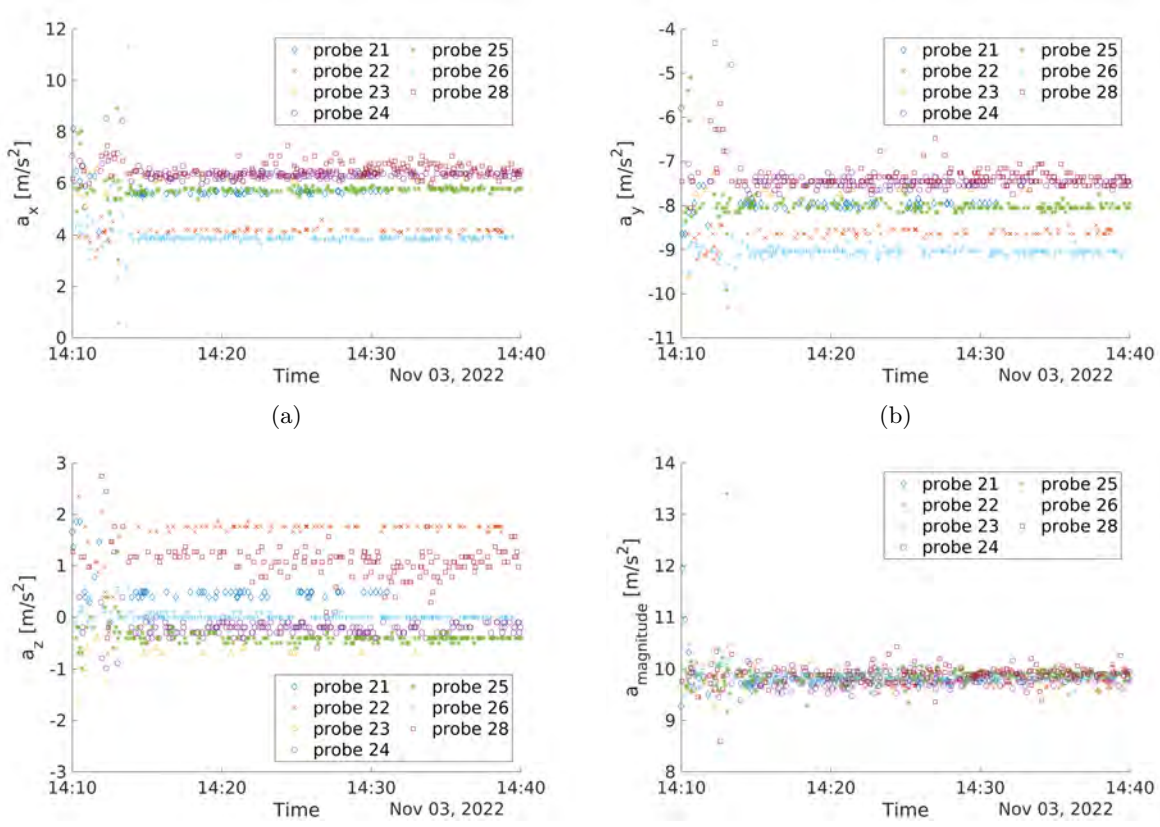


(b)



(c)

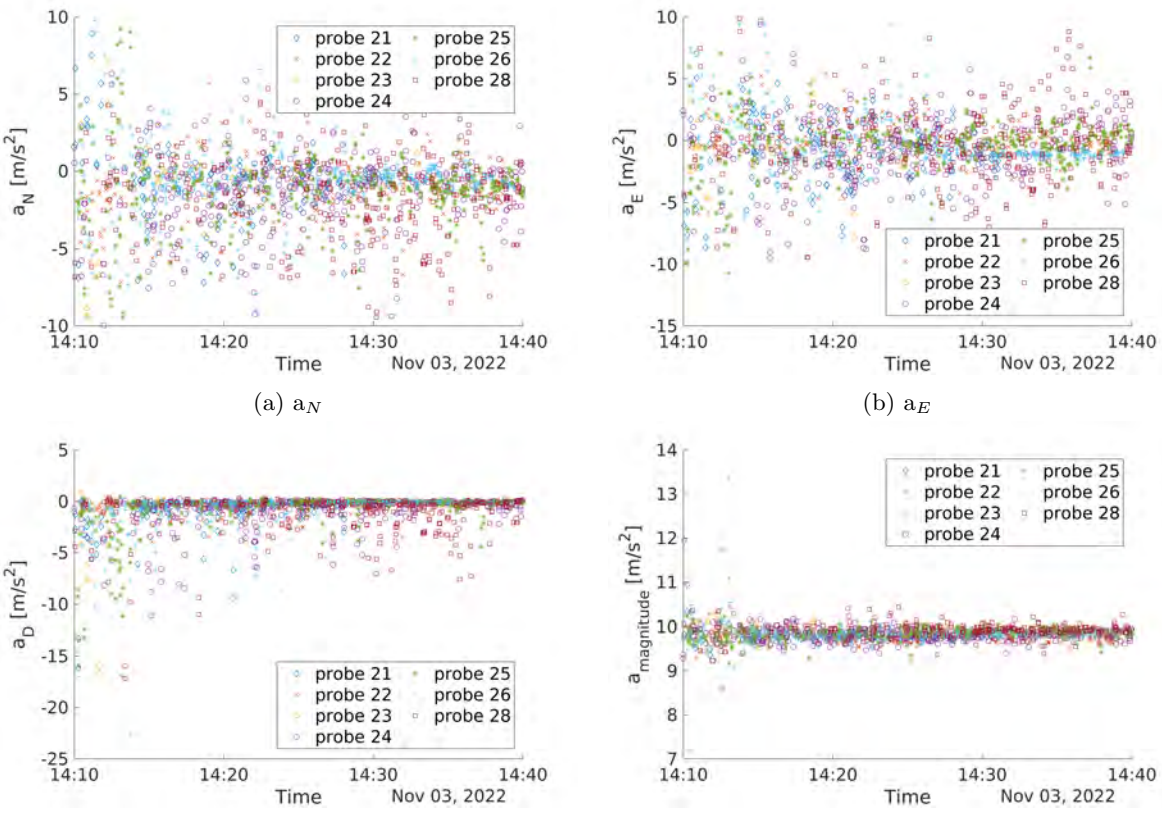
Figure 2: Raw humidity (a), temperature (b) and pressure (c) with respect to altitude axis.



(a) (b)

(c) (d) raw acceleration magnitude

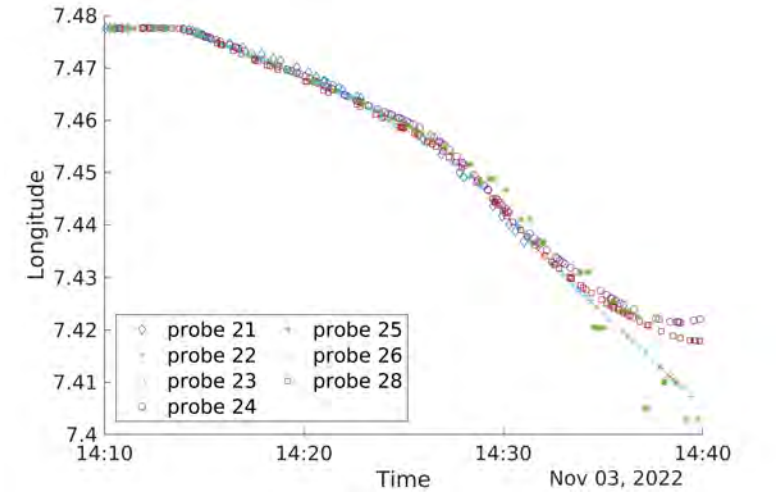
Figure 3: Raw acceleration readings.



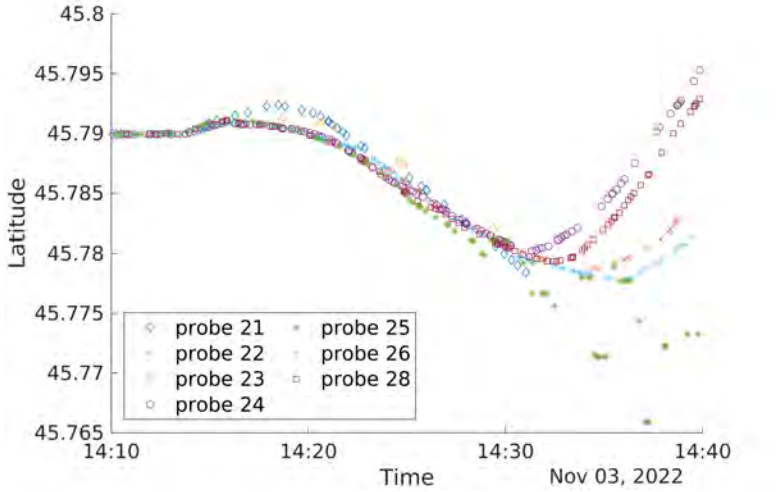
(a) a_N (b) a_E

(c) a_D (d) NED acceleration magnitude

Figure 4: North, East and Down (NED) acceleration readings and its magnitude.



(a)



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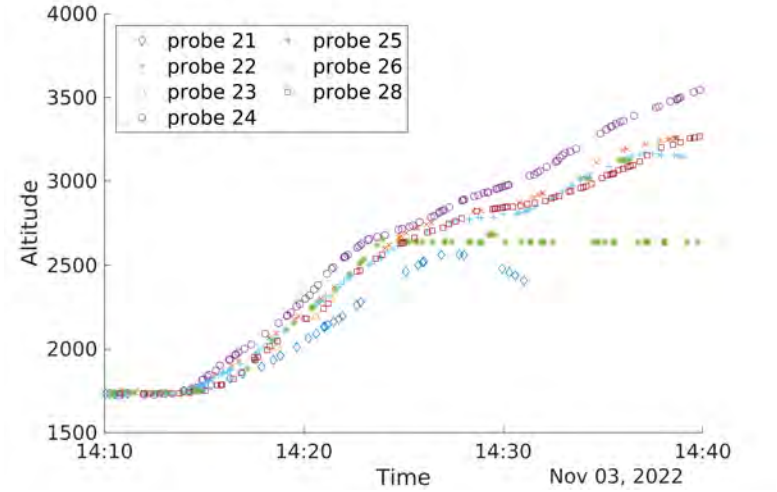
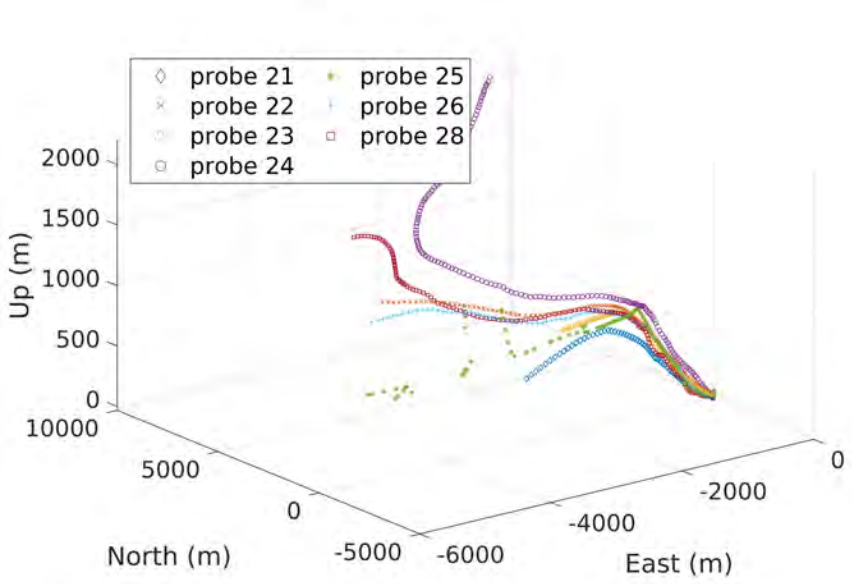
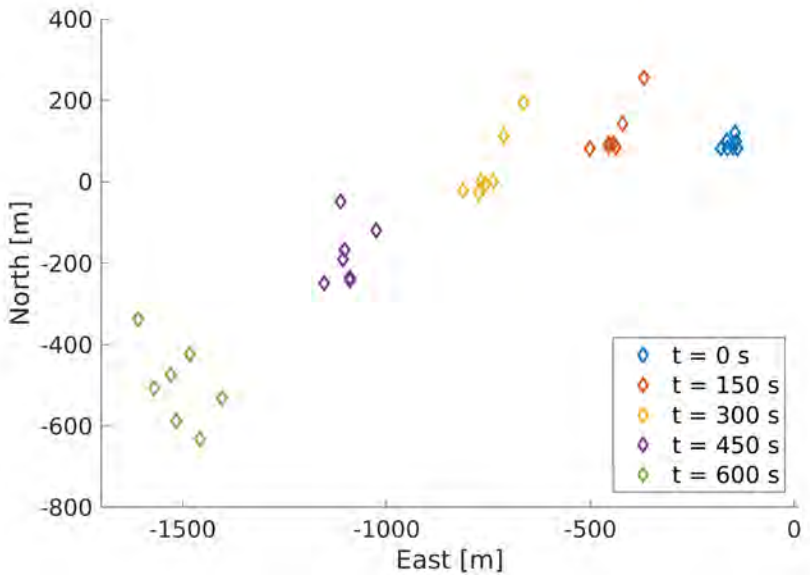


(c)

Figure 5: Raw GNSS sensor readings.

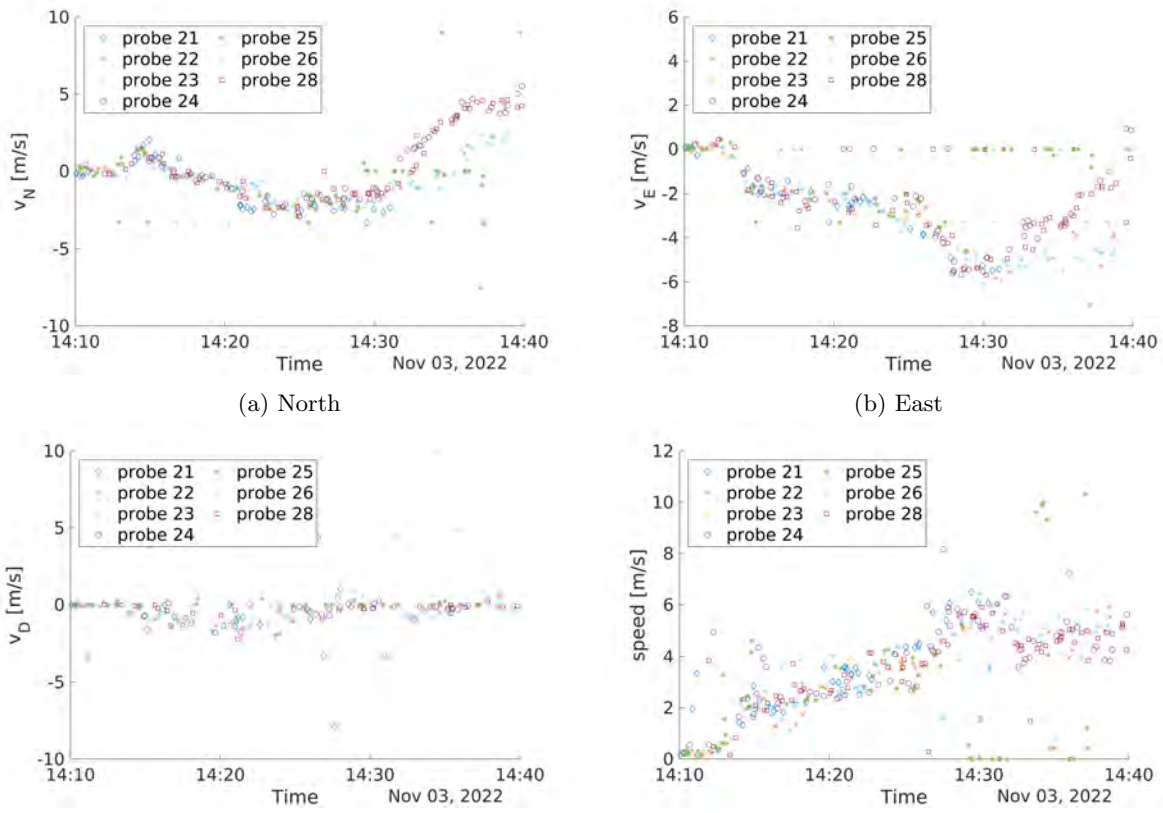


(a)



(b)

Figure 6: (a)3D trajectory of the radioprobes towards north, east and up directions starting from the reference observation point. (b) Scattering (diffusion) of radiosondes in north-east frame, different colors indicate time passed (seconds) after the launch. Reference point: latitude = 45.78994 °, longitude = 7.47764 °, altitude = 1700 meters.



(a) North

(b) East

(c) Down

(d) Magnitude

Figure 7: Raw velocity from GNSS sensor readings.

3 Experiment at the Osservatorio Astrofisico St. Barthelemy, Valle d'Aosta, Feb 10, 2022

Objective

Our intention is to test entire radiosonde system with 5 radioprobes. All radiosondes were tied to the ground with thread as in the below panel of the Figure 8.

Experiment setup

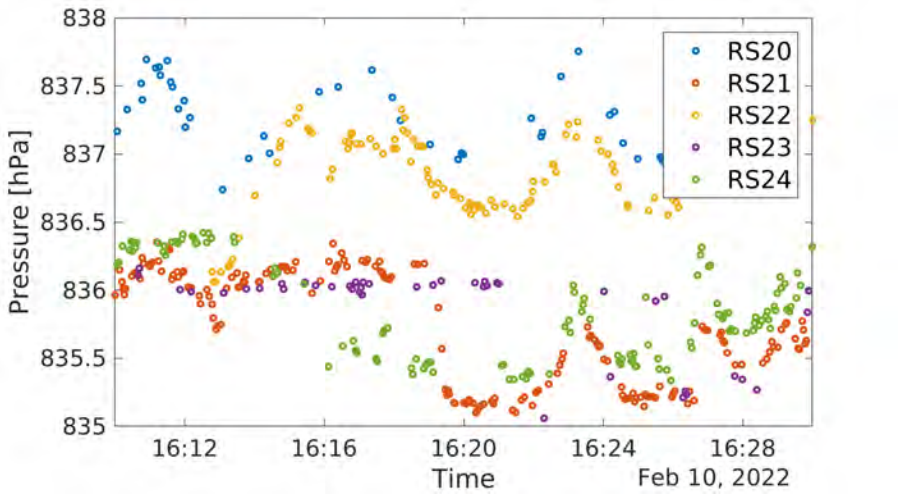
- 5 radiosondes, all balloons are filled with helium..
- 2 ground stations were ready to receive packets from all radiosondes, both receivers were connected to pc to store and analyze coming packets in real-time.
- We used 2 Sony HDV cameras to capture radiosonde movement during the experiment.

Figure 8: Experiment setup

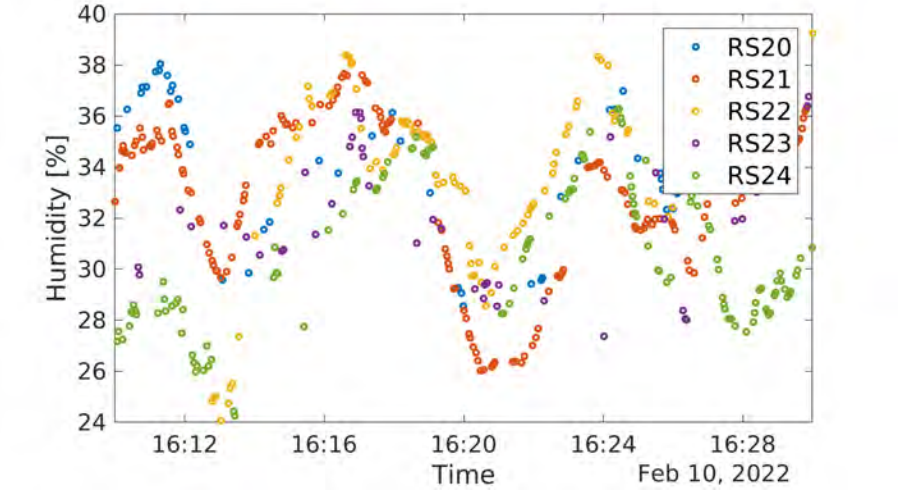
3.1 Pressure, humidity and temperature readings

3.2 IMU dataset

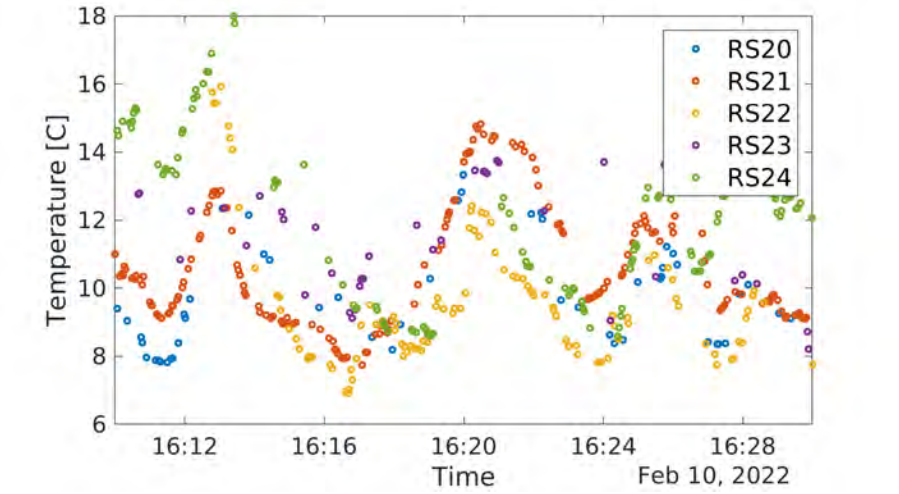
3.3 GNSS (GPS) dataset



(a)

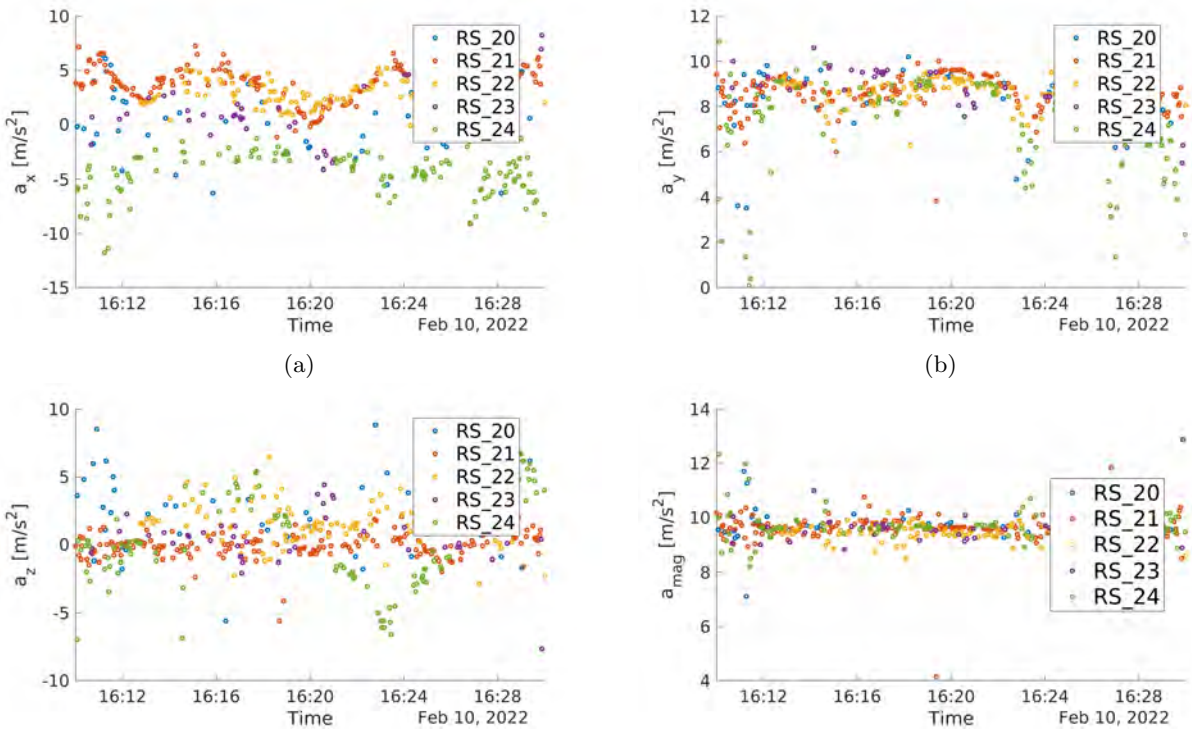


(b)



(c)

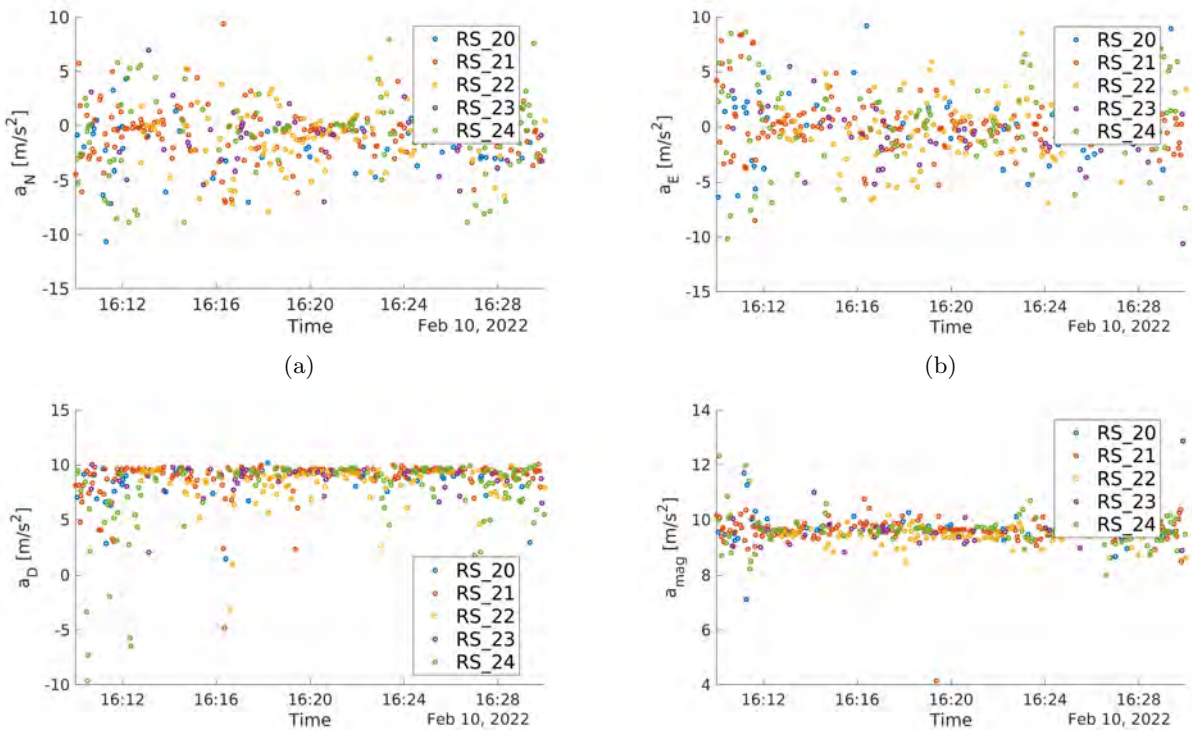
Figure 9: Pressure, humidity and temperature readings.



(a) (b)

(c) (d) Magnitude of raw acceleration readings

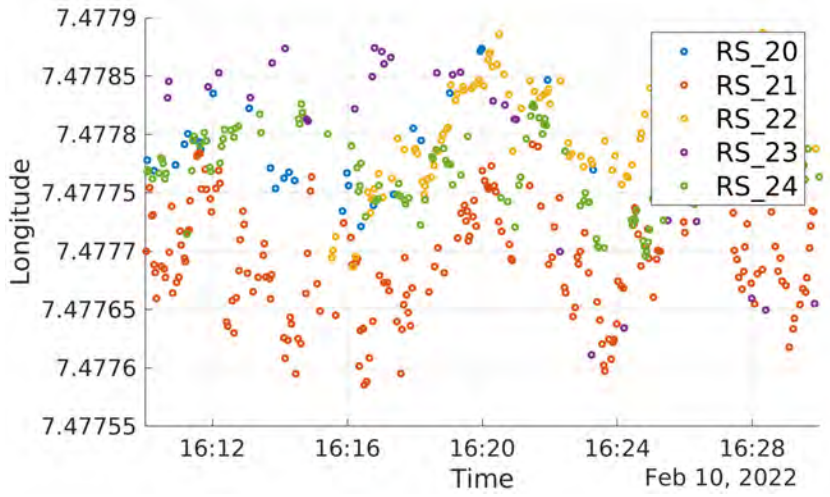
Figure 10: Raw acceleration readings in xyz body frame of the radioprobes.



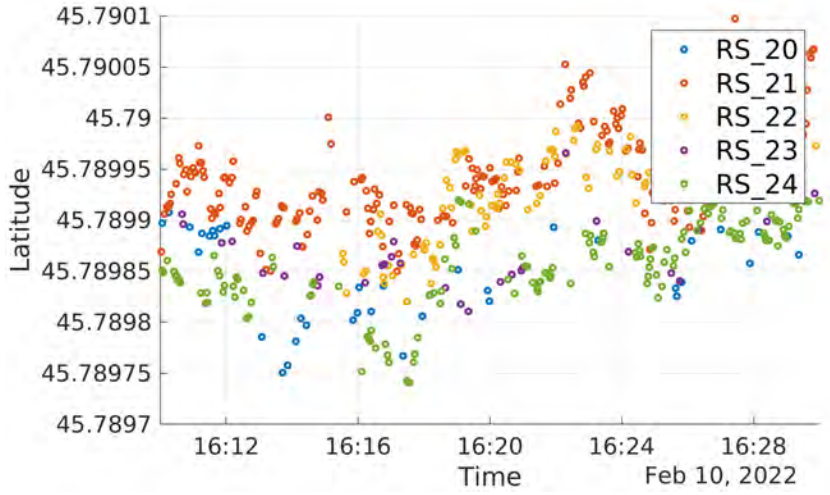
(a) (b)

(c) (d)

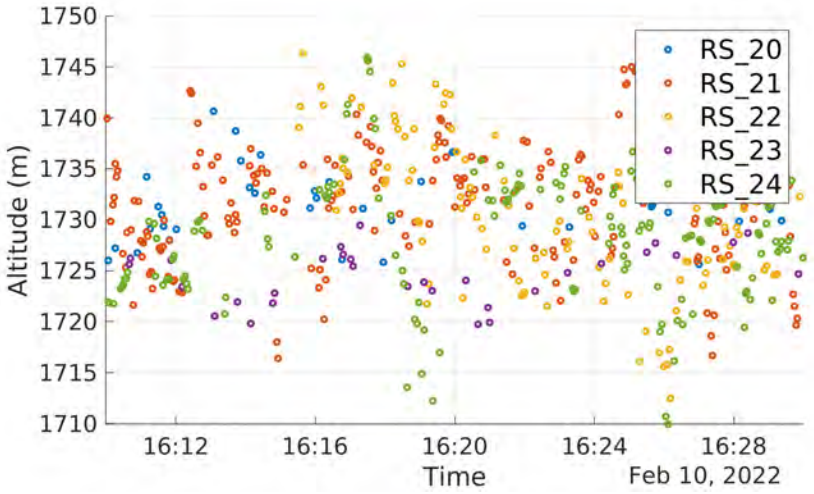
Figure 11: Raw acceleration readings in NED reference frame.



(a) Longitude

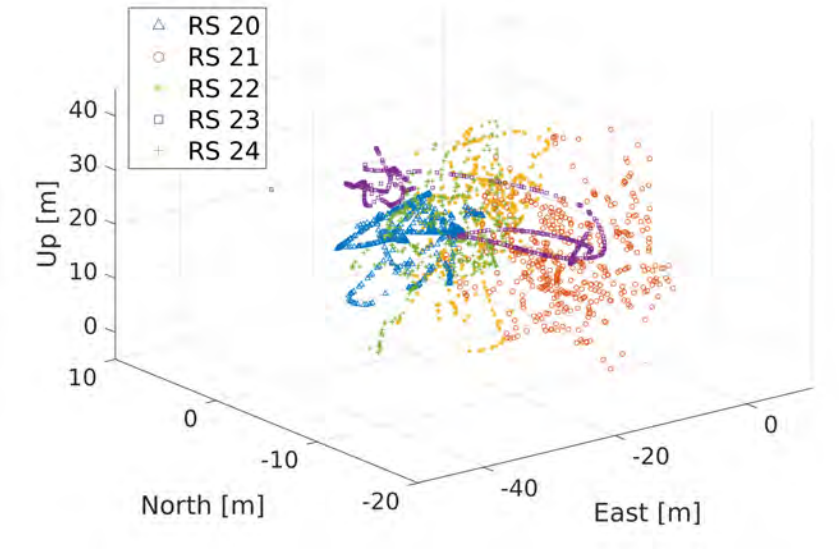


(b) Latitude

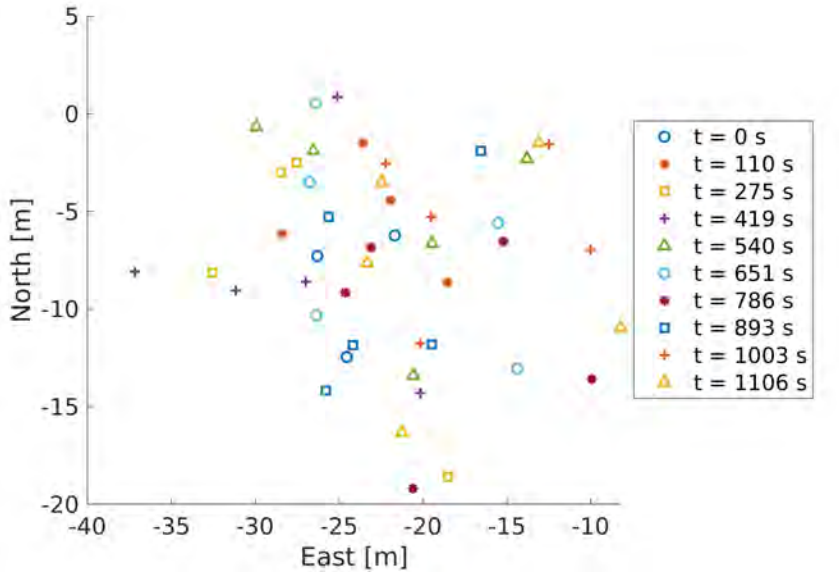


(c) Altitude

Figure 12: Raw longitude, latitude and altitude readings from GNSS sensor of all radiosondes.

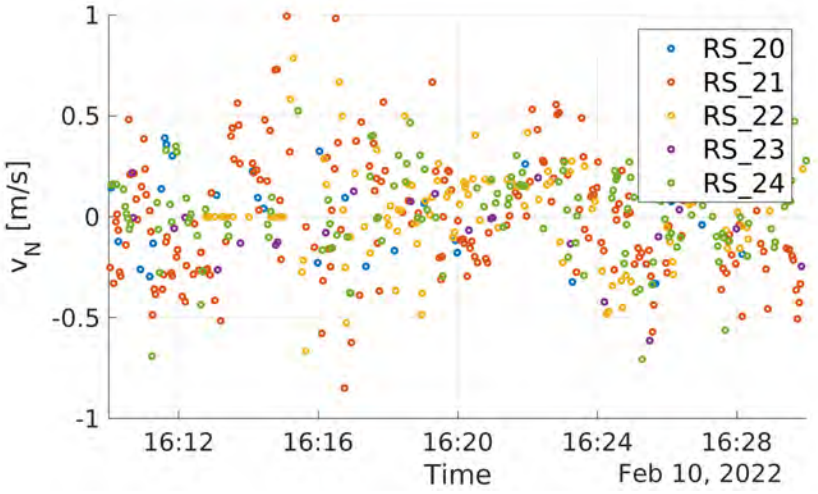


(a)

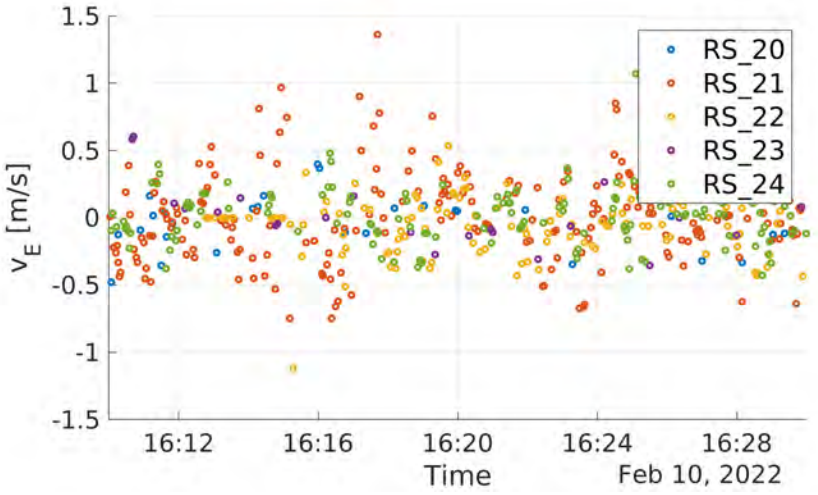


(b)

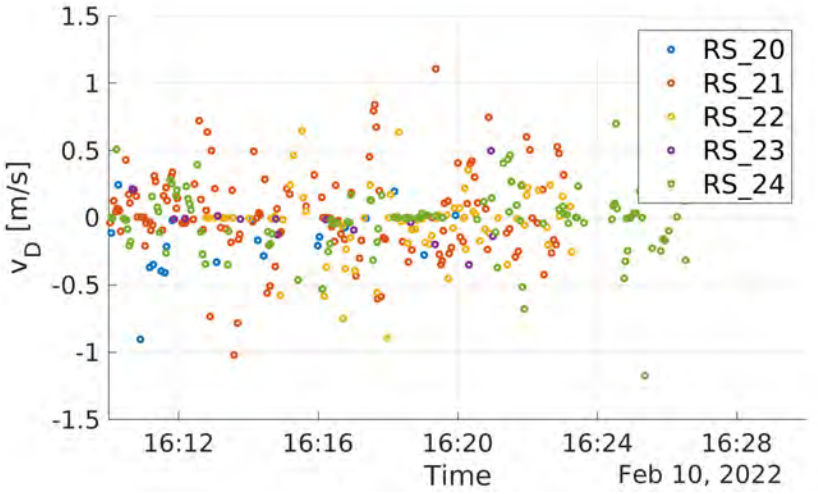
Figure 13: (a) 3D trajectory of the radioprobes towards north, east and up directions starting from the reference observation point. (b) Scattering (diffusion) of radiosondes in north-east frame. Geodetic position of one of two cameras was taken as reference observation point, which has latitude = 45.79009 °, longitude = 7.47786 °, altitude = 1700 meters.



(a) North



(b) East



(c) Down

Figure 14: Raw north, east and down velocity readings from GNSS sensor of all radiosondes.

4 Multiple balloon experiment at the INRIM, Turin, Sep 29, 2021

The experiment is held in the campus of INRiM, close to meteorological station.

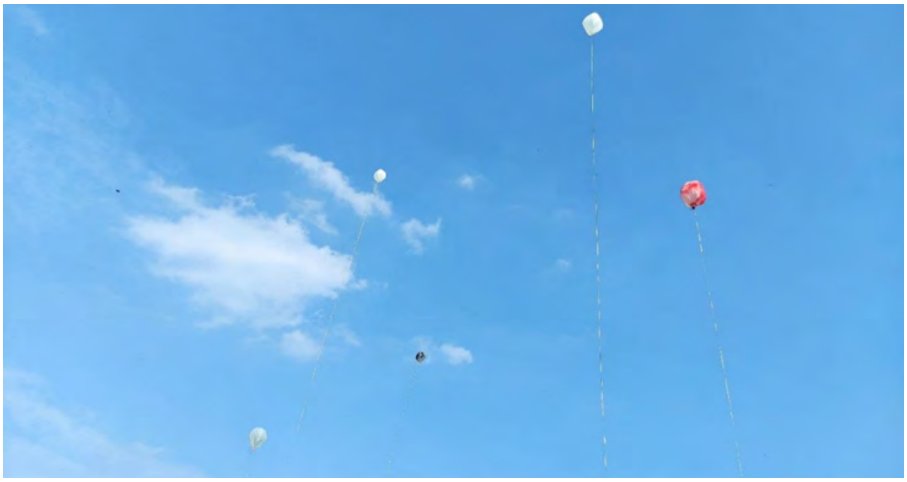
Objective

Our intention is to test entire radiosonde system: mini radioprobe, biodegradable balloon, transmission and data acquisition. We mainly focus on the testing multiple radiosondes in the same time.

Experiment setup

- 5 radiosondes, all balloons are filled with helium and tied to the ground with thread, in order not to lose them.
- 2 ground stations were ready to receive packets from all radiosondes, both receivers were connected to pc to store and analyse coming packets in real-time.
- Sony HDV camera to capture radisonde movement during the experiment.

(a)



(b)

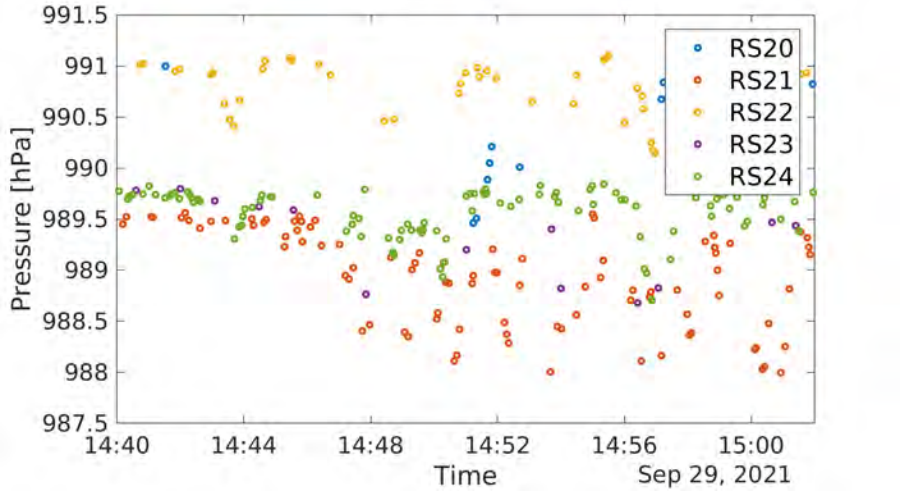
(c)

Figure 15: Experiment setup with 5 radisondes (a) and 2 ground stations. For the validation of positioing sensors we have used a camera (b).

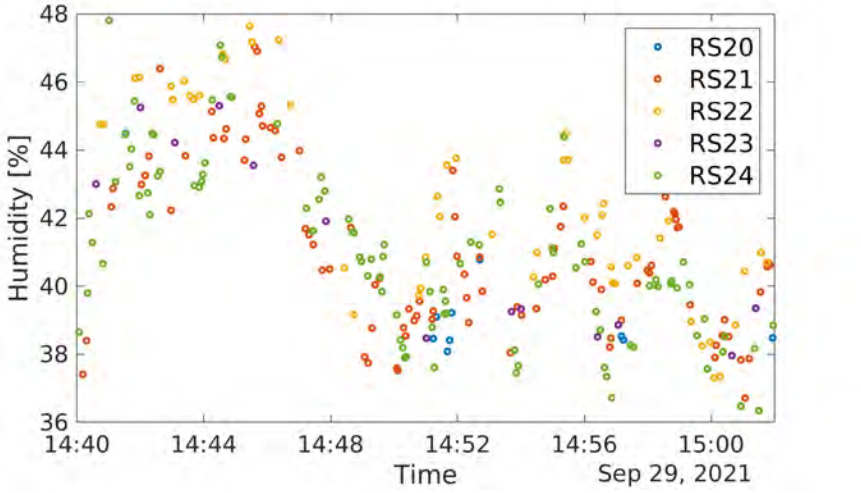
4.1 Pressure, humidity and temperature readings

4.2 IMU dataset

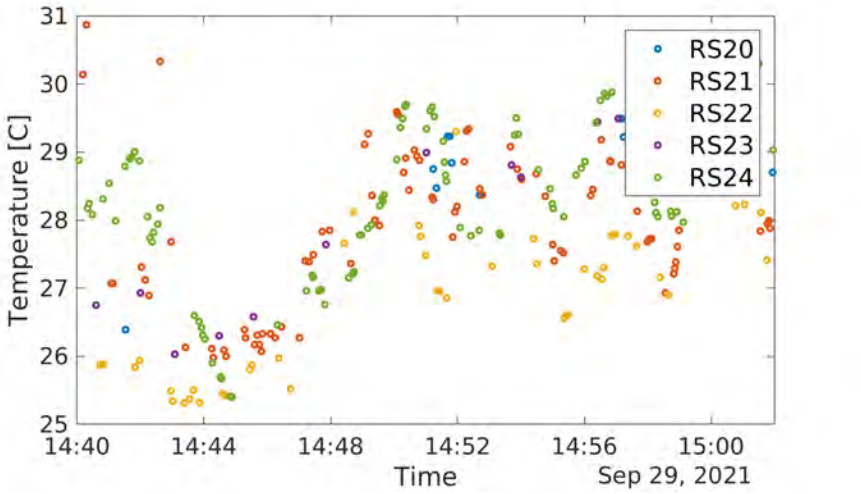
4.3 GNSS (GPS) dataset



(a)



(b)



(c)

Figure 16: Pressure, humidity and temperature readings.

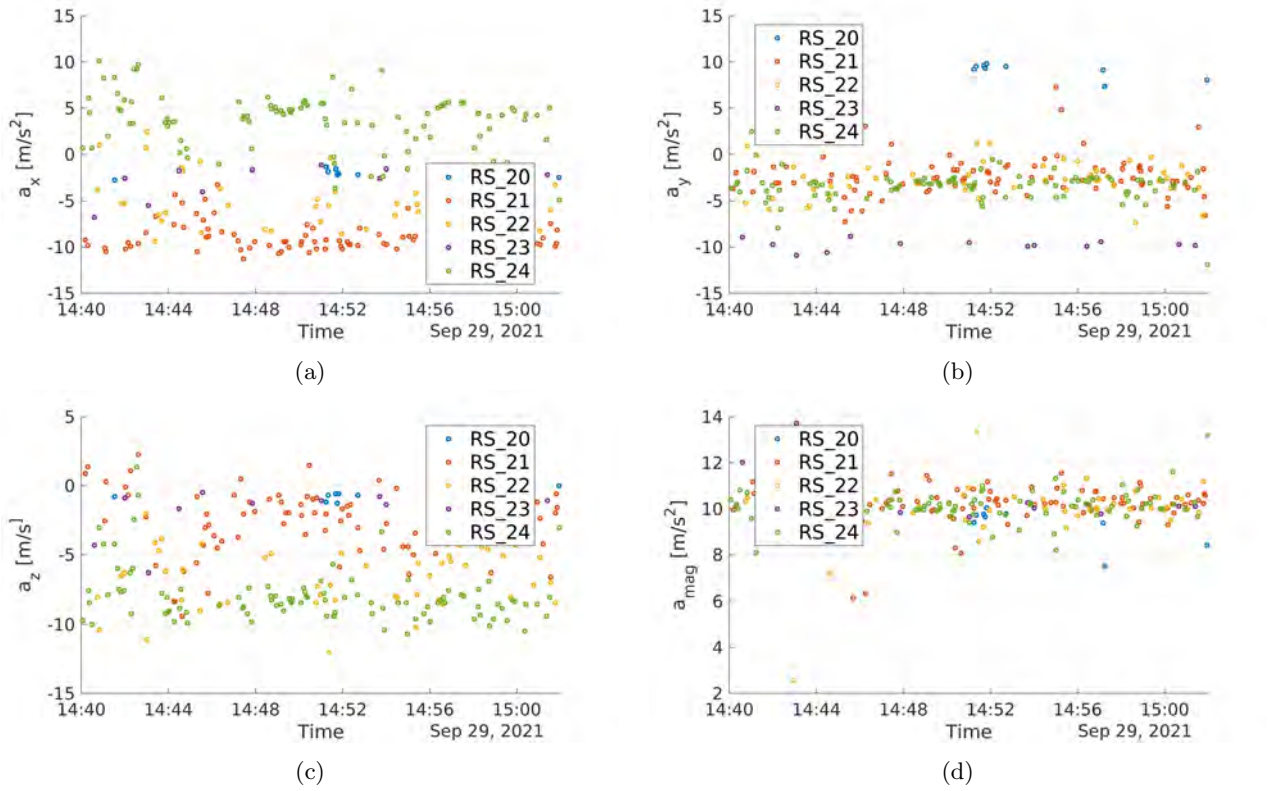


Figure 17: Raw acceleration readings in **xyz** body frame of the radioprobes.

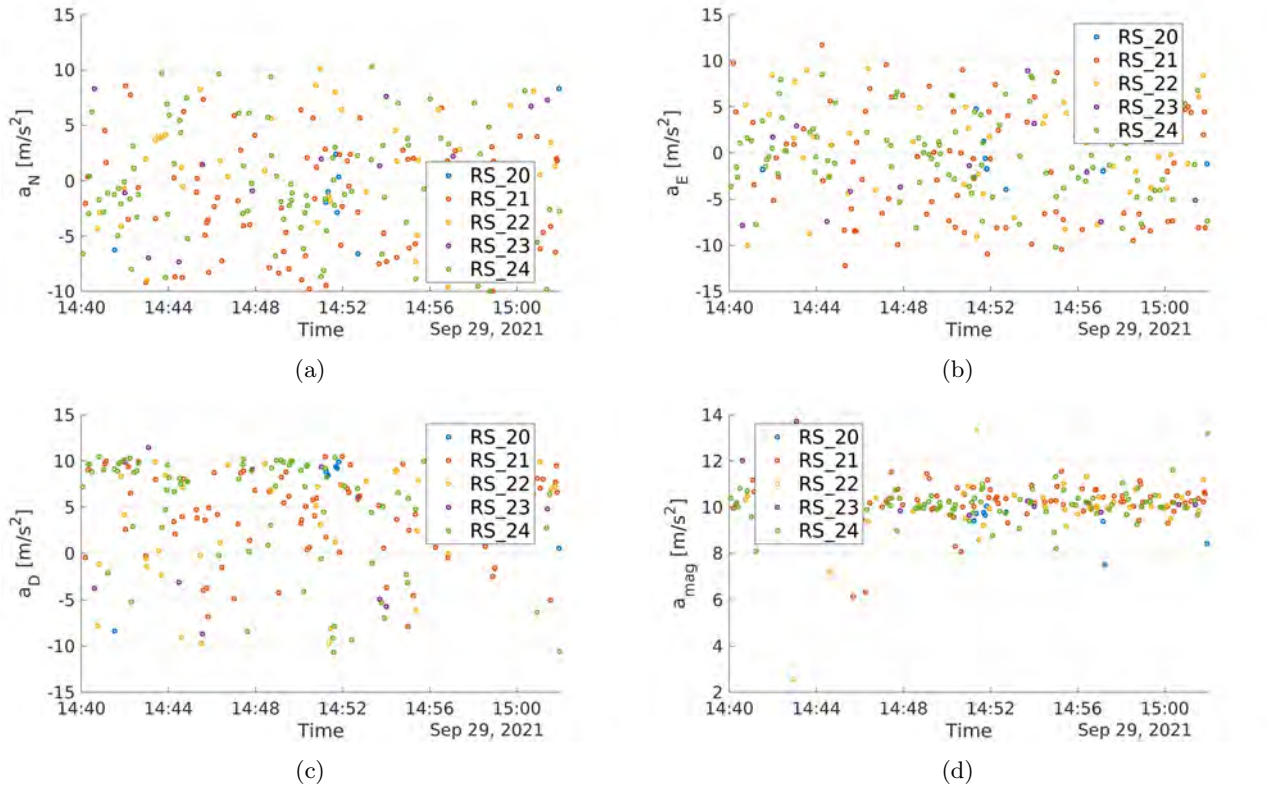
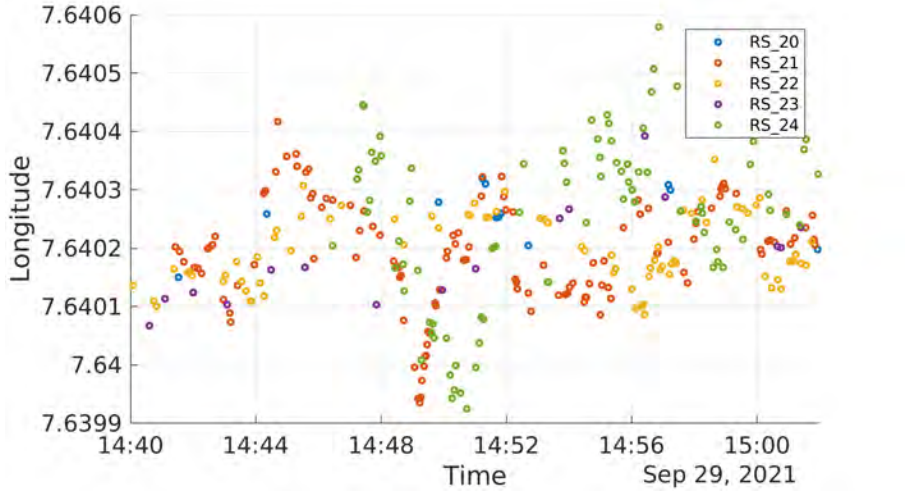
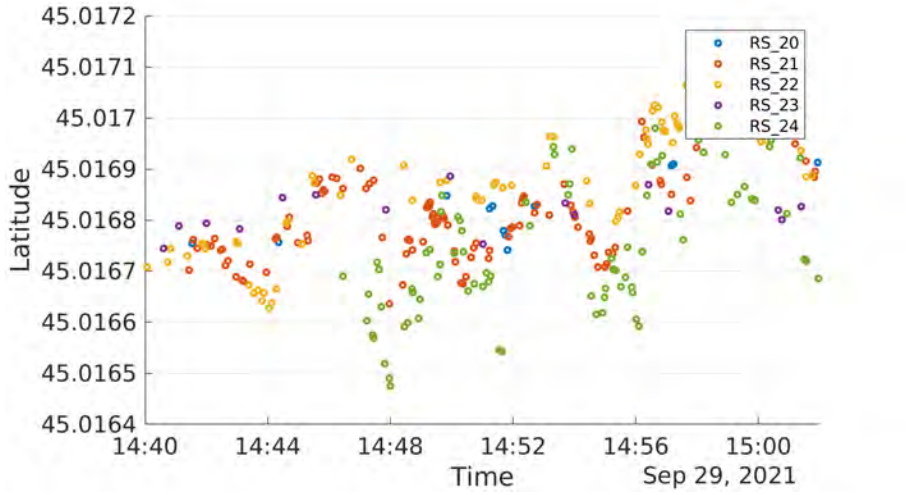


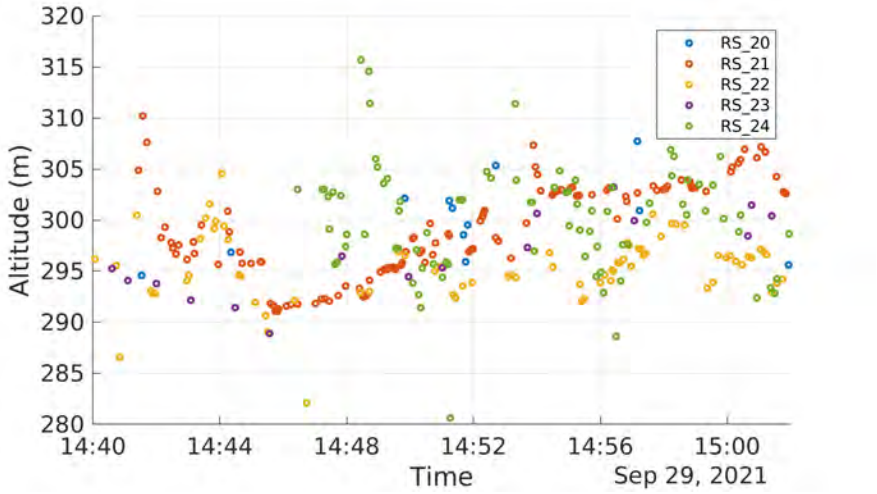
Figure 18: Raw acceleration readings in **NED** reference frame.



(a) Longitude

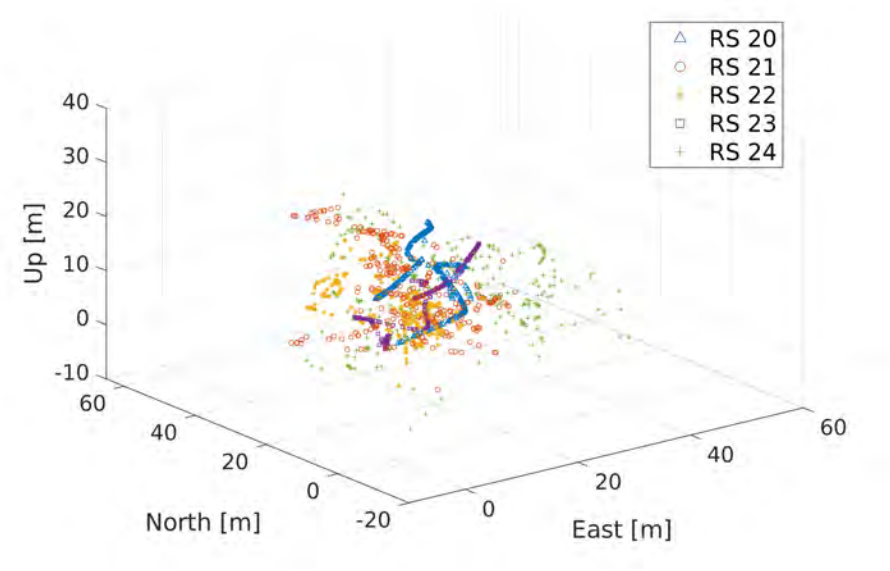


(b) Latitude

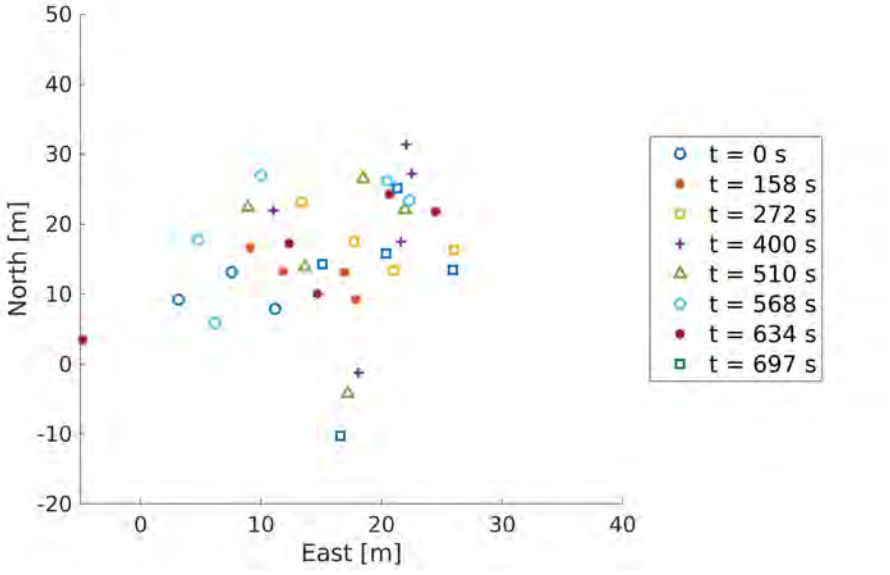


(c) Altitude

Figure 19: Raw longitude, latitude and altitude readings from GNSS sensor of all radiosondes.

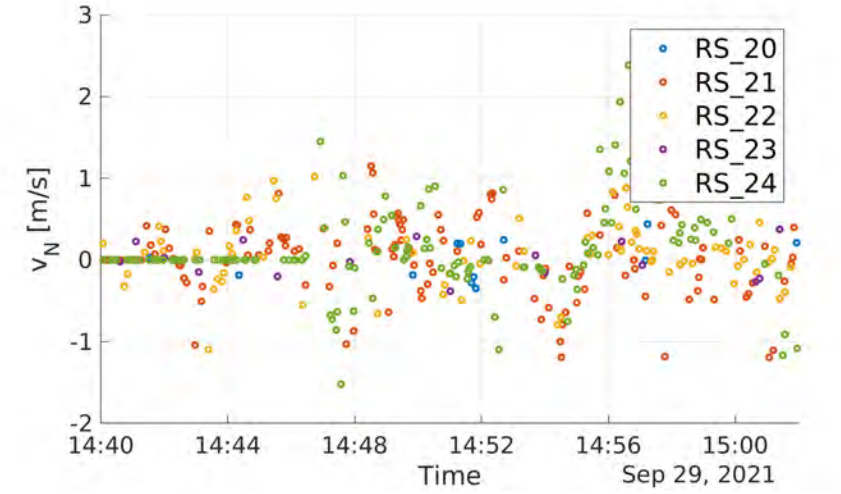


(a)

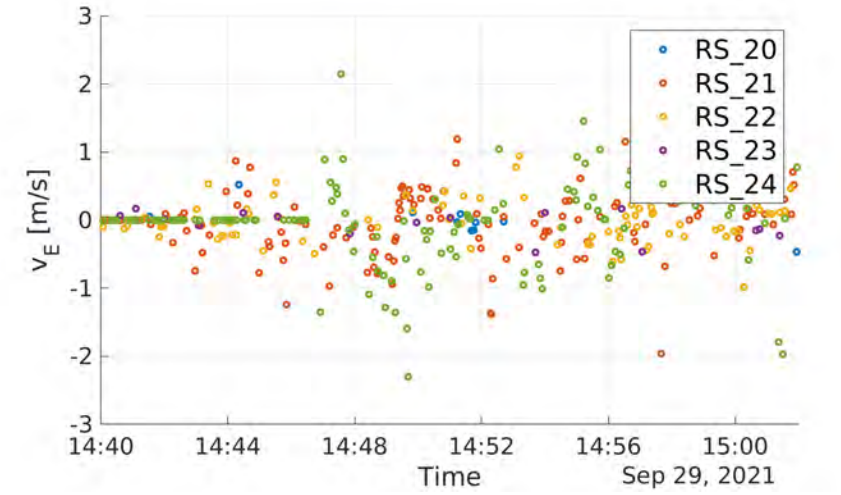


(b)

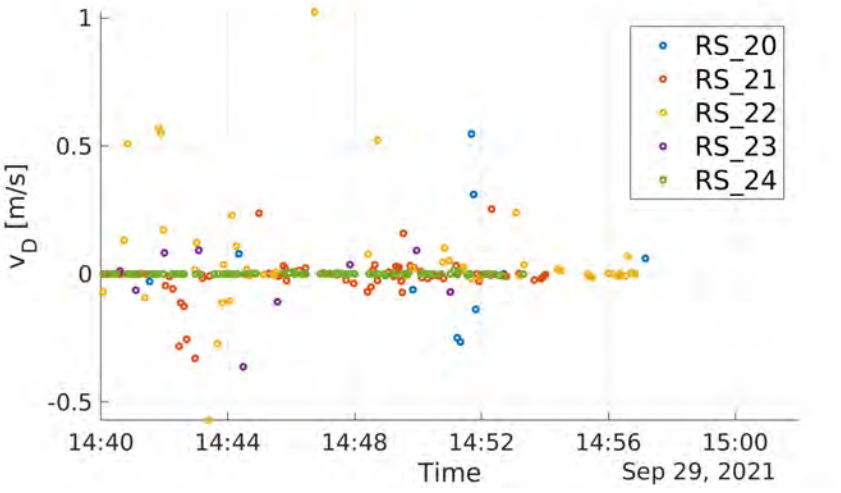
Figure 20: (a) 3D trajectory of the radioprobes towards north, east and up directions starting from the reference observation point. (b) Scattering (diffusion) of radiosondes in north-east frame. Reference point: latitude = 45.016637 °, longitude = 7.639994 °, altitude = 240 meters.



(a) North



(b) East



(c) Down

Figure 21: Raw north, east and down velocity readings from GNSS sensor of all radiosondes.

5 Configuration testing experiment at the INRIM, Turin, July 20, 2021

Objective

Our intention is to test entire radiosonde system: mini radioprobe, biodegradable balloon, transmission and data acquisition. Moreover, we focused on to study the effect of balloon enclosure to pressure, humidity and temperature measurements.

Experiment setup

In order to reach to above objective, we used to radiosondes:

- Radiosonde 1 (RS1): radioprobe board is inside the balloon, put in the pocket made by the same material as balloon (mater-Bi) (id=24)
- Radiosonde 2 (RS2): radioprobe board is outside the balloon, hangs on via thread and thread is attached to the ballon (id=20)
- To guarantee stability and precision in fluctuations reproduction a new version of balloons has been adopted which is more spherical than the previous and with the PCB placed as much as possible close to the gravity center of the balloon to avoid unwanted oscillations.

Timeline

The following table describes the timeline of the events during the experiment.

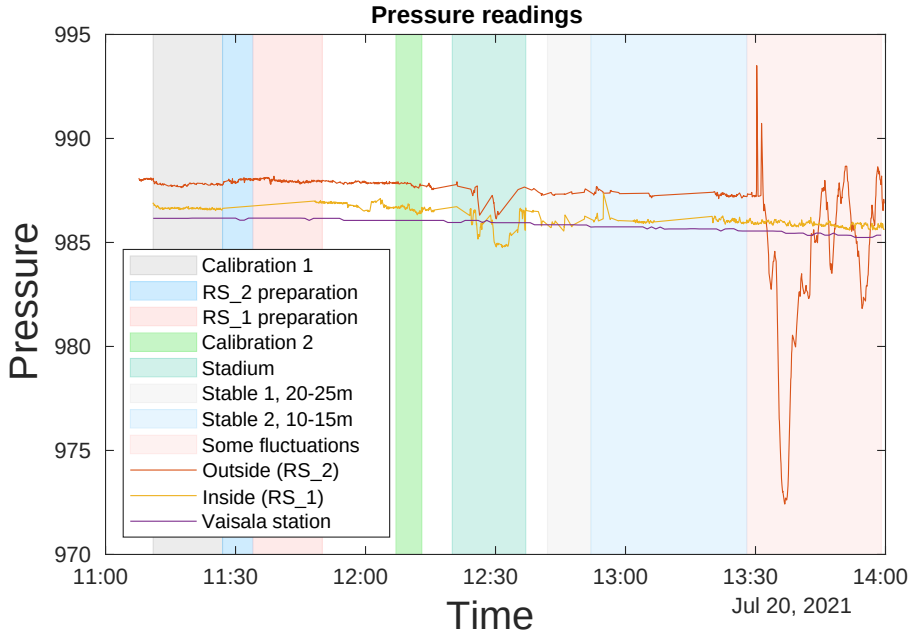
Time	**Comments**
11:12	Start, calibration step.
11:34	Setup of RS2 is completed.
11:50	Setup of RS1 is completed, two balloons are ready.
12.10 – 12.16	Measurements near to meteorological station. Low altitude, radiosondes are close to each other, less fluctuations.
12.21 – 12.37	Measurements in the stadium, receiver station is near to meteorological station. Different altitudes (upto 10 meters), some fluctuations. Packet losses, especially for setup RS2.
12.42 – 12.51	Measurements near to meteorological station. Low altitude, radiosondes are 20-25 meters from each other, less fluctuations.
12.51	Measurements near to meteorological station. Low altitude, radiosondes are 10-15 meters from each other, some fluctuations.
13.41	Measurements near to meteorological station. Low altitude, under shadow, close to each other (2m), some fluctuations.
13.55	Measurements near to meteorological station. Low altitude, under sun, distance (10m), some fluctuations.
15.10	Measurements near to meteorological station. Low altitude, under sun, attached together.
15.13	Finished.

Table 1: Experiment timeline.

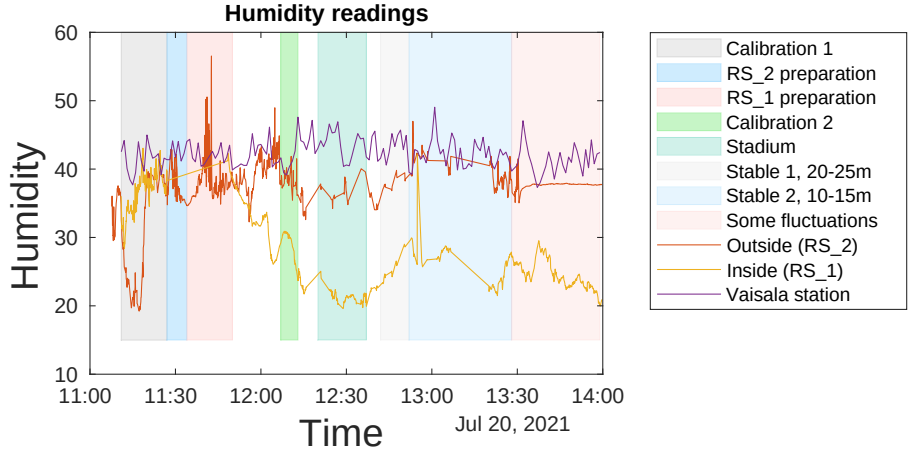
5.1 Pressure, humidity and temperature readings

5.2 IMU dataset

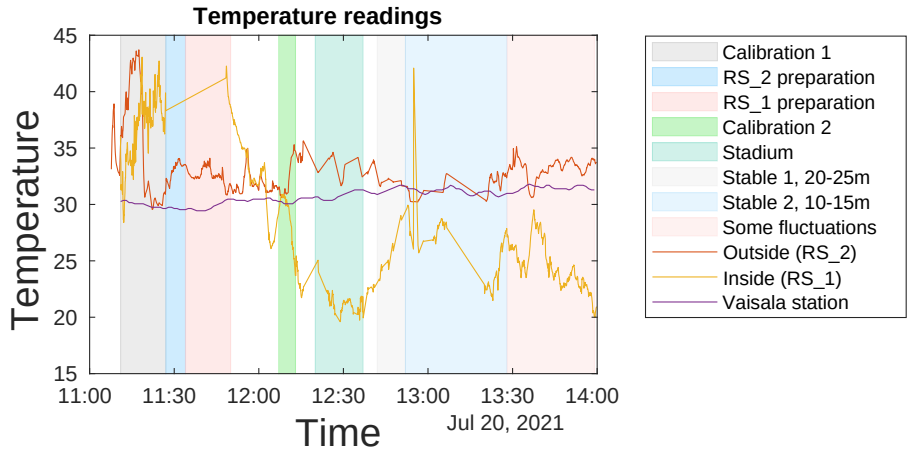
5.3 GNSS (GPS) dataset



(a)

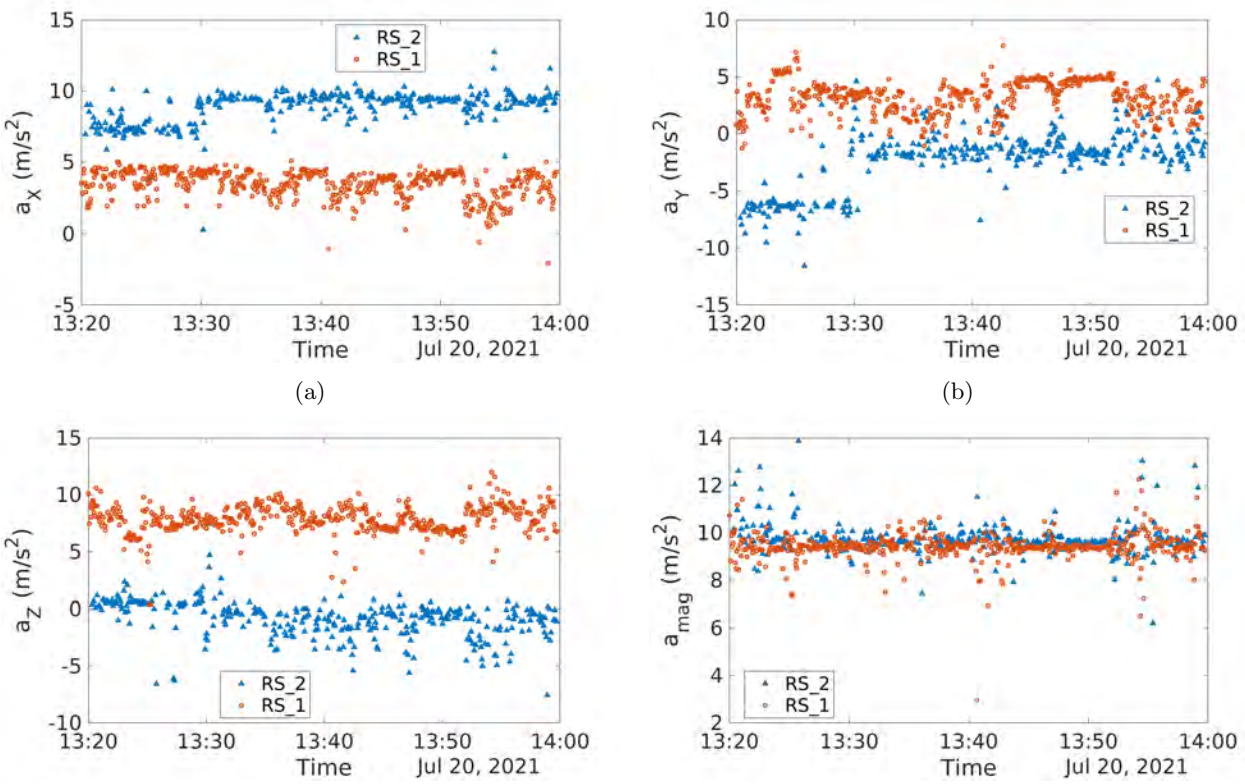


(b)



(c)

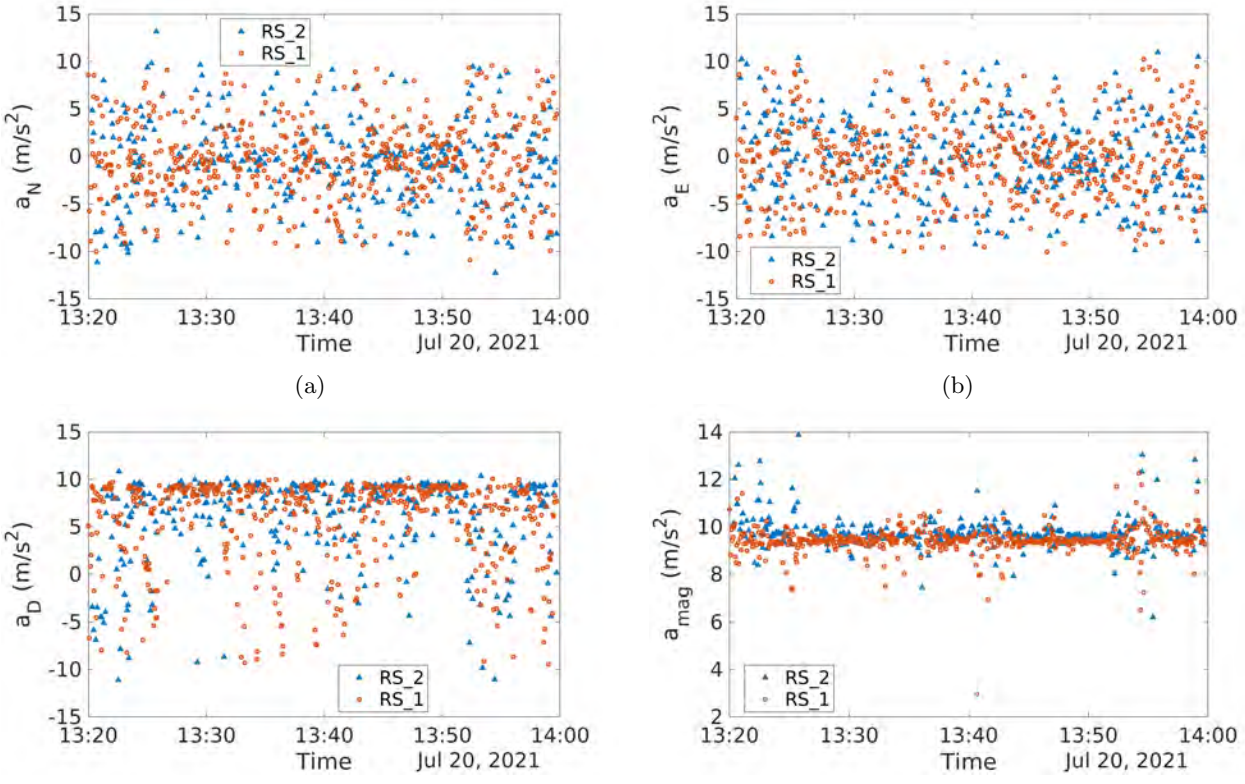
Figure 22: Pressure, humidity and temperature readings and experiment timeline.



(a) (b)

(c) (d) Acceleration magnitude

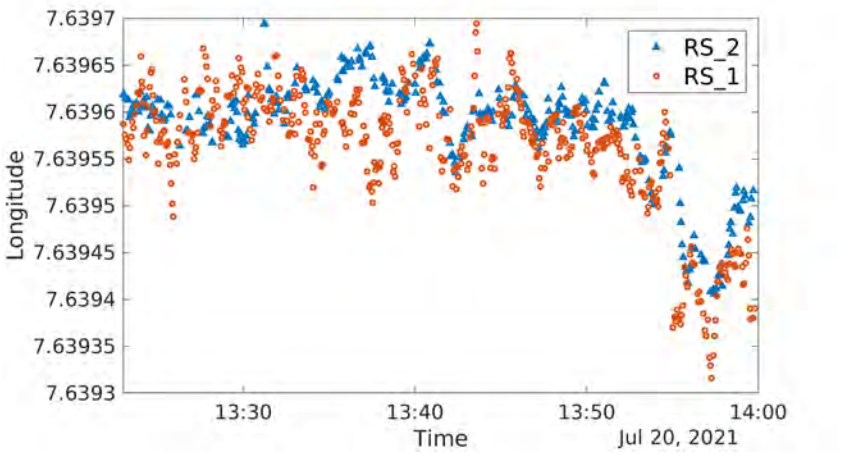
Figure 23: Raw acceleration readings in xyz body frame of the radioprobes.



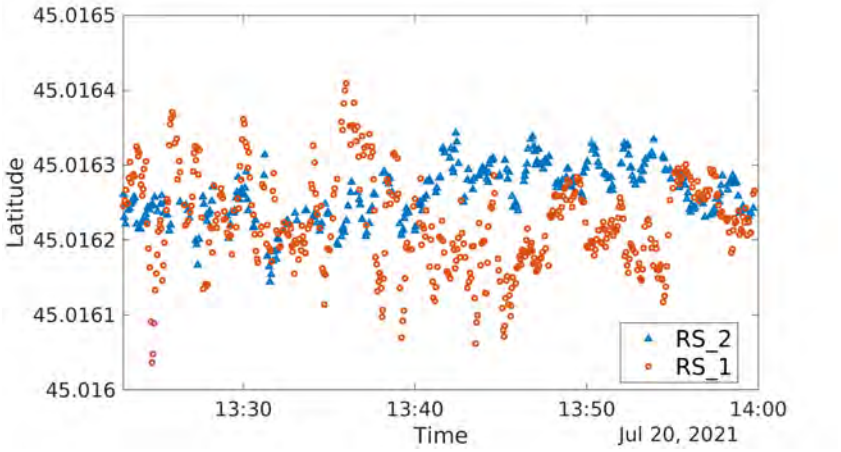
(a) (b)

(c) (d) Acceleration magnitude

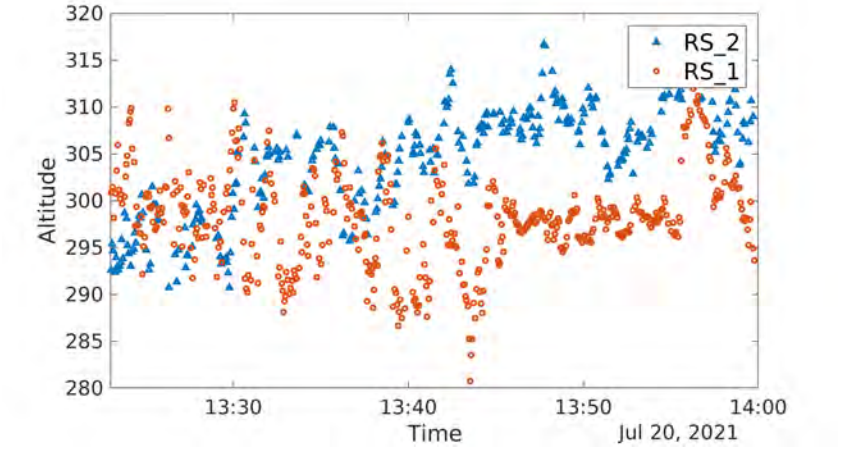
Figure 24: Raw acceleration readings in NED reference frame.



(a) Longitude

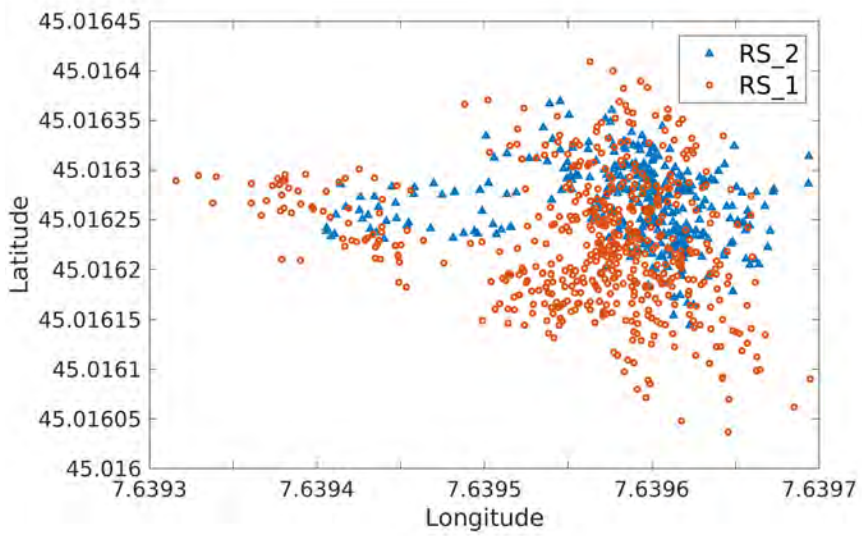


(b) Latitude

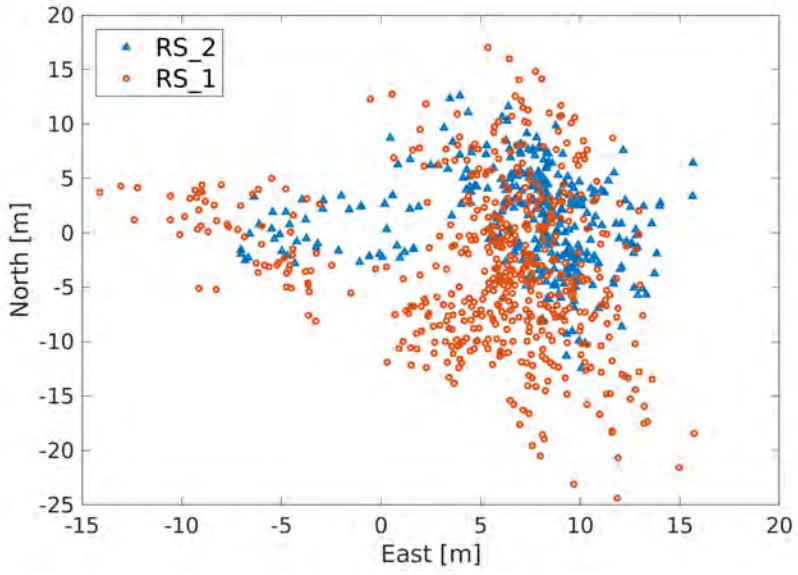


(c) Altitude

Figure 25: Raw longitude, latitude and altitude readings from GNSS sensor from both radiosondes.

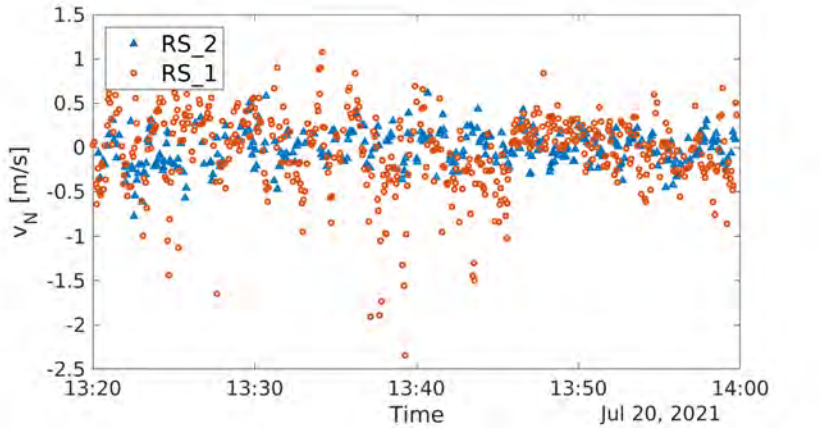


(a)

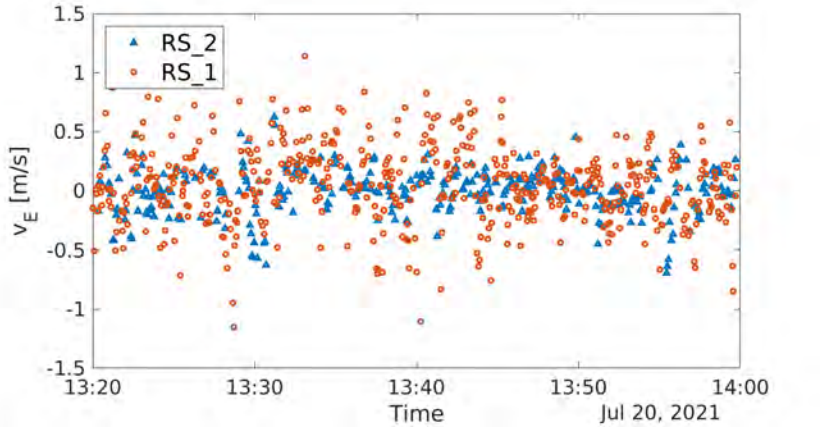


(b)

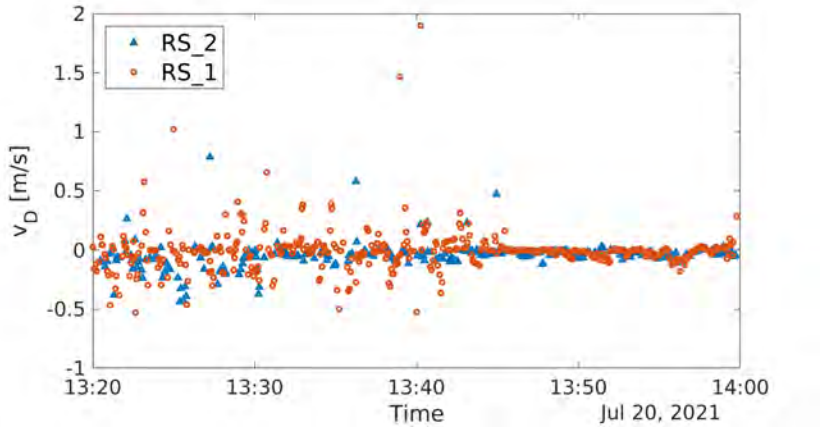
Figure 26: 2D trajectory of the radioprobe in (a) longitude-latitude and (b) north-east axis.



(a) North



(b) East



(c) Down

Figure 27: Raw north, east and down velocity readings from GNSS sensorof both radioprobes.

6 2nd Dual launch at Levaldigi airport in collaboration with ARPA (Piemonte), Cuneo, June 9, 2021

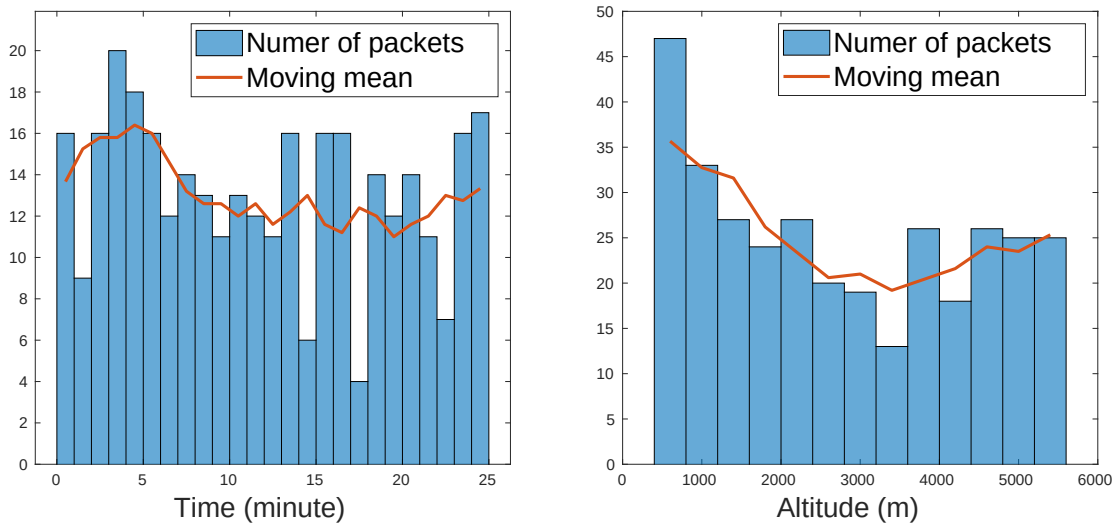
The experiment was held in the Levaldigi Airport, Cuneo. ARPA, Piemonte has automatic balloon launching station inside airport.

Objective

Our intention is to test transmission distance and data quality from the single radiosonde and the receiver station.

Experiment setup

- A single radiosonde attached to the Vaisala probe.
- A single ground station were ready to receive packets. The receiver station were connected to pc to store and analyse coming packets in real-time.



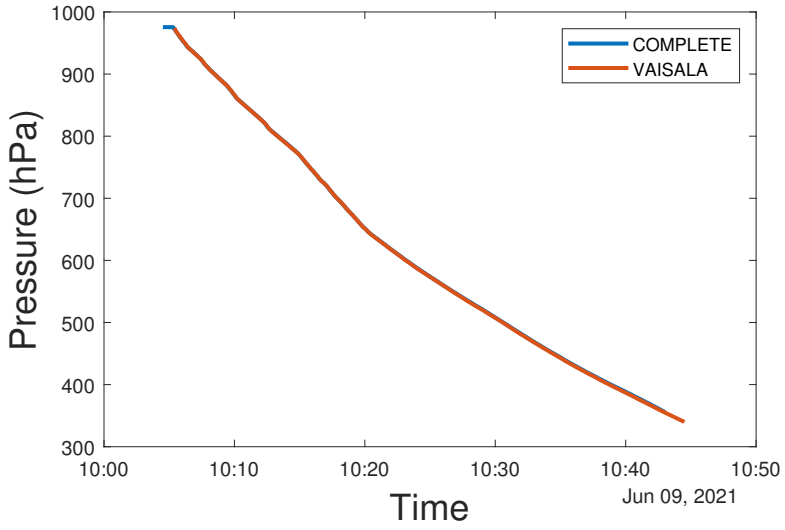
(a) (b)

Figure 28: Number of packets received during the experiment timeline.

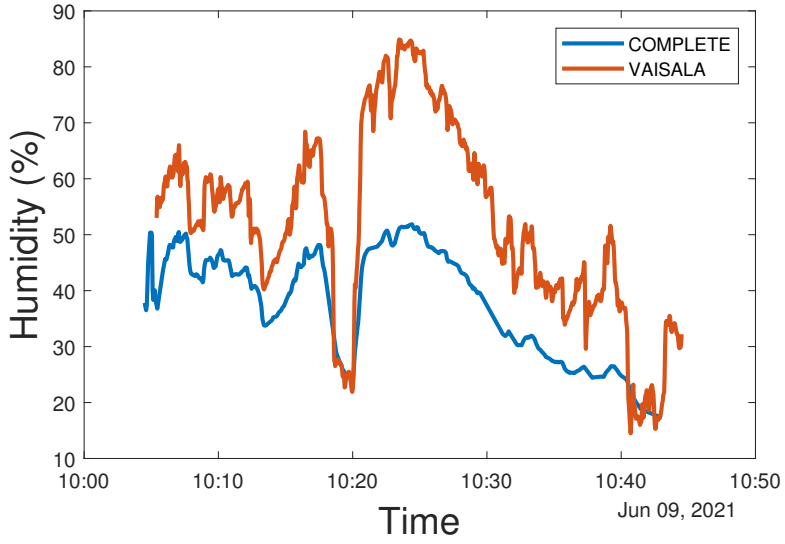
6.1 Pressure, humidity and temperature readings

6.2 IMU dataset

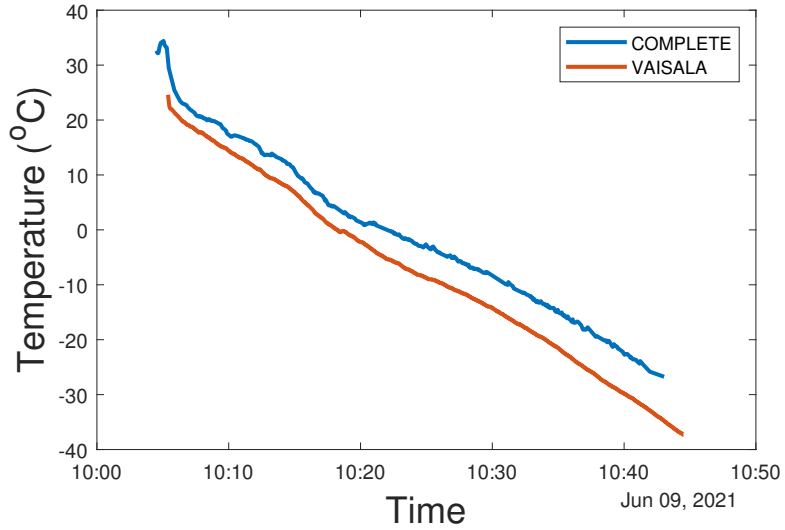
6.3 GNSS (GPS) dataset



(a)

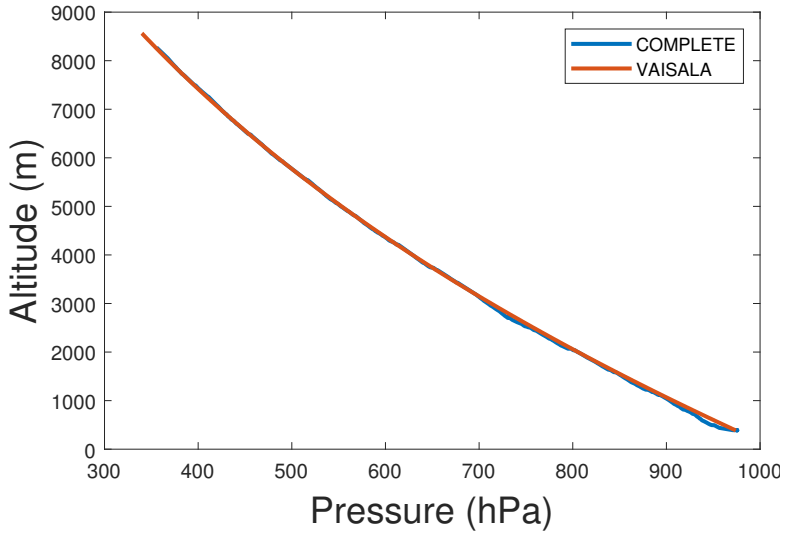


(b)

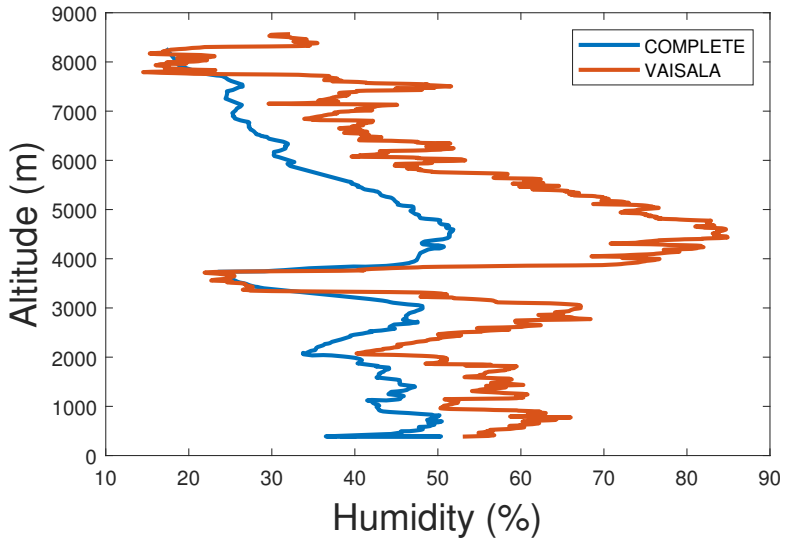


(c)

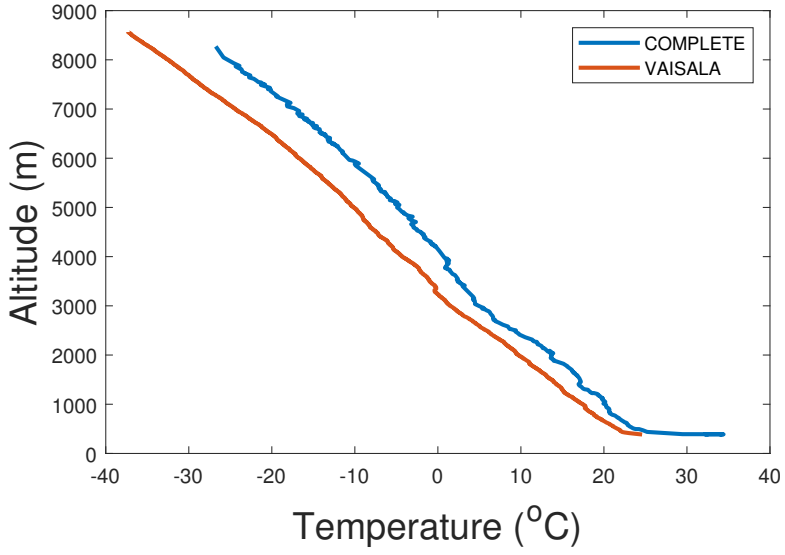
Figure 29: Pressure, humidity and temperature readings with respect to time.



(a)

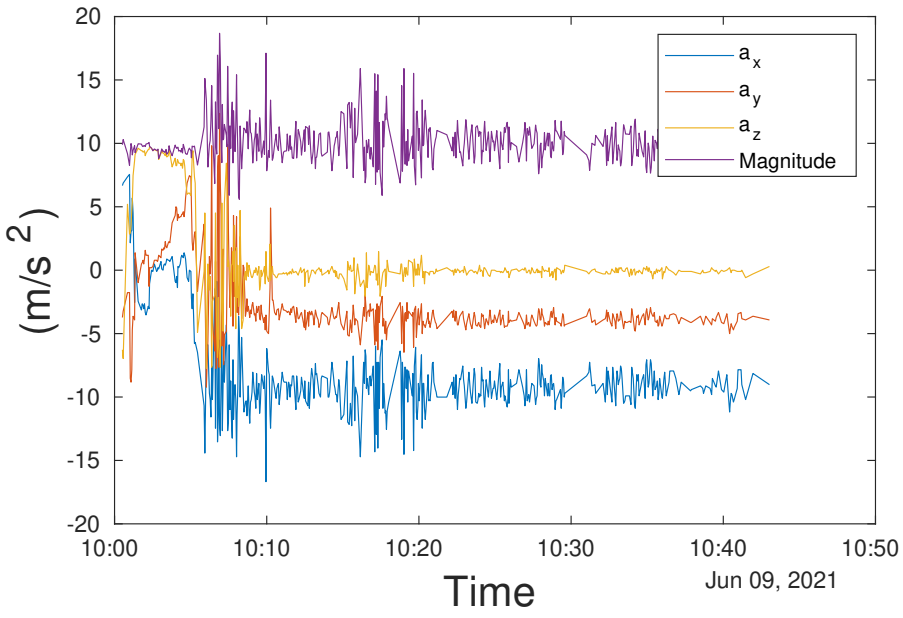


(b)

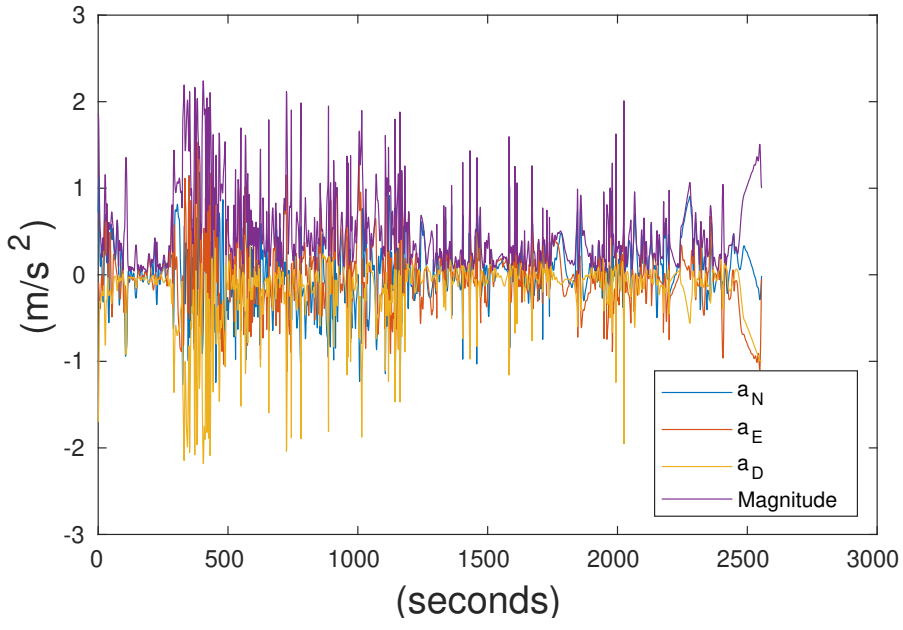


(c)

Figure 30: Pressure, humidity and temperature readings with respect to altitude.

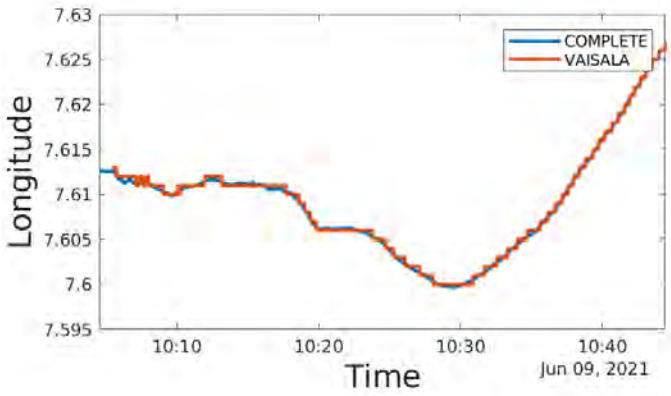


(a)

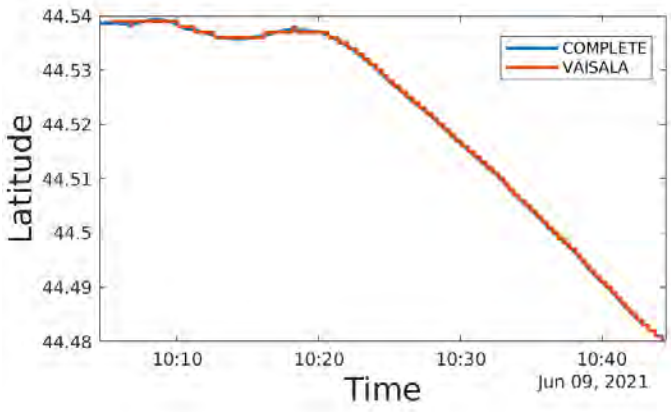


(b)

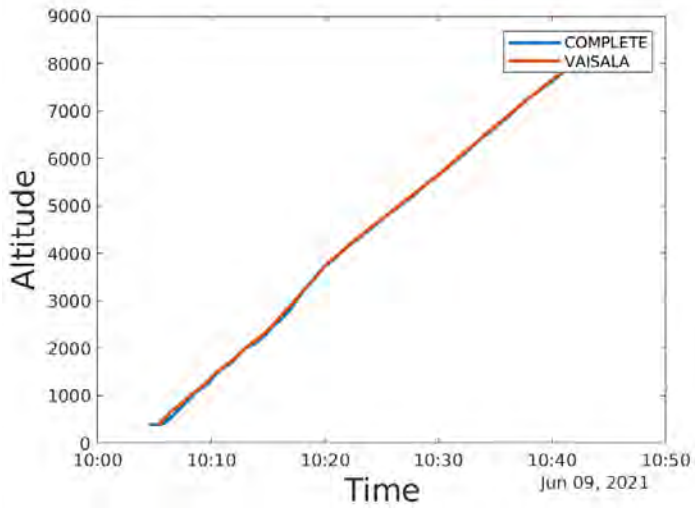
Figure 31: Raw acceleration readings in xyz body frame and NED reference frame of the radioprobe.



(a) Longitude

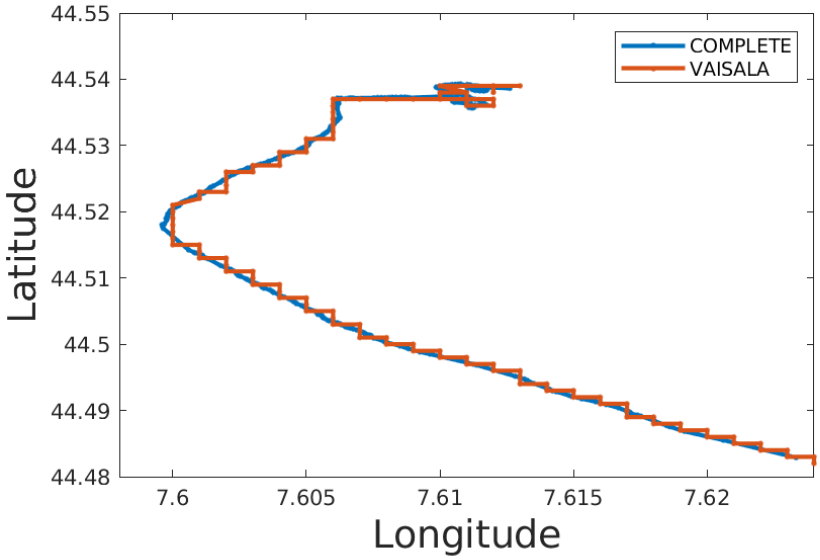


(b) Latitude



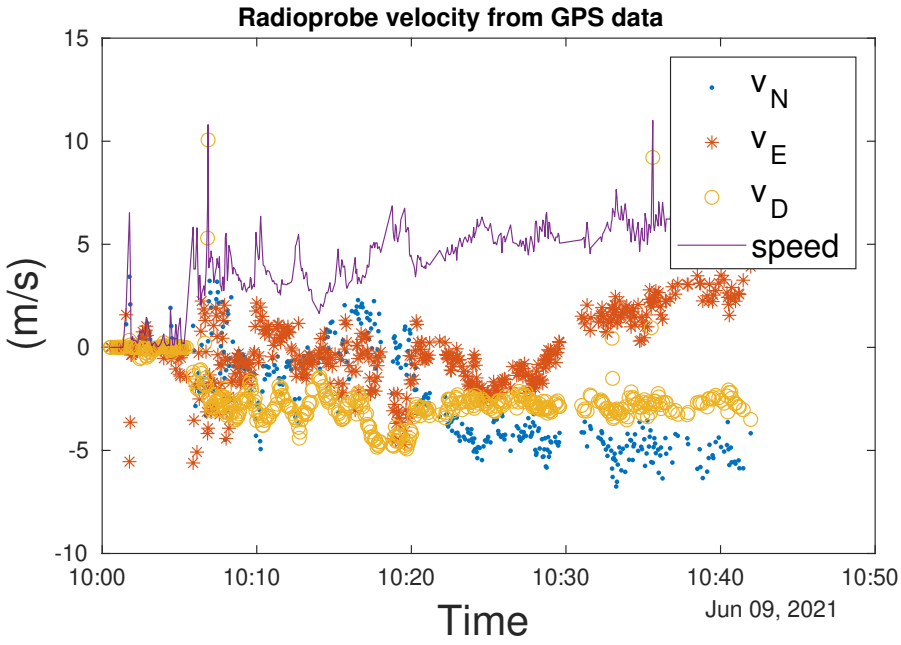
(c) Altitude

Figure 32: Raw longitude, latitude and altitude readings from GNSS sensor and comparison with Vaisala probe of ARPA.

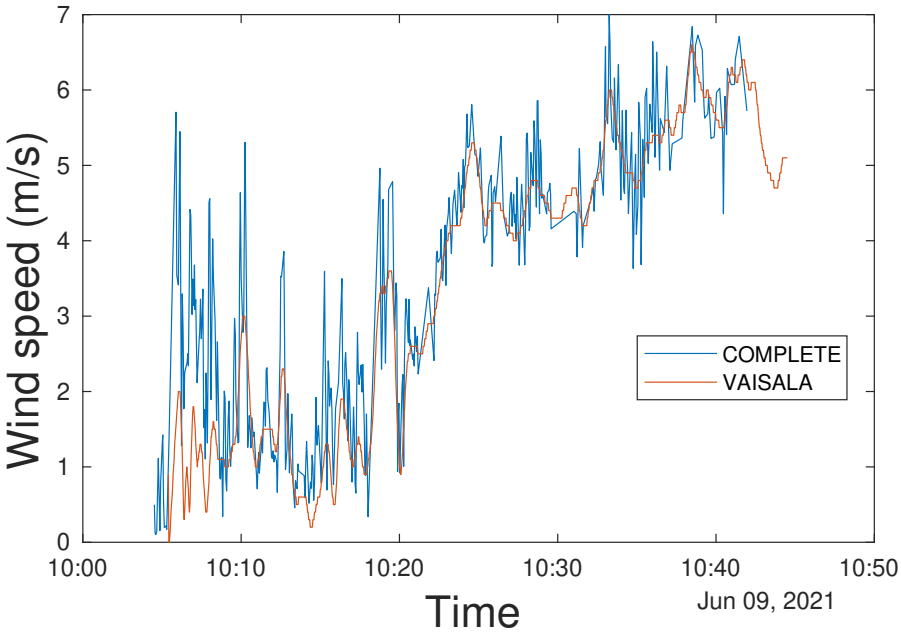


(a)

Figure 33: 2D trajectory of the radioprobe in longitude and latitude axis.



(a) Velocity components and magnitude



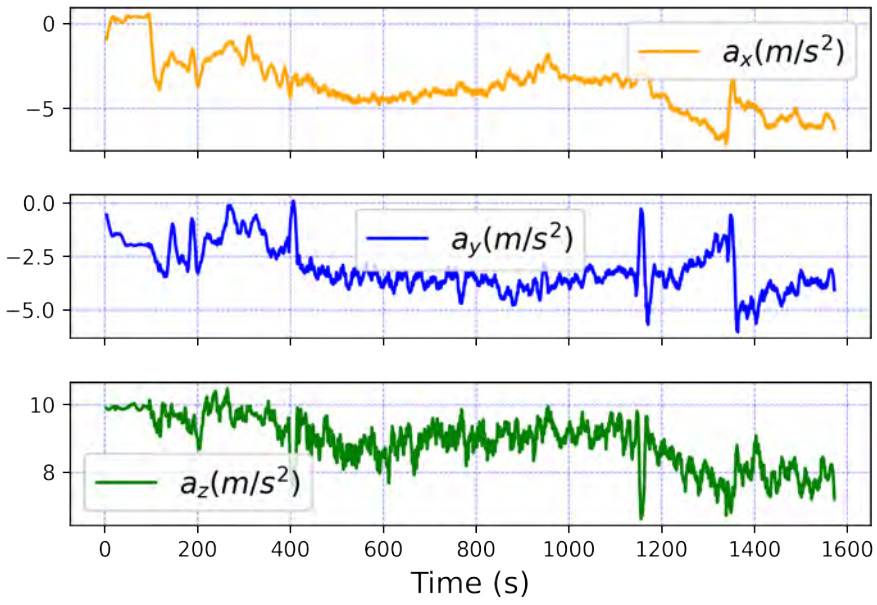
(b) Horizontal wind speed comparison

Figure 34: Raw north, east and down velocity readings from GNSS sensor and wind speed comparison with Vaisala probe of ARPA.

7 Positioning experiment with phone at Piazza d'Armi, Torino, Nov 26, 2020

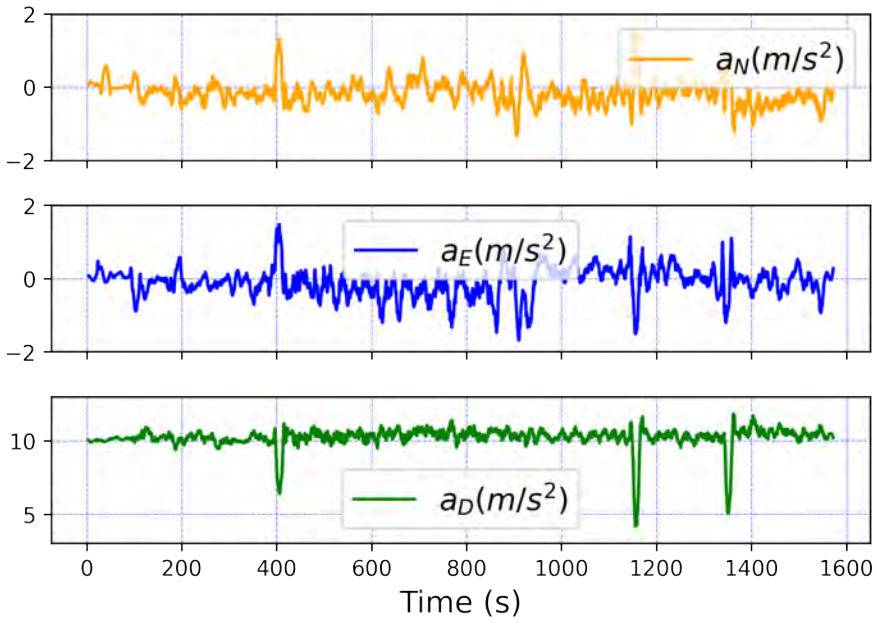
The experiment was held to validate positioning sensor readings with respect to phone position dataset. In this experiment, pressure, humidity and temperature readings were not measured.

7.1 IMU dataset



(a)

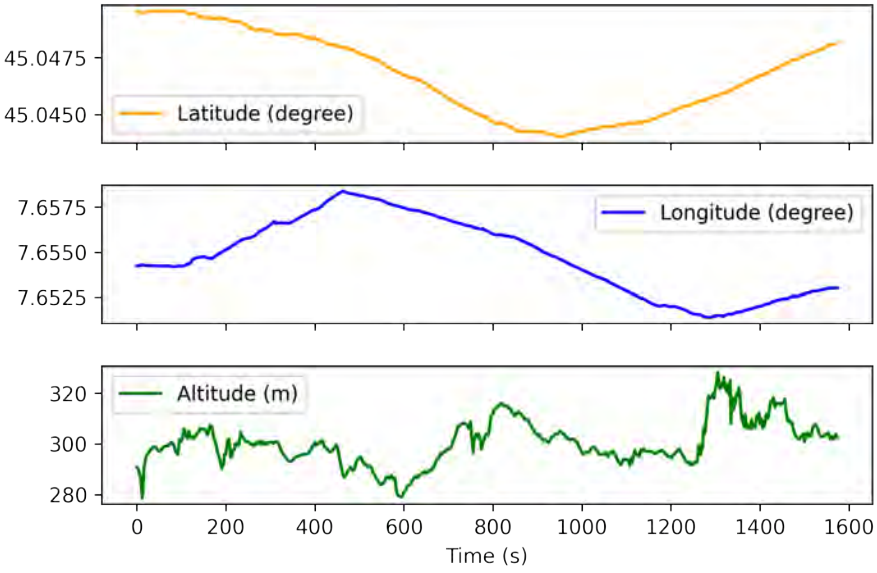
Figure 35: Raw acceleration readings in xyz body frame of the radioprobe during launch period.



(a)

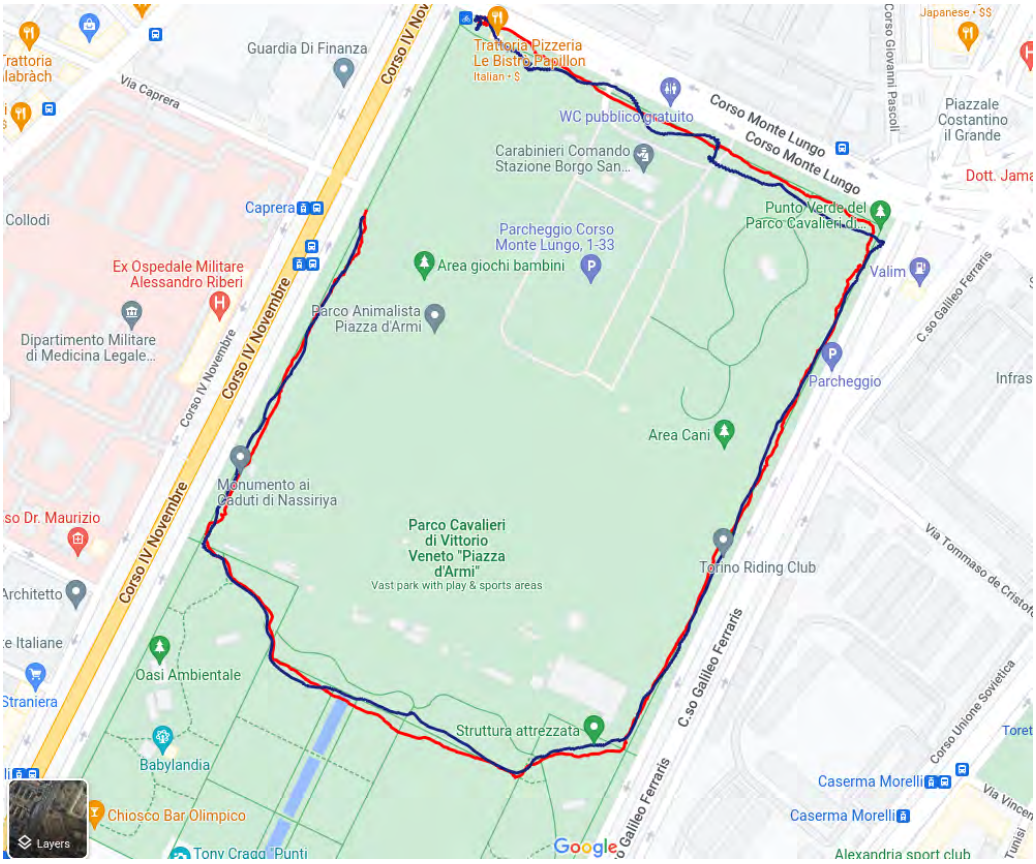
Figure 36: Raw acceleration readings in NED reference frame of the radioprobe during the experiment.

7.2 GNSS dataset



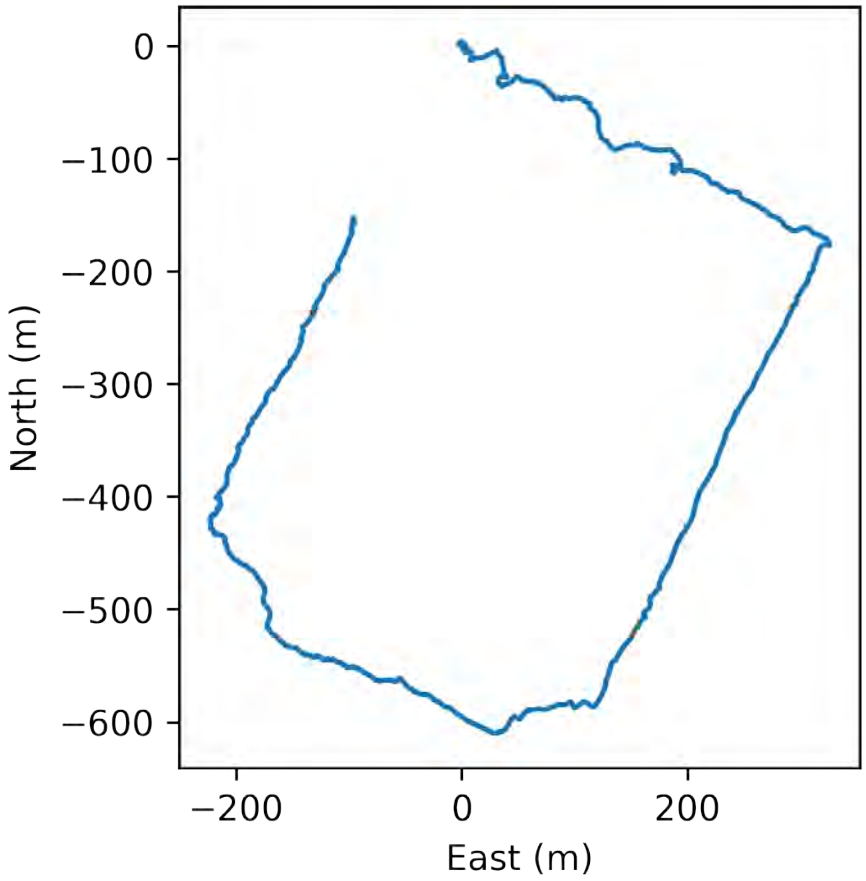
(a)

Figure 37: Raw longitude, latitude and altitude coordinates of the radioprobe during the experiment.



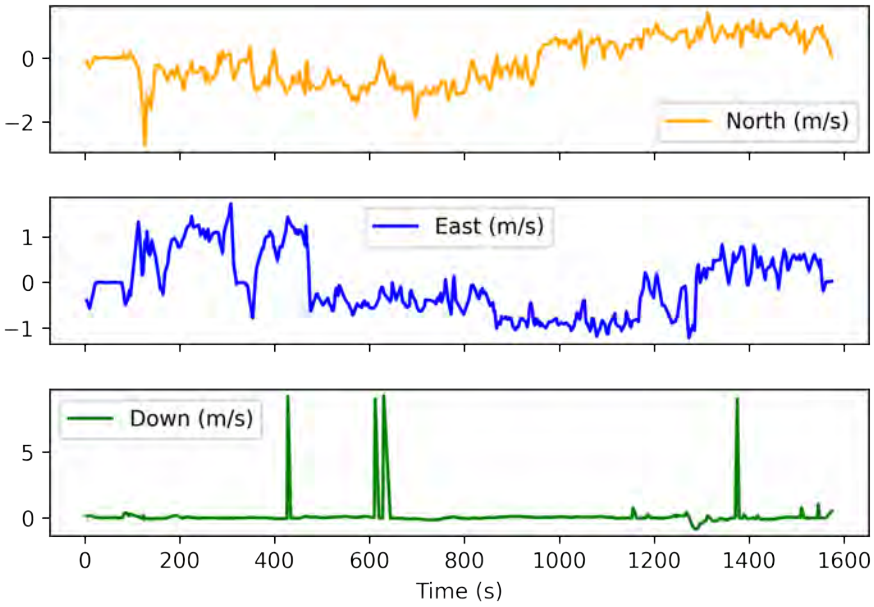
(a)

Figure 38: Comparison of phone and radioprobe positions in google maps. Dark blue line represents radiosonde trajectory, while red line represents trajectory of the phone, which is the reference for our experiment.



(a)

Figure 39: North, east position coordinates of the radioprobe during the experiment.



(a)

Figure 40: North, east and down velocity readings of the radioprobe during the experiment .

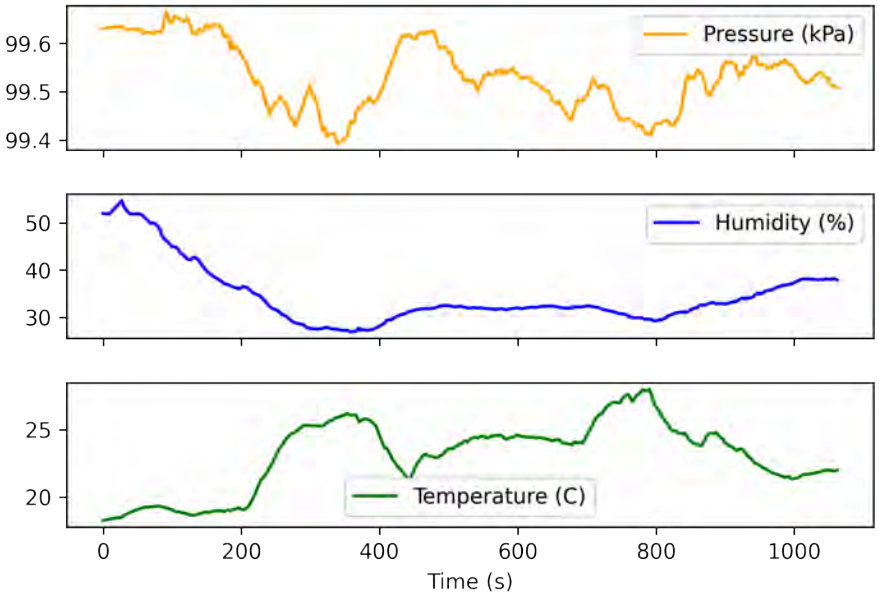
8 First experiment with balloon at Parco Piemonte, Torino, Nov 9, 2020

The first test with biodegradable balloon and radioprobe. The radioprobe was located in the pocket, which is inside the biodegradable balloon.

8.1 Pressure, humidity and temperature dataset

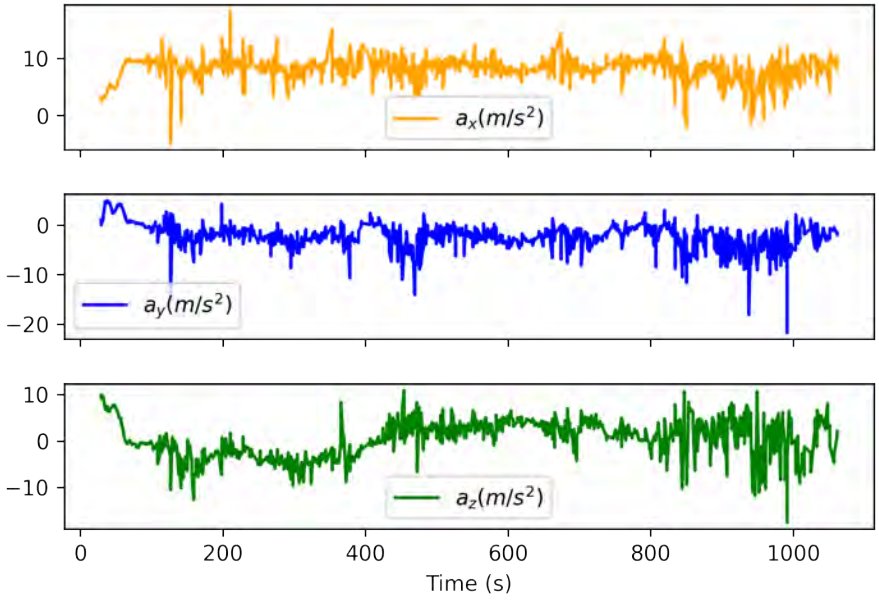
8.2 IMU dataset

8.3 GNSS dataset



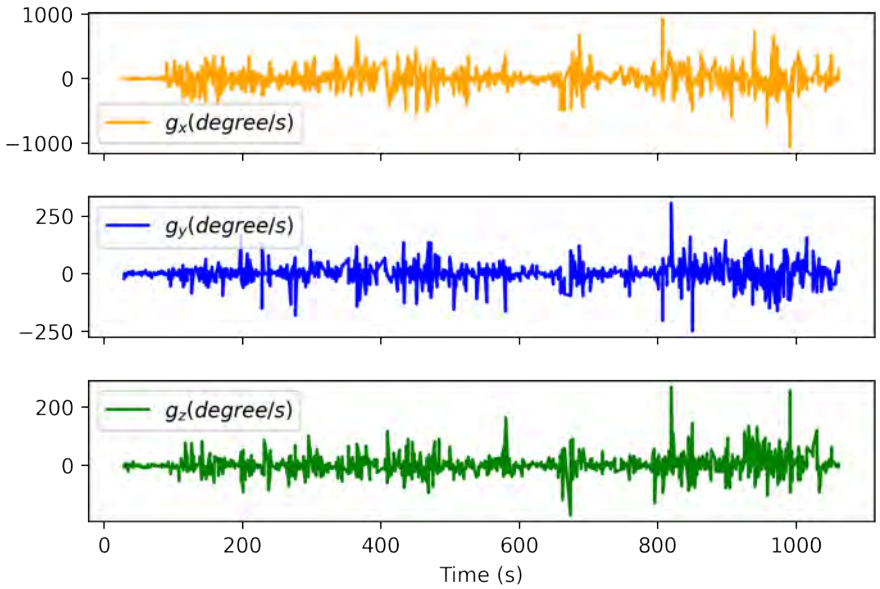
(a)

Figure 41: Raw pressure, humidity and temperature measurements of the radioprobe during launch period.



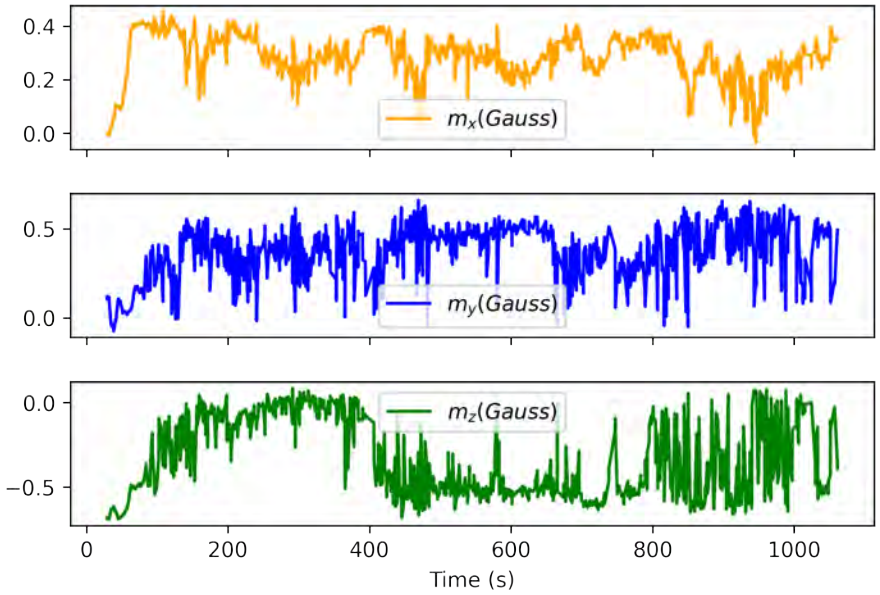
(a)

Figure 42: Raw acceleration readings in xyz body frame of the radioprobe during launch period.



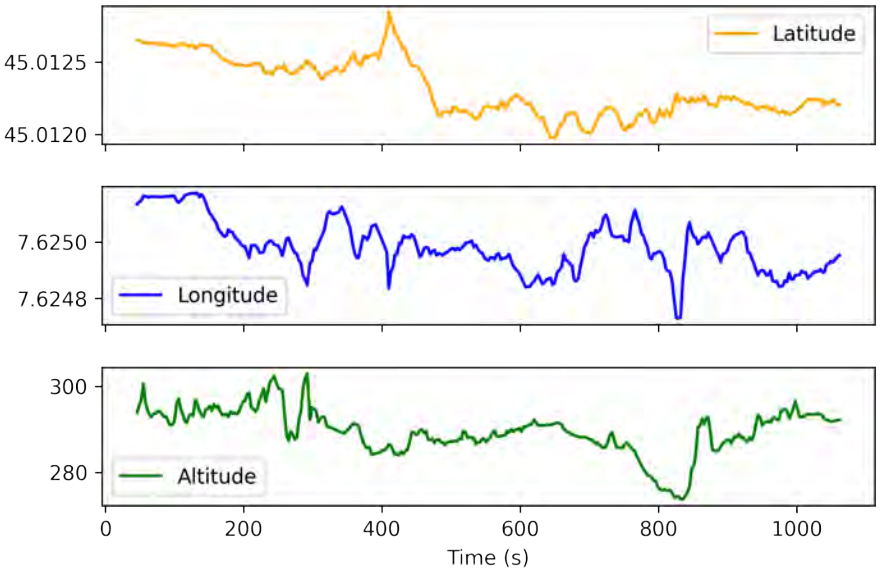
(a)

Figure 43: Raw gyroscope readings in xyz body frame of the radioprobe during launch period.



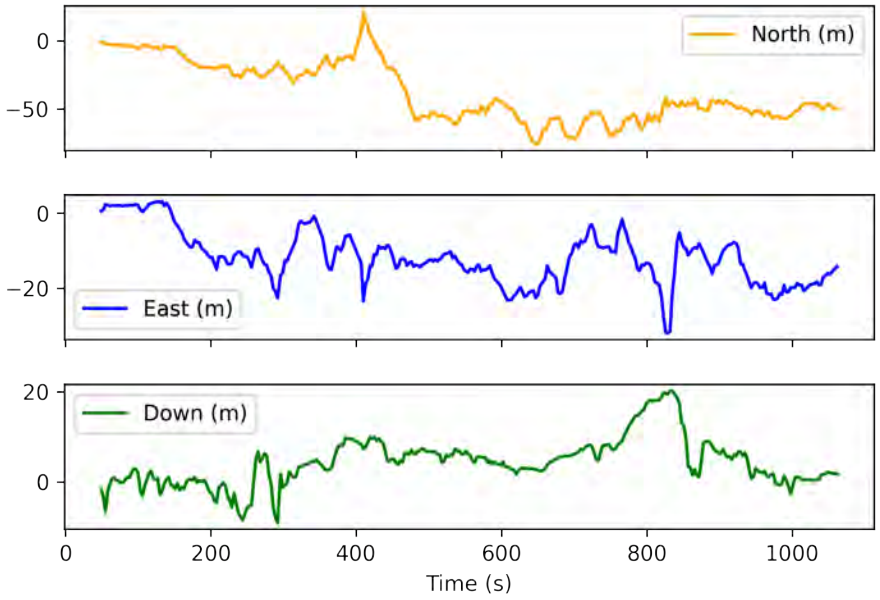
(a)

Figure 44: Raw magnetometer readings in xyz body frame of the radioprobe during launch period.



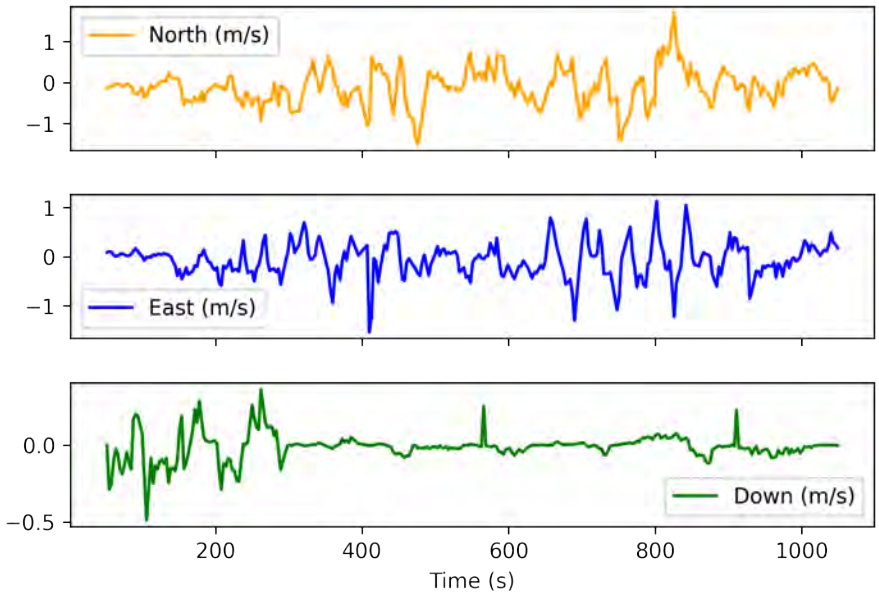
(a)

Figure 45: Raw longitude, latitude and altitude coordinates of the radioprobe during launch period.



(a)

Figure 46: North, east and down position coordinates of the radioprobe during launch period.



(a)

Figure 47: North, east and down velocity readings of the radioprobe during launch period.

9 1st Dual launch at Levaldigi airport in collaboration with ARPA (Piemonte), Cuneo, Oct 28, 2020

Objective

Our intention is to test transmission distance and data quality from the single radiosonde and the receiver station.

Experiment setup

- A **mini radioprobe** attached to the **reference Vaisala RS-41** probe as in Fig. 48.
- A single ground station were ready to receive packets. The receiver station were connected to pc to store and analyse coming packets in real-time.

Figure 48: Preparation: attaching cloud walker (COMPLETE) radioprobe to Vaisala RS-41 probe.

9.1 Sensor dataset and transmission results

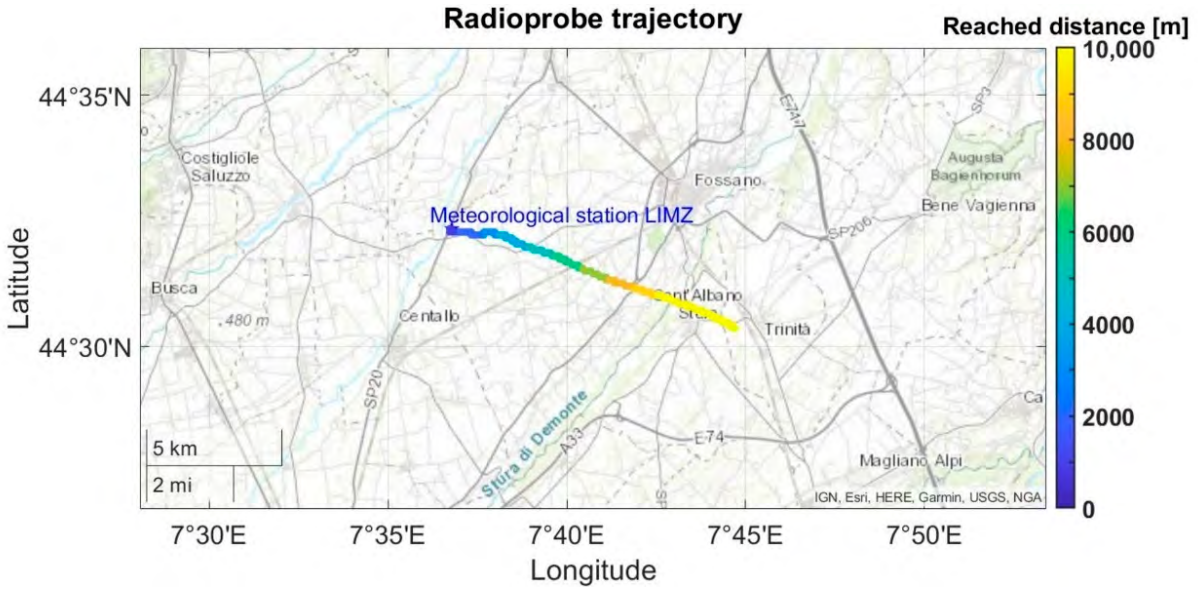
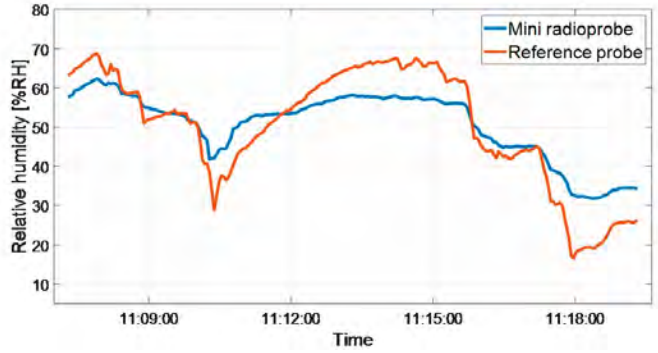


Figure 49: Trajectory of the fully operational radioprobe attached to the reference atmospheric sounding system, displayed on a map. The color bar indicates the separation distance reached by the system with respect to the ground station.

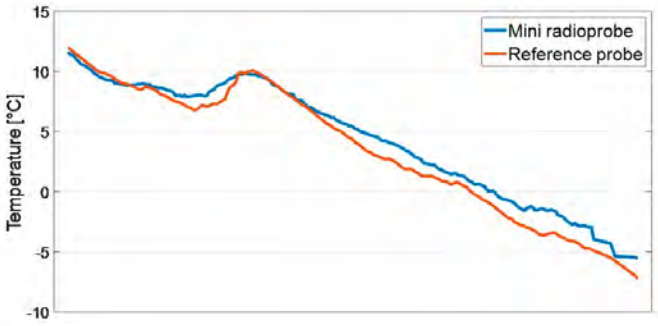
Distance [m]	SNR Mean [dB]	RSSI Mean [dBm]	Total Transmitted Packets	Number of Received Packets	Received Packets [%]
Up to 1000	5	−95	40	37	92.5
Up to 2000	4	−99	103	98	95.2
Up to 3000	2	−102	156	146	93.6
Up to 4000	2	−103	210	196	93.3
Up to 5000	1	−104	243	226	93.0
Up to 6000	1	−104	276	240	87.0
Up to 7000	0	−105	297	259	87.2
Up to 8000	0	−105	322	283	87.9
Up to 9000	−1	−106	348	294	84.5
Up to 10,000	−1	−106	376	296	78.7
Up to 11,000	−1	−106	449	297	66.2
Up to 14,000	−1	−106	462	298	64.5

Figure 50: Results of the point-to-point tranmission with custom LoRa protocol in open environment.

(a)



(b)



(c)

Figure 51: Pressure, humidity and temperature readings with respect to time and comparison with reference Vaisala RS-41 probe.

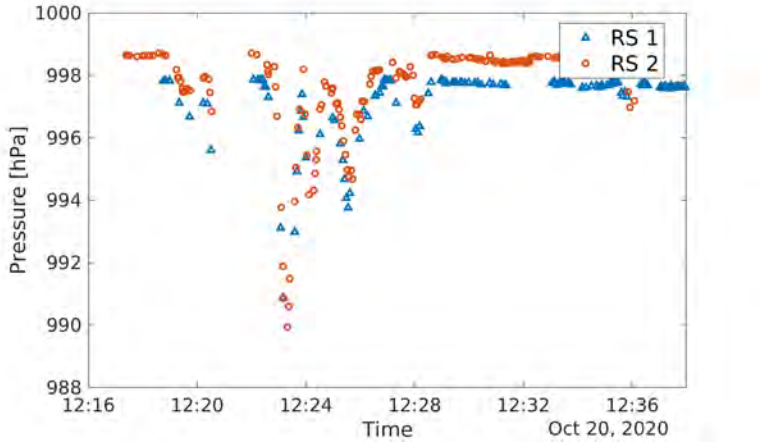
	VAISALA Reference Sensor Measurements (Mean)	Radioprobe Measurements		
		Mean	Mean Error [1]	Standard Deviation [2]
Temperature [°C]	4.16	4.93	0.87	0.56
Pressure [mbar]	774.14	773.53	0.63	0.58
Relative humidity [%RH]	50.74	50.86	5.53	3.71

[1] Difference between reference sensor reading and the radioprobe sensor reading. [2] Standard deviation of radioprobe sensor readings.

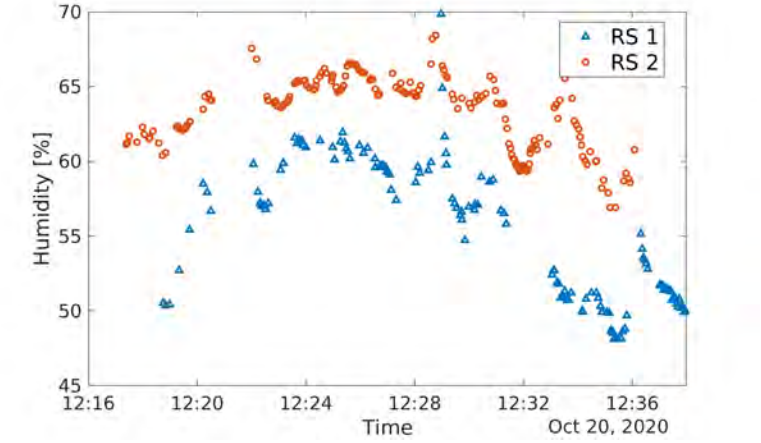
Figure 52: Statistical comparison between radioprobe sensor readings and ARPA reference sonde readings.

10 Radioprobe attached to Drone, at Parco Piemonte, Torino, Oct 20, 2020

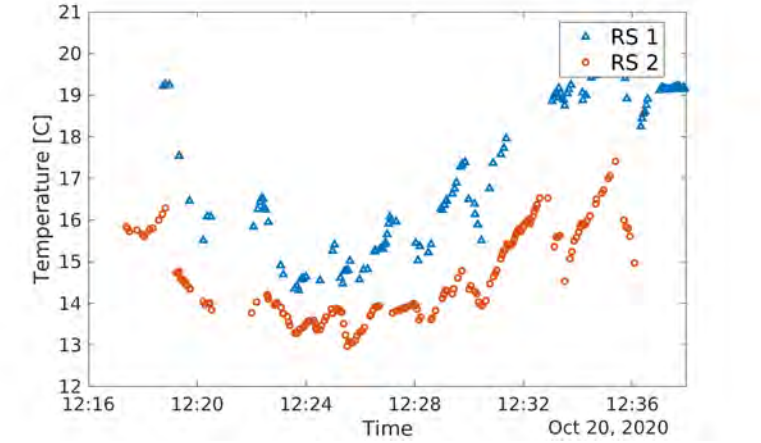
10.1 Pressure, humidity and temperature readings



(a)

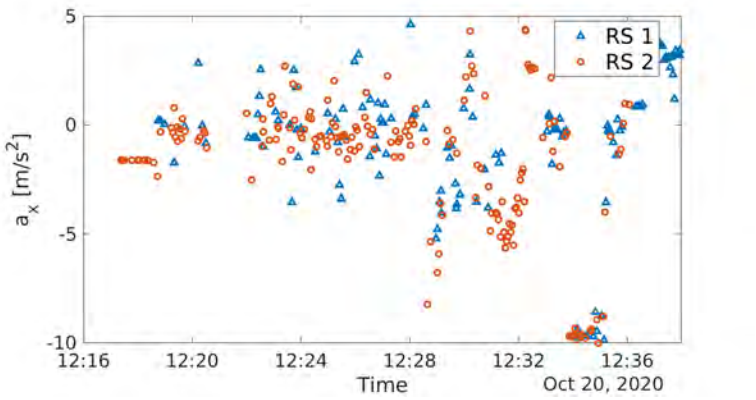


(b)

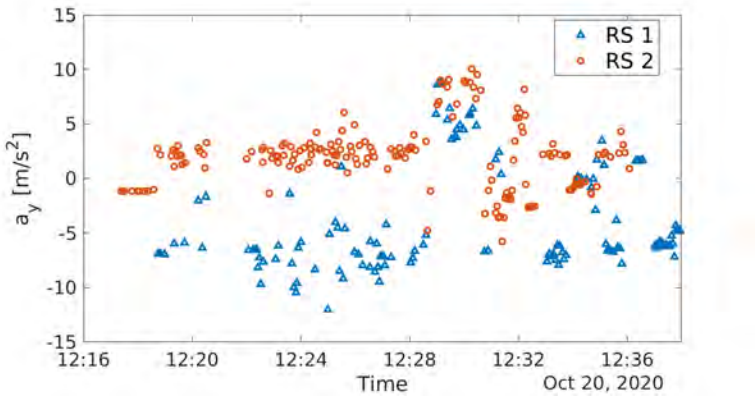


(c)

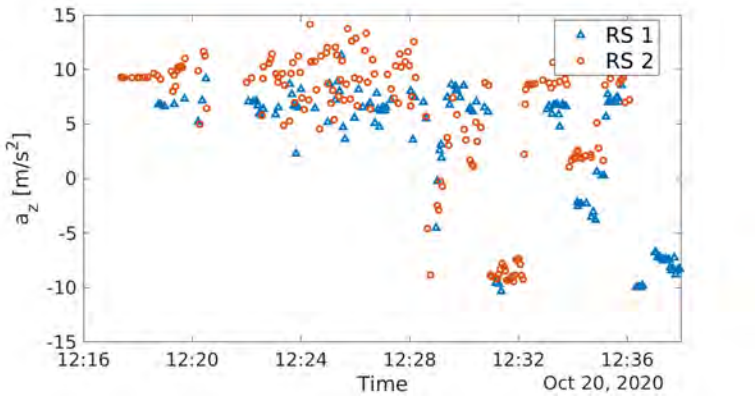
Figure 53: Raw pressure, humidity and temperature readings.



(a)



(b)

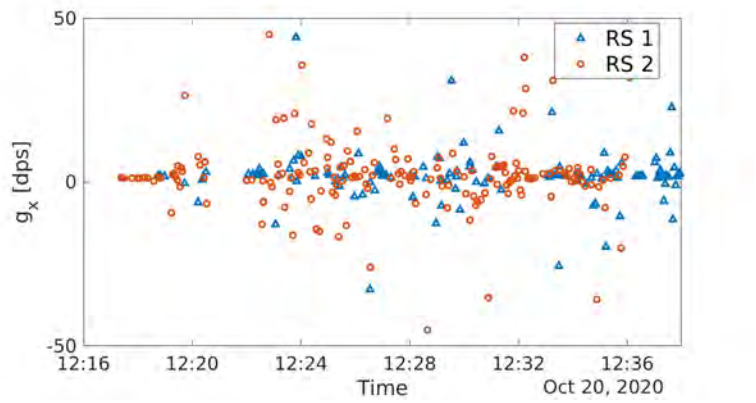


(c)

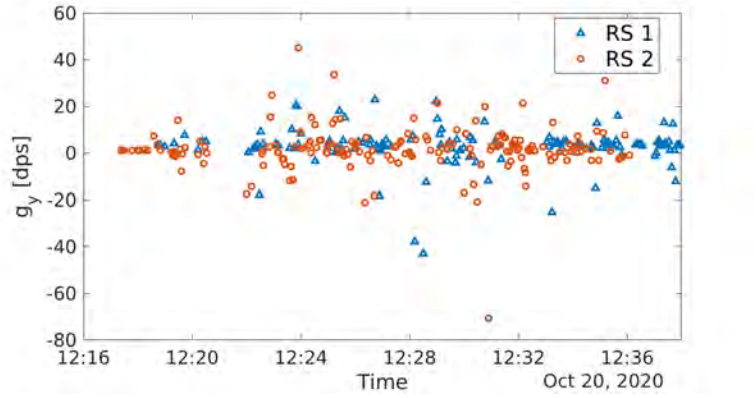
Figure 54: Raw acceleration readings in xyz body frame of the radioprobe during launch period.

10.2 IMU dataset

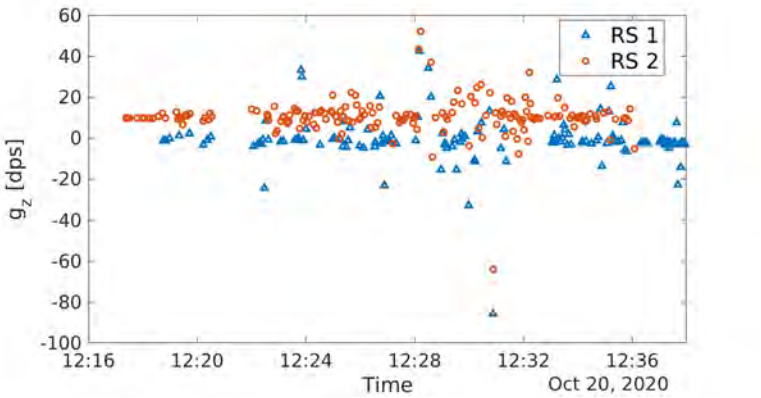
10.3 GNSS dataset



(a)

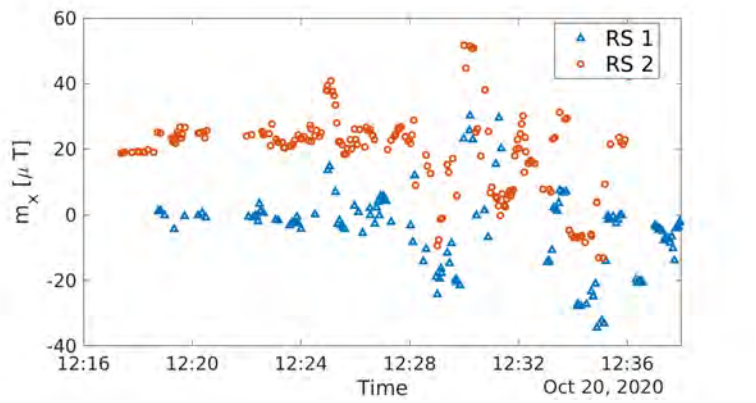


(b)

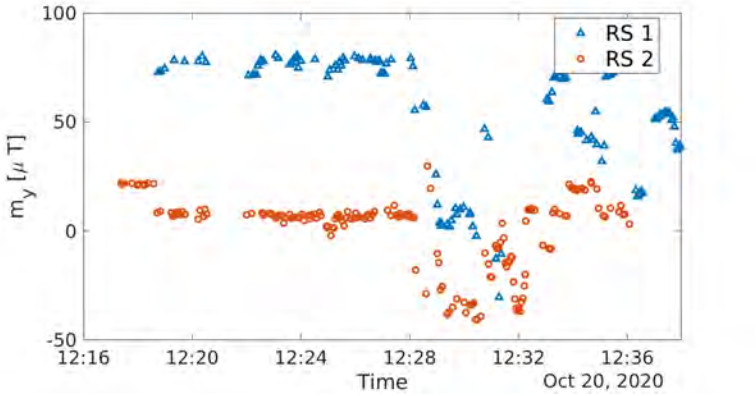


(c)

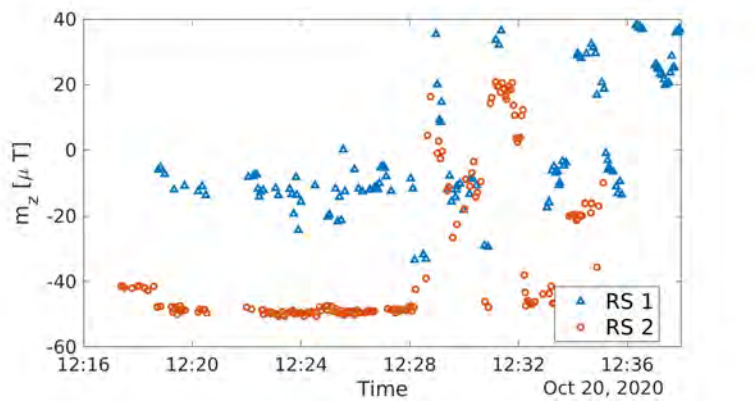
Figure 55: Raw gyroscope readings in xyz body frame of the radioprobe during launch period.



(a)

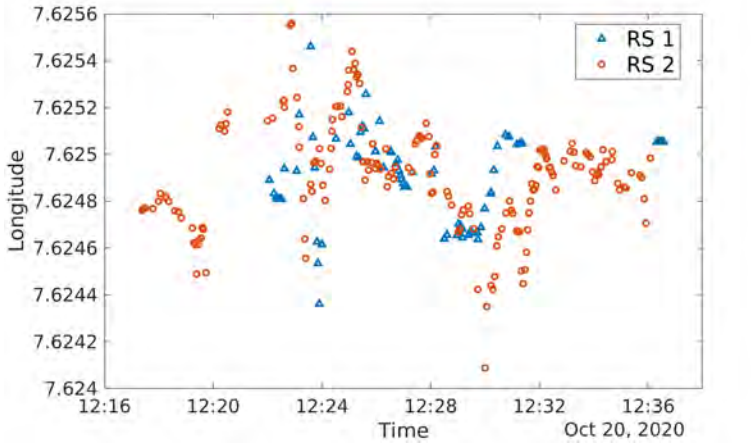


(b)

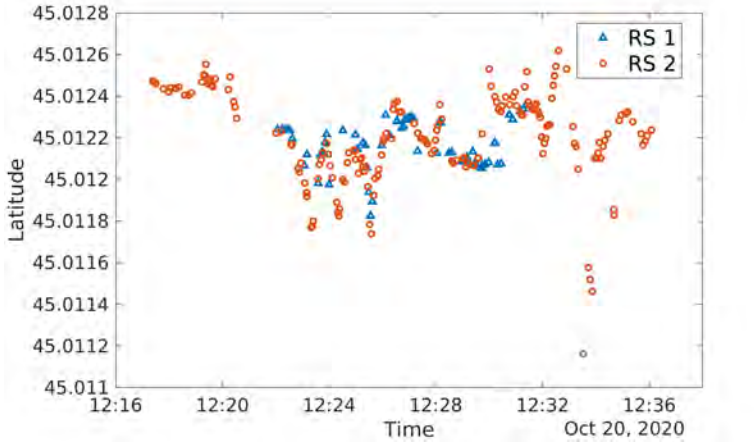


(c)

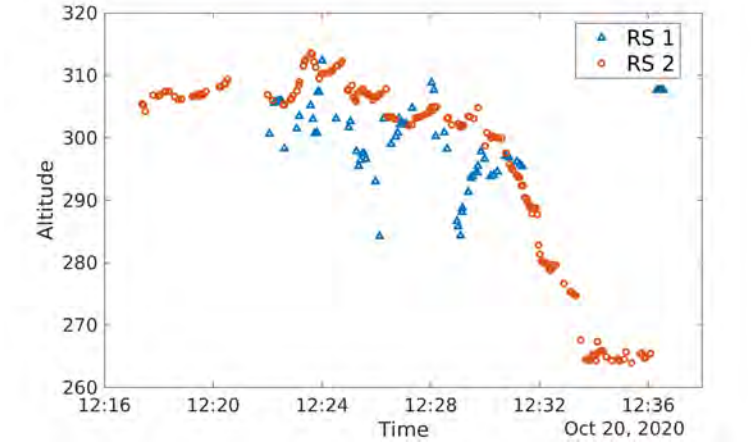
Figure 56: Raw magnetometer readings in xyz body frame of the radioprobe during launch period.



(a)

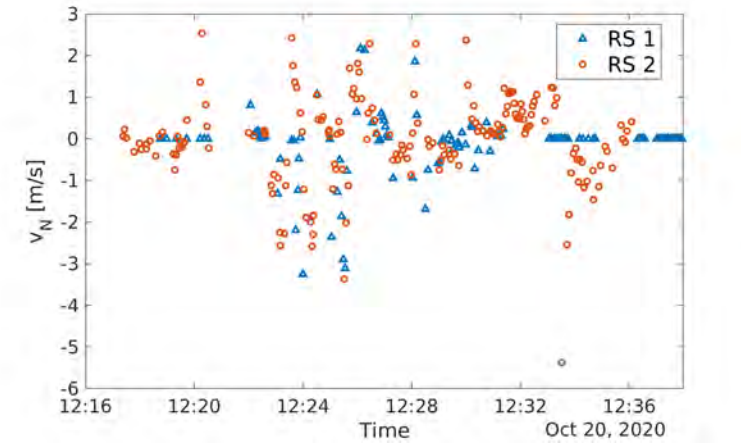


(b)

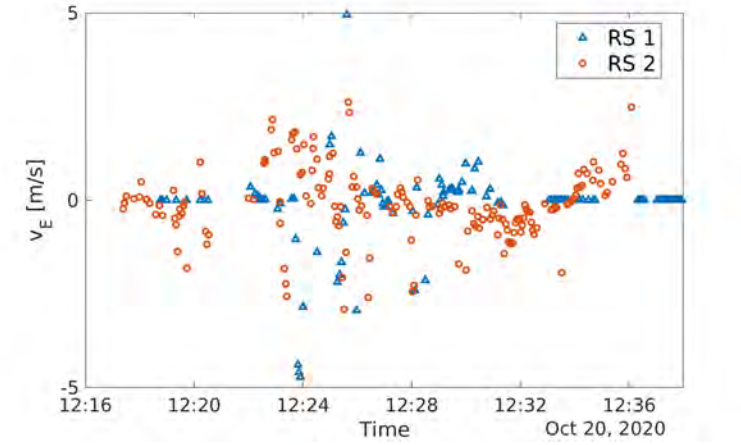


(c)

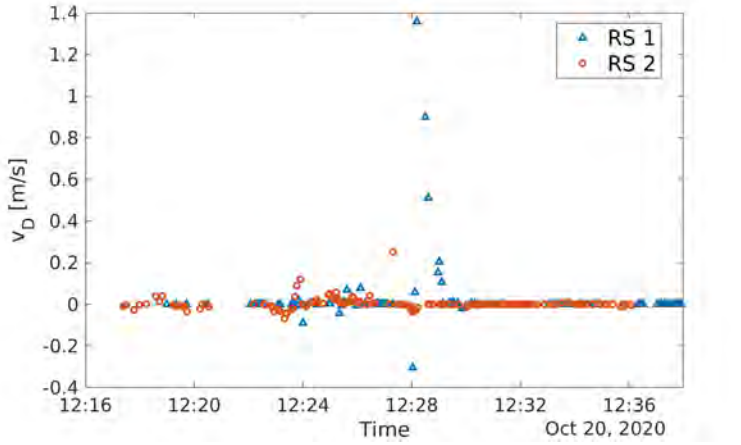
Figure 57: Raw longitude, latitude and altitude coordinates of the radioprobe during launch period.



(a)



(b)



(c)

Figure 58: Raw north, east and down velocity readings fro GNSS sensor of the radioprobe during launch period.