

Politecnico di Torino

Master's Degree in Aerospace Engineering



**Politecnico
di Torino**

Master's Degree Thesis

**In field experiments in the
Atmospheric Boundary Layer
by means of mini instrumented
radiosondes**

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Academic Year 2025–2026

Abstract

The Atmospheric Boundary Layer (ABL) is characterized by turbulent processes spanning a wide range of temporal and spatial scales. Understanding the dynamics underlying these processes is crucial for improving weather prediction models and studying atmospheric transport phenomena. In this work, Lagrangian dispersion and turbulent convection are investigated using data collected by clusters of radiosondes developed within the HOUSEFLIES project. Data was acquired during two experimental campaigns. The first one was held in Sterzing, in the context of TEAMx Observational Campaign, where a cluster of 10 radiosondes was released. The second took place in Carmagnola, where a cluster of 20 radiosondes, the largest deployed so far, was released. Experimental data was used to estimate turbulence characteristics through spectral analyses and the computation of Turbulent Kinetic Energy (TKE) dissipation rates. Atmospheric stability was assessed through the evaluation of Brunt-Väisälä frequencies. Distance Neighbour Graphs (DNG) and Richardson-Obukhov theory were crucial tools for Lagrangian dispersion characterization. More analyses were performed to validate the radiosondes measurements. A dual launch experiment was conducted to have a comparison with reference Vaisala radiosonde, while collected data by the cluster was also compared with ICON-2I numerical simulations. The results demonstrate the capability of the sondes to track small-scales atmospheric fluctuations and provide valuable insights into atmospheric transport and dispersion processes

Acknowledgements

Alla conclusione del mio percorso di laurea triennale, la mia tesi non conteneva nessuna pagina dedicata ai ringraziamenti. Oggi invece mi ritrovo con una lista lunghissima tra le mani, stilata minuziosamente per timore di dimenticarmi qualcuno: prova del fatto che tempo e situazioni mutano di pari passo.

Prima tra tutti, un sentito ringraziamento va alla Professoressa Daniela Tordella: mi ha accolta e sotto la sua guida ho avuto la possibilità non solo di svolgere una tesi magistrale, ma anche di poter vivere delle esperienze che mai avrei immaginato di poter intraprendere durante il mio corso di studi. A lei va un sentito ringraziamento per aver creduto nelle mie capacità nonostante io fossi scettica a riguardo e per essere stata, per me, anche modello da seguire e a cui fare riferimento.

Seguono subito ringraziamenti a Virginia Poli, con la quale ho avuto l'onore di collaborare durante la stesura di questa tesi. Mentore preziosissima, la sua disponibilità e professionalità sono sempre state accompagnate da una grande umanità nei nostri confronti, qualità che ho apprezzato profondamente. Oltre ai tanti ricordi di questa esperienza, conservo ancora con affetto anche tutti i gadget di ItaliaMeteo.

Shahbozbek Abdunabiev (Shahboz) è invece stato una guida importantissima durante questo lavoro: qualsiasi mia domanda dettata da curiosità o confusione ha sempre trovato una sua risposta. Con immensa pazienza sono stata guidata nonostante, a volte, abbia ripetuto le stesse domande più e più volte per essere davvero sicura di aver capito tutto, risultando di certo un po' pedante. La sua pazienza resta per me qualcosa di quasi mistico, oltre che fonte di grande stima e ammirazione.

Riccardo Villa, Bo Yi (Stefano) Zhang e Maria Palomba sono stati colleghi eccezionali con cui ho avuto il piacere di poter condividere l'esperienza di lavorare su questo progetto di tesi non solo con serietà, ma anche con momenti di leggerezza ed ironia.

Durante la campagna sperimentale presso Vipiteno ho invece avuto il piacere di poter collaborare con Andrew Orr e Philip Rosenberg, che sono stati dei team leader incredibilmente disponibili nei nostri confronti. Oltre che ad Andrew e Philip, vorrei ringraziare, tra i vari volontari partecipanti alla campagna, il nostro "core team": Eliza, Lizzy e Luisa, con cui ho condiviso tante avventure, mangiato piatti gustosi, nuotato in laghi ghiacciati e scalato montagne dai panorami mozzafiato.

Si ringrazia inoltre Gabriella Crotti, con la quale ho recentemente svolto delle misurazioni presso l'INRiM, per la sua pazienza, professionalità e per aver condiviso il fascino per gli oscilloscopi.

Tra i miei amici che mi hanno accompagnato durante questo percorso, un sentito ringraziamento va ad Alessio (Xlessio): non solo un compagno di banco, ma un amico di tutti i giorni, che ha sempre avuto per me un biscotto di conforto e che non si è mai tirato indietro davanti ad una missione secondaria. Non so ancora dove tu riesca a trovare tutte le migliori esperienze mangerecce di Torino, ma ti sono profondamente grata per il fatto che le condivida.

Ringraziamenti vanno anche a Chiara, Andrea R. e Magris per aver alleviato con la loro presenza, assieme ad Alessio, un percorso che è stato talvolta tortuoso ma ricco di soddisfazioni.

A Federica va il mio affetto più sincero: amica da una vita, ritrovata una volta approdata a Torino, da sempre due comari che sanno a menadito pregi e difetti l'una dell'altra.

Samuele resta inevitabilmente legato ai ricordi di Padova e Circo Guazzo, dimora che abbiamo condiviso e le cui vicende rimarranno per sempre impresse a fuoco nel mio cuore. Siamo cresciuti assieme e continuiamo a gravitare nelle rispettive orbite nonostante la distanza. Sono profondamente grata di aver trovato un amico così, indipendente da spazio e tempo. La tua presenza sarà sempre casa.

Da Padova, mi porto dietro, nel cuore e nella vita, Luca e Alberto. Fidi compagni di viaggio, so sempre di poter contare sulla loro parola onesta e schietta.// Sentiti ringraziamenti agli amici di sempre: Giorgio, Alice, Frank, Maria, Dany, Irene, Leonardo, Berry, Dana, Michela. Casa Cama resterà sempre punto d'incontro nonostante la distanza.

Sentiti ringraziamenti ad Andrea B.: tra stambecchi e grigliate sempre pronto per avventure spensierate.

Ad Anna prometto che la Danimarca non sarà solo un buon proposito per il futuro. Per te, il mio anello aprirà tutti i bagni di cui avrai bisogno.

Un abbraccio caldissimo va al collettivo Effe Zero: Allegra, Ludo, Simone, Chico, Giulia, Matti, Pasquale, Sofia sono solo alcuni dei nomi degli zerini con cui condivido la passione per la fotografia. In loro non solo ho trovato

un gruppo, ma anche degli amici e, diciamolo, con loro ho ritrovato anche un po' di me.

Sentiti ringraziamenti anche ai ragazzi dell'ufficio: avere i loro discorsi in sottofondo ha reso il mio lavoro di tesi più piacevole e scorrevole. Attendo con ansia una lista completa di tutte le canzoni del giorno.

Un ringraziamento speciale va alla mia famiglia, di cui una nutrita parte ha deciso di intraprendere un lungo viaggio solo per vedermi incoronata. Il vostro supporto e la vostra fiducia nei miei confronti riempiono il mio cuore di gioia e commozione.

Ai miei genitori, Vito e Miriam/Miriam e Vito, va il ringraziamento più grande per avermi permesso di diventare ciò che sono oggi.

Un ringraziamento bizzarro ma necessario va a Torino: tra le sue strade ho trovato Xenia, mio alter ego, alla quale stringo la mano da un po' di tempo e che di certo continuerà ad accompagnarmi in questo lungo percorso che ho davanti.

Infine, ma non per importanza, ringrazio tutti coloro che ci sono stati, ma soprattutto, ringrazio tutti coloro che ci saranno.

Eleonora Zulli
Turin, July 2026

A: “Il tuo cervello è piccolo così! Il mio è grande grande”

...

F: “Ma è più o meno lontano della Germania?”

...Ci vedremo alla prossima puntata...

*See you Space Cowboys,
Someday, Somewhere!*

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Introduction

HOUSEFLIES (Atmosphere and clouds seen by a cluster of wireless sensors), is a project born with the goal to develop a new atmosphere observation method built on the use of a cluster of mini, ultralight, cheap and mostly biodegradable radiosondes designed to passively float inside the atmosphere boundary layer and warm clouds [5, 31].

The main idea behind this project came from the necessity to improve the understanding of turbulent processes taking place inside the Atmospheric boundary Layer (ABL) and inside clouds, which are still one of the main sources of uncertainties inside weather and climatic models [5, 21]. Clouds and atmospheric turbulence involve extremely complex physical phenomena characterized by a strong spatial and temporal variability and interactions taking place on many different scales, ranging from microscopic fluctuations of water droplets to convective motions on scales of kilometric range [21].

Conventional observations, like soundings, meteorological radars, lidars or satellite measurements, provide insightful information, but present some limitations when directly studying lagrangian evolution of atmospheric motions and turbulent fluctuations inside clouds [5]. Traditional soundings are specifically designed for vertical profiling of the atmosphere and do not allow prolonged monitoring of air masses along nearly-isopycnic trajectories [29, 31].

To overcome these limitations, an innovative approach was developed with HOUSEFLIES, based on the simultaneous use of a large number of mini radiosondes carried by biodegradable balloons filled with a mixture of air and helium [21]. This system enables simultaneous multi-point measurements of the atmospheric variables such as temperature, humidity, speed, acceleration and the position of the radiosonde. This allows for direct analysis of turbulent dispersion and the evolution of atmospheric fluctuations [5].

One of the most innovative aspects of this project is the use of a cluster of radiosondes. Unlike traditional observations where only a single profile is investigated, the simultaneous use of multiple radiosondes enables the reconstruction of spatial information on the relative dispersion of trajectories and turbulence, as well as the three-dimensional structure of atmospheric turbulence [5].

This approach is directly inspired by the lagrangian description introduced by Lewis Fry Richardson, whereby studying the relative motion of multiple particles enables us to understand the fundamental mechanisms of turbulent dispersion [24].

The environmental aspects and the sustainability of instrumentation are also of great importance to the project.

The HOUSEFLIES' radiosondes were designed to be as light, cheap and eco-friendly as possible: the balloons are biodegradable and some of the electronics were developed with the intent to use recyclable paper-based supports [30,31]. This approach not only reduces the environmental impact of atmospheric experiments, but also enables large-scale future observational campaigns to be planned relatively low cost [29].

The project's applications are not only exclusively about atmospheric research: clusters can also be used for environmental and air quality monitoring near urban areas, industrial sites, and areas prone to environmental risk, enabling the tracking of aerosols and pollutants dispersion [30,31]. Moreover, the collected data can contribute to improving weather and climate models by providing new experimental information on turbulent processes that are still difficult to correctly parameterise in numerical simulations systems [21,31].

Over the past few years, the HOUSEFLIES system has been progressively validated through laboratory experiments and field campaigns, in collaboration with research institutions such as INRiM, ARPA Piemonte and alpine meteorological observatories [5,29].

These campaigns verified the quality of the measurement, the reliability of the sensors and the possibility of using a cluster of radiosondes to study atmospheric Lagrangian dispersion under real conditions [5].

Chapter 1

Tracking turbulence inside Atmospheric Boundary Layer

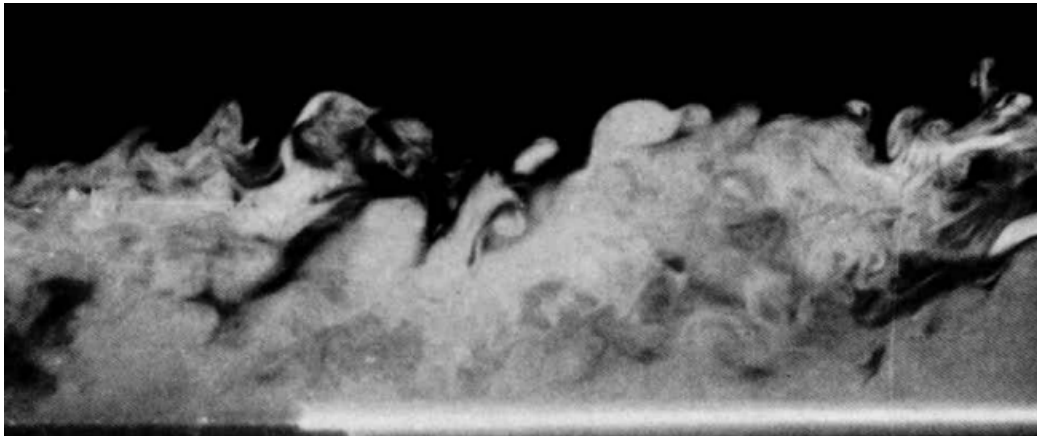


Figure 1.1: Turbulent boundary layer on a wall [14]

The aim of this chapter is to provide a deeper understanding of the phenomena investigated in this work.

This is by no means a simple task, as short and exhaustive definition of turbulence does not appear in the literature. Nevertheless, it is possible to describe the main features associated with the concept of "turbulence" and to formulate a brief summary that attempts to capture its essential characteristics.

One of the best definitions of turbulence describes it as "a state of continuous instability" [32].

Whenever a flow state changes due to the presence of some kind of instability, the ability to predict the behaviour and detailed characteristics of

the flow is drastically reduced. If instabilities occur repeatedly within the system, predictability decreases progressively, to the point where only a statistical representation of the flow could be adequate. Flows for which only a statistical representation seems adequate can be regarded as turbulent. This implies that random features are dominant in the flow, but not that the entire flow is random: all types of flows present some degree of organized structures. It simply means that random features prevail over organized ones.

This approach, however, seems to define a broad category of flows which might or might not be classified as turbulent. One should then be able to properly designate the point at which turbulent motion begins when transition to turbulence occurs.

On the other hand, it should be considered that, for certain flows, a detailed description may be useful for one purpose, while a statistical description may be more suitable for another.

The opposite flow state to turbulence is laminar flow 1.2. This kind of flow is characterized by an organized motion of particles along regular and well defined trajectories. Adjacent fluid layers move relative to one another without a significant transversal mixing and speed fluctuations are negligible compared to main flow speed.

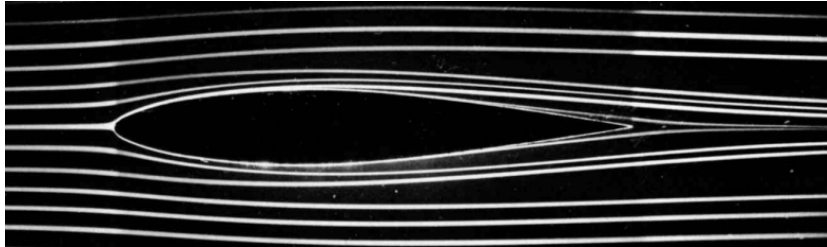


Figure 1.2: Laminar, unseparated flow around an airfoil with zero incidence with respect to the flow [14]

In order to discuss the different flow states and the circumstances under which each different flow type occurs, the concept of Reynolds number will now be introduced.

Reynolds number is an adimensional value which shows the rate between inertial and viscous forces in a fluid in motion:

$$Re = \frac{\rho U L}{\mu} \quad (1.1)$$

where ρ ($kg\ m^{-3}$) is the fluid's density, U is the fluid's speed (m/s) with

respect to the considered object, L (m) is the object's characteristic length and μ ($kg\,m^{-1}\,s^{-1}$) is the dynamical viscosity of the fluid.

Equation 1.1 can be rewritten also by using kinematic viscosity ($\nu = \frac{\mu}{\rho}$) :

$$Re = \frac{UL}{\nu} \quad (1.2)$$

Lower values of Reynolds number are associated with laminar flows, while higher values are associated with turbulent ones. However, the critical Reynolds number associated with the laminar-to-turbulent transition is not universal, as it depends on the specific flow configuration, boundary conditions and perturbation levels.

1.1 Energy Cascade

Many theoretical investigations about turbulence are based on the hypothesis of homogeneous, isotropic turbulence, which means that all recorded statistical properties do not vary as a function of considered position and do not have a preferential direction. This assumption also disregards the presence of an energy production term, which is considered to be equal to zero. This means that the generated turbulence, at an initial instant, will decay over time as a consequence of viscous dissipation.

Considering the equation for the temporal variation of energy spectra:

$$\frac{\partial E(k, t)}{\partial t} = F(k, t) - 2\nu k^2 E(k, t) \quad (1.3)$$

we can see that the energy spectra E is a function of both time (t) and the wavenumber, k .

The second term on the right is the energy dissipation term, which becomes more significant as the wavelength number k increases. This means that dissipation is more relevant for smaller eddies, since turbulent flows usually occur at higher Reynolds numbers.

The term $F(k, t)$, instead, is related to the Fourier transform of the triple correlation and represents the transfer of energy between wavenumbers as it can be shown that:

$$\int_0^\infty F\,dk = 0 \quad (1.4)$$

Interpreting the behaviour of the terms in Equation 1.3 leads to the development of a turbulence model relevant to both homogeneous isotropic turbulence and most turbulent flows.

In turbulence, the energy fed into the flow primarily goes into larger eddies. Starting from these, smaller eddies are generated, followed by even smaller ones, in a process known as the *Energy Cascade*.

For flows with high Reynolds numbers, this is a long process in which the size of the eddies at the end of the cascade differ significantly from their size at the beginning. Larger eddies transfer energy, while smaller ones dissipate it.

The rate of dissipation does not depend on the magnitude of the viscosity but on the rate at which energy is supplied to the cascade by the large eddies.

It can be assumed that the dynamics of the energy cascade and dissipation are governed by the energy per unit time (per unit mass) supplied by large eddies (those with a low wavenumber): this is known as dissipation ϵ .

The energy spectrum does not depend on the energy production processes for all wavenumbers which are large compared to those at which the energy is produced. E will then depend on the wavenumber, dissipation and viscosity:

$$E = E(k, \epsilon, \nu) \quad (1.5)$$

However, if the process is long enough, there will be an intermediate range where the effect of viscosity has not yet been felt. This range is known as the *inertial sub-range*:

$$E = E(k, \epsilon) \quad (1.6)$$

And dimensional analysis in this range gives:

$$E = A \epsilon^{2/3} k^{-5/3} \quad (1.7)$$

A is a constant, and this result is known as *Kolmogorov -5/3 law*.

1.2 Kolmogorov's hypothesis

After analyzing the energy cascade phenomenon, some questions about the behaviour of the flow remain.

In particular, the dimension of the smallest energy dissipating vortices still needs to be explored.

Another important issue to be investigated is the correlation between the characteristic lengthscale, kl , of the vortices and its characteristic velocity, $u(l)$, and timescale, $\tau(l)$, in order to determine whether they grow, maintain their values, or decrease as the length l changes.

The answer to these questions could be found by analyzing the theory developed by Kolmogorov, which is based on the formulation of three fundamental hypotheses. According to this theory, both velocity and timescales decrease as the length decrease.

The first Kolmogorov's hypothesis is based on the assumption of isotropy at small scales of motion, while the larger scales are anisotropic and display a behaviour that is heavily influenced by boundary conditions. This dependency tends to be lost during the energy cascade process, as do the geometrical characteristics of vortices and information linked to anisotropy. Consequently, the statistical characteristics of small-scale turbulence motion tend to exhibit universal features shared by all turbulent flows at high Reynolds numbers.

The next logical step is to determine the main parameters on which this state of motion depends.

The energy cascade process is characterized by the transfer of energy from the largest to the smallest scales of motion, as well as by viscous dissipation. It is therefore possible to assume that fundamental parameters affecting motion are the rate of energy transfer, T_{EI} , and kinematic viscosity, ν . It should be noted that energy dissipation, ϵ , is strictly dependent on energy transfer itself, and the two quantities are nearly equal.

The second Kolmogorov's hypothesis is the first similarity hypothesis, which states that the statistical characteristics of the motion at small length scale assume a universal form that is solely determined by kinematic viscosity, ν , and rate of energy dissipation ϵ . Taking these parameters, it is possible to determine the characteristic length, speed and time scales of the motion:

$$\eta = \left(\frac{\nu^3}{\epsilon} \right)^{1/4} \quad (1.8)$$

$$u_\eta = (\epsilon \nu)^{1/4} \quad (1.9)$$

$$\tau_\eta = \left(\frac{\nu}{\epsilon} \right)^{1/2} \quad (1.10)$$

These scales of motion characterize the smallest dissipative eddies, and this point is highlighted by other two equations that stem from the aforementioned above:

- Reynolds number that can be computed starting from Kolmogorov scales is equal to unity $\eta u_{eta}/\nu = 1$. This values is consistent with the theory stating that energy cascade continues until the Reynolds number is small enough to make dissipation efficient.

1.2. Kolmogorov's hypothesis

- by considering the energy dissipation rate using Kolmogorov variables:

$$\varepsilon = \nu \left(\frac{u_\eta}{\eta} \right)^2 = \frac{\nu}{\tau_\eta^2} \quad (1.11)$$

It is possible to notice how $u_\eta/\eta = 1/\tau_\eta$ provides a good characterization of speed gradients inside dissipative vortices.

The relationships between the values of smaller and larger scales of vortices can be identified.

$$\frac{\eta}{\ell_0} \sim Re^{-3/4} \quad (1.12)$$

$$\frac{u_\eta}{u_0} \sim Re^{-1/4} \quad (1.13)$$

$$\frac{\tau_\eta}{\tau_0} \sim Re^{-1/2} \quad (1.14)$$

Considering the case of high Reynolds numbers, it is possible to see how the speed and timescales of small vortices are way much smaller than those of larger dimensions and these rates tend to decrease as the Reynolds number increases.

Considering the length scale, η , for high enough Reynolds numbers, there will be a range of scales l that are much smaller than the characteristic length scales of large structures ℓ_0 but much larger than Kolmogorov's characteristic length scale, η . The vortices in this range are larger than the those connected to dissipation, so it is possible to assume that their Reynolds number is still high and viscosity in their motion is nearly negligible. The third Kolmogorov hypothesis follows from these considerations.

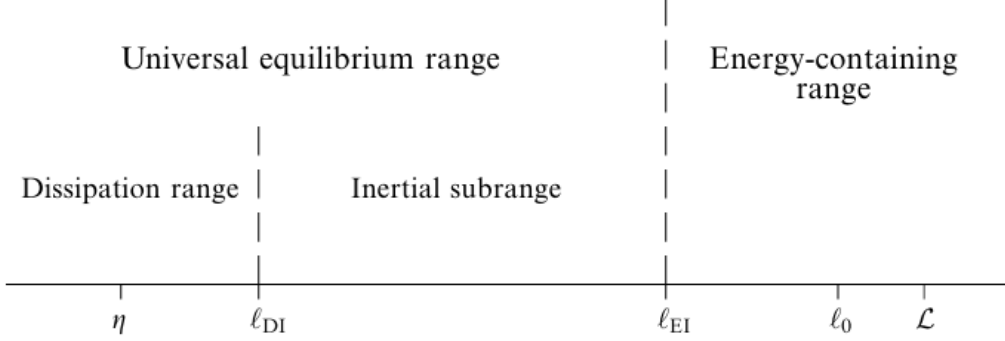


Figure 1.3: Representation of eddy sizes l at various lengthscales and ranges. Suffixes EI and DI state that l_{EI} is the demarcation between energy and inertial ranges and l_{DI} is the same, but between dissipation and inertial subranges [22]

The second Kolmogorov's similarity hypothesis states that in a flux with high enough Reynolds number, scales of motion with characteristic length between l_0 and η have a universal form which is only determined by ϵ and not ν . This range is known as the inertial subrange. As the name suggests, inertial effects dominate this range of motions, while viscous effects remain negligible. Only vortices with a length inside the dissipation range will have a significant dependency on dissipation.

If a characteristic lengthscale is given and the considered vortex has dimensions inside the inertial subrange, the characteristic scales of speed and time can be defined as follows:

$$u(\ell) = (\epsilon \ell)^{1/3} = u_\eta \left(\frac{\ell}{\eta} \right)^{1/3} \sim u_0 \left(\frac{\ell}{\ell_0} \right)^{1/3} \quad (1.15)$$

$$\tau(\ell) = \left(\frac{\ell^2}{\epsilon} \right)^{1/3} = \tau_\eta \left(\frac{\ell}{\eta} \right)^{2/3} \sim \tau_0 \left(\frac{\ell}{\ell_0} \right)^{2/3} \quad (1.16)$$

As l decreases, it is possible to observe a decrease in both velocity $u(l)$, and timescales $\tau(l)$, respectively.

In the description of the energy cascade the rate of energy transfer $T(l)$ is a fundamental variable, which is defined as the energy transferred per unit time from eddies characterized by sizes greater than (l) to those with sizes smaller than (l) . If energy transfer is mostly characterized by vortices of a scale comparable to vortices of scale l , this quantity can be estimated as follows:

1.2. Kolmogorov's hypothesis

$$T(\ell) \sim \frac{u(\ell)^2}{\tau(\ell)} \quad (1.17)$$

And substituting with equations 1.15 and 1.16:

$$\frac{u(\ell)^2}{\tau(\ell)} = \epsilon \quad (1.18)$$

which shows that energy transfer is independent of the considered scale within the inertial subrange. Energy is transferred between all intermediate scales at a constant flux, which is equal to the dissipation rate ϵ .

This is a fundamental aspect of Kolmogorov's theory: within the inertial subrange, energy is neither produced nor dissipated significantly. The consequence is that the rate at which energy is transferred through larger scales, the rate at which energy is transferred in the inertial subrange and the dissipation rate at small scales are all in balance with each other:

$$T_{EI} = T(\ell) = T_{DI} = \epsilon \quad (1.19)$$

where T_{EI} is the transfer of energy from scales containing energy at the initial state to the inertial subrange and T_{DI} is the transfer from inertial subrange to the dissipation one.

The consequence is that, in conditions of developed and statistically stationary turbulence, energy entering the system at larger scales is transferred through the cascade to smaller scales, where it is dissipated at the same mean rate. Thus, energy production and dissipation are balanced, with the inertial subrange acting as a transfer medium between the two extremities of the energy cascade.

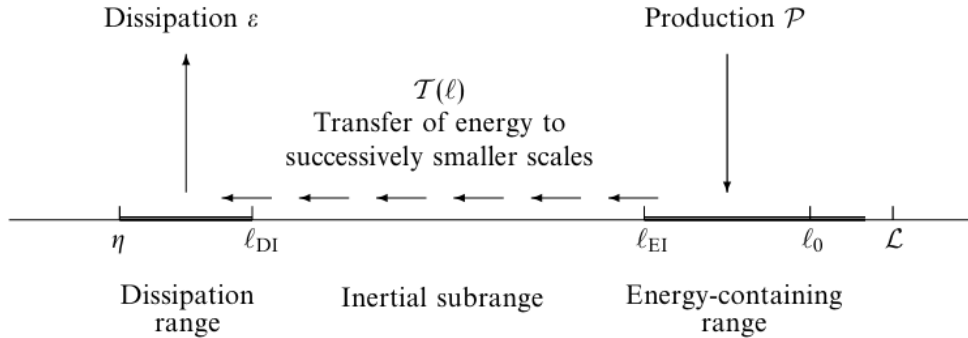


Figure 1.4: Representation of the energy transfer between different scales [22]

1.3. Turbulent Diffusion

The following relationship holds for isotropic turbulence in (both wavenumber and frequency domains) as described by Batchelor [8]:

$$E(k) = C \varepsilon^{2/3} k^{-5/3} \quad (1.20)$$

and by applying Taylor's Hypothesis ($k = \frac{2\pi f}{U}$):

$$S(f) = \alpha \varepsilon^{2/3} \left(\frac{U}{2\pi} \right)^{2/3} f^{-5/3} \quad (1.21)$$

where k is the wavenumber, $E(k)$ the energy spectrum, $F(k)$ the wavenumber spectrum, ε the mean energy dissipation rate, U the mean wind speed, f the frequency, $S(f)$ is the power spectral density in the frequency domain and α is the one-dimensional Kolmogorov constant (it can be considered equal to 0.5 for streamwise speed component u).

Considering measurements of $S(f)$ within the inertial subrange, the mean TKE dissipation rate $\bar{\varepsilon}$ can be computed as:

$$\bar{\varepsilon} = \frac{2\pi}{U} \left(\frac{f^{5/3} S(f)}{\alpha} \right)^{3/2} \quad (1.22)$$

1.3 Turbulent Diffusion

Turbulent diffusion of fluid particles plays an important role in the study of turbulence. It consists of the process by which particles spread from an area of high density to areas of low concentration within a medium or between different media due to turbulent motions present at various scales. Unlike molecular diffusion, which is driven by the random motion of particles, turbulent diffusion is governed by vortices and turbulent structures of the flux [24].

It is also crucial for studying the dispersion of pollutants in the atmosphere or the ocean. It affects mixing mechanisms and the dynamics of ocean currents, too.

In general, turbulent diffusion can be described as the process by which a scalar quantity is spread within a fluid medium due to chaotic and irregular fluctuations in the velocity of the fluid.

In 1926 [24], Lewis Fry Richardson, was one of the first to observe and describe this phenomenon. His observations revealed that atmospheric diffusivity levels tend to increase drastically with the considered space scale. This suggests that diffusivity inside the atmosphere cannot be described by a constant coefficient, as expected by Fick's law. Richardson suggested

that the diffusion coefficient itself was a function of the distance between the particles. As the distance between particles increases, they begin to be affected by larger turbulent structures containing higher energy levels, while particles in close proximity are affected by smaller vortices and structures.

To describe this phenomenon, Richardson introduced a Lagrangian approach based on the evolution of the separation between couples of particles. The basic idea is that the speed at which they will distance themselves from each other increases with their separation. This is the most important result of the theory and the main basis of the modern theory of turbulent diffusion.

1.3.1 Distance Neighbour Graphs (DNG)

To describe turbulent diffusion, Richardson observed that the spatial distribution of a cluster of particles cannot be adequately represented by mean concentration alone. During atmospheric diffusion, particles tend to gather into clusters, which then undergo deformations and transformations under the action of turbulent vortices. This is why a tool is necessary to describe both the global extension of the particle cluster and its internal structure. To this end, Distance-Neighbour-Graph (DNG) function, denoted by Q , was employed. This function is a statistical representation based on mutual particle positions: the main idea is to take each particle as a reference point and count the mean number of particles present within a distance l . By repeating this process for all particles within the system and computing the mean we obtain the function $Q(l, t)$, which identifies the mean number of neighbours within a specified spatial interval.

$$Q_{n,n+1} = \frac{1}{N} (P_{n,n+1}^1 + P_{n,n+1}^2 + P_{n,n+1}^3 + \cdots + P_{n,n+1}^N) \quad (1.23)$$

where $Q_{n,n+1}$ is the average number of sondes which can be found between $n * l$ and $(n + 1) * l$, where l is the chosen constant distance interval (neighbourhood) and $P_{n,n+1}^k$ is the number of neighbours for the k -th radiosonde within the distance bin $(n, n + 1)$.

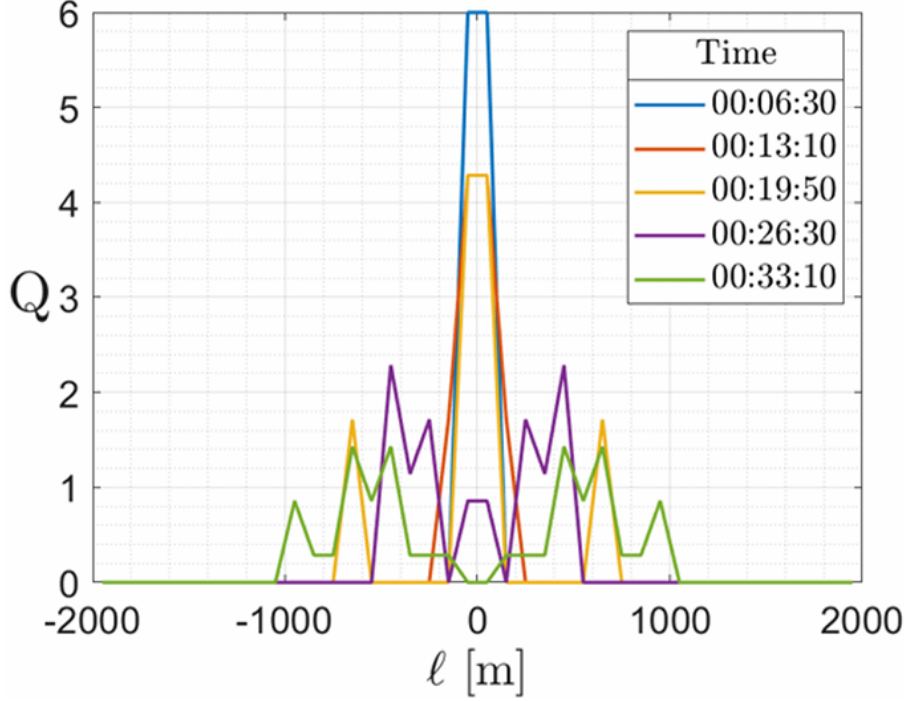


Figure 1.5: Example of Distance-Neighbour-Graph obtained after the measurements performed during Chilbolton’s cluster launch on July 5th, 2023 at Chilbolton Observatory. This experiment was held in the context of the Wessex Convection (WESCON) campaign organized by the British Met Office.

The DNG function depends on both space and time. Figure 1.5 shows a typical example of a DNG function behaviour. DNG graphs evolve over time: an initially compact cluster is characterized by a compact graph, concentrated on small distances. As diffusion proceeds, DNG curves tend to progressively become wider over distances, while the height decreases and the total number of considered particles is maintained, as expressed below:

$$\frac{dQ}{dt} = \frac{d}{d\ell} \int_{-\infty}^{+\infty} \frac{dQ}{dt} d\ell = 0 \quad (1.24)$$

This kind of behaviour highlights the progressive growth of the separation between the considered particles due to the action of turbulence. One of the main innovations of DNG is that it directly describes particle separation statistics, the physical quantity that governs turbulent diffusion.

Thanks to this formulation, Richardson was able to demonstrate that diffusion rates increase with the distance between particles.

1.3.2 Richardson's law

Richardson provided an equation that described the temporal evolution of the separation distribution between particle couples.

$$\frac{\partial q(\ell, t)}{\partial t} = \frac{1}{\ell^2} \frac{\partial}{\partial \ell} \left(\ell^2 D(\ell) \frac{\partial q(\ell, t)}{\partial \ell} \right) \quad (1.25)$$

where $q(\ell, t)$ is the probability of finding a pair of particles within a distance of ℓ , and $D(\ell)$ is the relative diffusion coefficient, which depends on the considered distance.

Richardson experimentally determined the dependency of $D(\ell)$ on distance ℓ , arriving at the famous result $D(\ell) \propto \ell^{4/3}$, which shows how diffusion increases with the distance between pairs of particles.

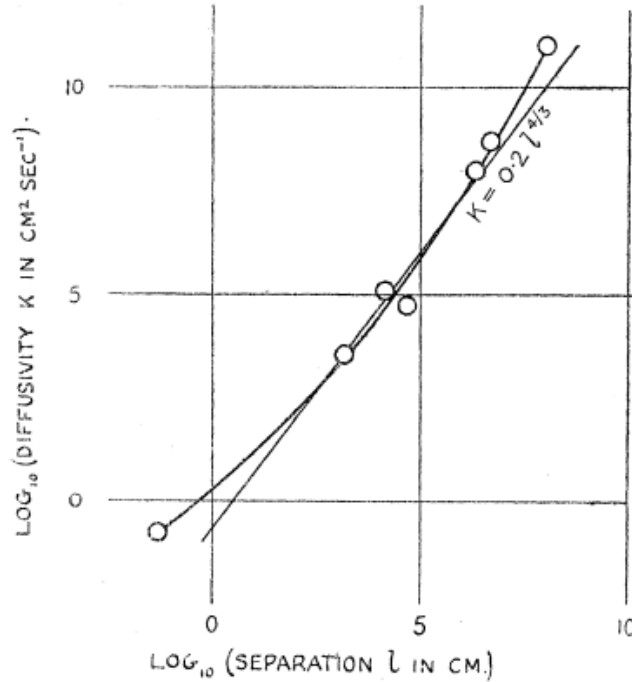


Figure 1.6: Graph from [24], showing the dependency between diffusivity D as a function of the distance and the considered distance itself. Starting from these data, the dependency $D(\ell) \propto \ell^{4/3}$ was proposed

one way to compute the mean separation distance between particles is to

1.4. Capturing stability conditions

use the Richardson-Obukhov (R-O) scaling, which relates the mean square separation distance, ℓ^2 , to time via a cubic dependency:

$$\ell^2 = \ell_0^2 + g_\ell \epsilon t^3 \quad (1.26)$$

where ℓ^2 is the mean square separation distance, ℓ_0 is the initial separation distance, ϵ is the energy dissipation rate, t is the elapsed time and g_ℓ is a constant related to the scaling behaviour.

1.4 Capturing stability conditions

Brunt-Väisälä frequencies N^2 are a useful tool while investigating the atmosphere's stability.

Positive values of the Brunt-Väisälä frequency ($N^2 > 0$), indicate stable stratification meaning that vertical displacements of air particles are opposed by buoyancy forces. Conversely, negative values $N^2 < 0$ denote instability and increased vertical displacement. Finally, values close to zero correspond to neutral conditions.

Stratification tends to change considerably at different altitudes, alternating between stable and unstable regions.

Brunt-Väisälä frequencies for dry air N_d^2 can be computed using the established formula presented in [34]

$$N_d^2(k) = \frac{g}{\theta(k)} \left(\frac{d\theta}{dz} \right)_k = \frac{g(k)}{\theta(k)} \frac{\theta(k+1) - \theta(k)}{dz} \quad (1.27)$$

where θ is the moist-conservative potential temperature, dz is the altitude displacement between points k and $k+1$, $g(k)$ is the gravitational acceleration at point k .

Gravitational acceleration can be approximated as a constant, or computed using the following formula, which considers the altitude:

$$g(z) = G \frac{M}{(R_{\text{earth}} + z)^2} \quad (1.28)$$

where $G = 6.674 * 10^{-11} [Nm^2/kg^2]$ is the universal gravitational constant, $M = 5.98 * 10^{24} [kg]$ is the esteemed Earth's mass, $R_{\text{earth}} = 6.371 * 10^6 [m]$ is Earth's radius and z is the altitude tracked by the radiosonde.

It is also important to remember that potential temperature is defined as:

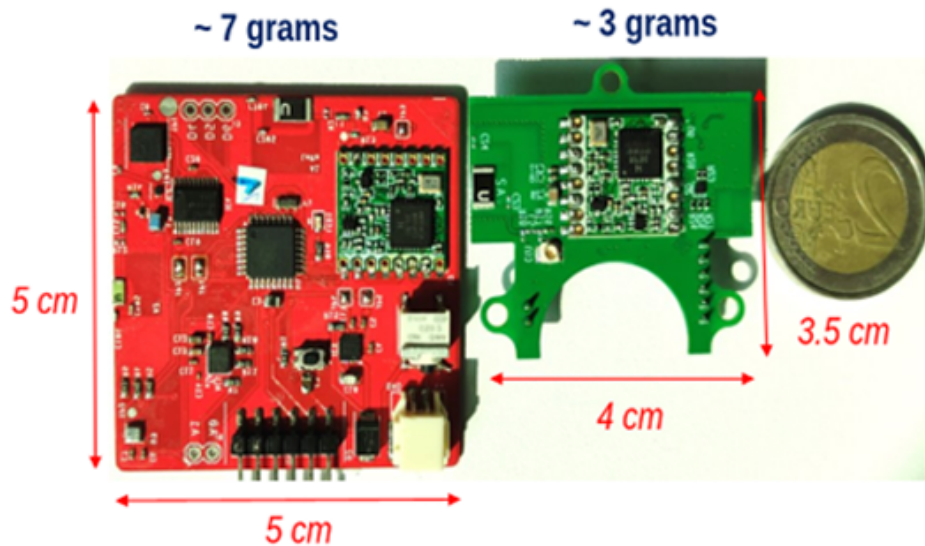
$$\theta(k) = T(k) \left(\frac{P_0}{P(k)} \right)^{\frac{R}{c_p}} \quad (1.29)$$

1.4. Capturing stability conditions

where $T(k)$ is the tracked temperature in Kelvin, $P(k)$ the tracked pressure in Pascal, P_0 the reference pressure ($10^5 Pa$), $R = 287.05 \text{ J/(kg K)}$ and $c_p = 1005 \text{ J/(kg K)}$.

Chapter 2

Radiosonde



2.1 introduction

It is challenging to characterise the dynamics inside the clouds.

It is important to understand that a good knowledge of these dynamics is fundamentals to improve the reliability of weather forecasts and climate systems modelling.

One of the main challenges is understanding turbulence behaviour at small scales. However, this is difficult to determine due to the great challenge of performing measurements caused by a lack of adequate instrumentation.

This is why, when writing the proposal for a European Horizon 2020 Marie Skłodowska Curie project that was approved in 2016 (H2020 MSCA ITN ETN COMPLETE, GA 675675: Innovative Training Network on Cloud-MicroPhysics-Turbulence-Telemetry), the concept of mini radioprobes was introduced. This concept is presented in Paredes et Al. [21].

Clouds are one of the main sources of uncertainty in weather predictions due to their wide range of temporal and spatial scales, from a few microns to thousands of kilometers.

On the other hand, the formation and development of rain depends on both turbulent fluxes within the clouds and the and calm air fluxes above them.

It is also important to note that non-linear processes such as vortex stretching and entrainment can increase the nucleation of droplets.

To study these processes, various methods were employed to determine the principle of microphysics and the interactions between different physical processes, such as numerical simulations, laboratory experiments and field observations.

The following method is intended to provide in-situ measurements, particularly of small-scale turbulence in cloud formation. This is achieved using a mini ultralight radioprobe, having an approximate maximum weight of 20g, which is connected to a balloon with a maximum diameter of 30 cm.

The radiosonde is battery-powered and, due to its expendability, it is important to minimise its environmental impact by making the radiosonde as small as possible and developing a biodegradable purpose-made, a topic which will be deeply discussed in depth in Chapter 3.

2.1. introduction

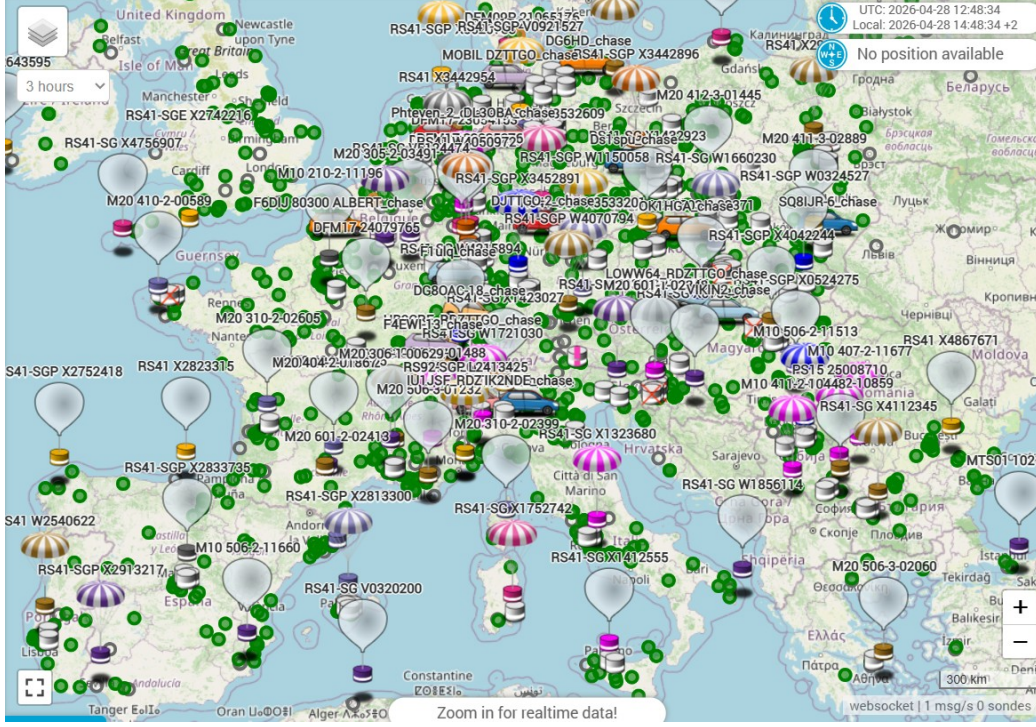


Figure 2.1: Active soundings recorded on SondeHub [26]

Figure 2.1 shows all the soundings that were taking place at the time of the search in the selected geographical zone, to illustrate how important it is to use an eco-friendly material while performing soundings. While the majority of the soundings use a natural latex balloon, this still takes between six months and few years to decompose. Additionally, the majority of radiosondes, such as those produced from Vaisala and used in Sub-section 4.2.1, not only are carried by a large latex balloon, but also use a parachute. Furthermore, these radiosondes are considerably larger than the proposed prototype and are enveloped in a polystyrene structure, which is certainly not biodegradable.

Therefore, it is understandable why it is important to reduce the size of the radiosondes and consider an alternative material for the balloon's construction.

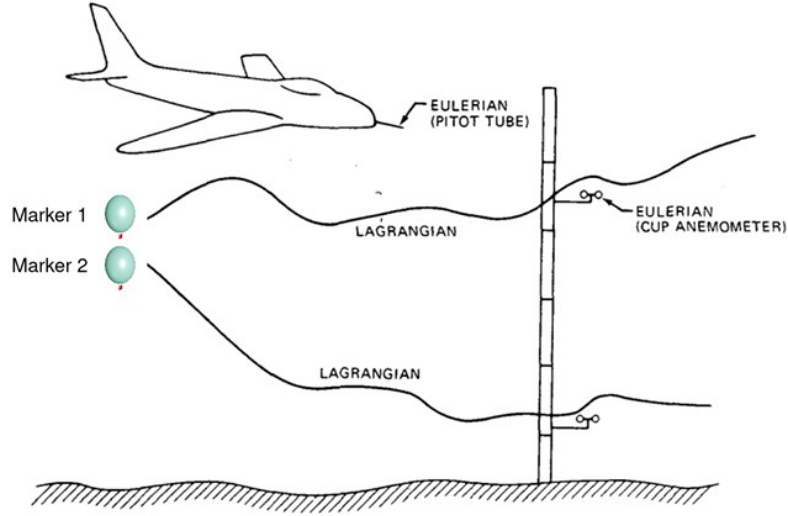


Figure 2.2: graphical representation of the difference between eulerian and lagrangian measurements

Another important point to mention is the shape of the balloon: the aim is to create a cluster of radiosondes that can be deployed by an aircraft or unmanned system. These radiosondes rise to a certain altitude and then start to float, being passively carried by atmospheric flows. They act as Lagrangian particles, tracking fluctuations in speed, temperature, humidity, pressure and magnetic field. Future prototypes that can also track carbon dioxide are under development. Acting as a Lagrangian particle means that the radiosondes behave like fluid particles moving within the studied flow. This is an ideal way to describe trajectories and turbulent dispersion, which is a topic of huge importance when studying the dispersion of pollutants in the atmosphere.

It is also worth mentioning that, at present, soundings are nearly-eulerian: sounding balloons rise from the release point to higher altitudes, until the material can no longer stretch anymore, ending the mission with the balloon bursting data being recorded at different altitudes. Our main goal is to provide data relating to the atmosphere boundary layer, (which can have a maximum thickness of 5km and where turbulence is highest), while the balloons are still rising. Then, we provide data at nearly constant altitudes while the balloons follow the atmosphere's fluxes as they act as Lagrangian particles transported by the flow (Figure 2.2).

2.2 Environment and design requisites

As we have mentioned, our aim is to create a system that acts as a group of Lagrangian particles. To achieve this, it is important that our system meets certain requirements.

Firstly, our system must be much smaller than the characteristic size of the phenomena we want to study.

Secondly, it is important that the balloon is as round as possible to minimize any movements caused by the system's inertia. This could lead to the formation of unexpected clusters and alter trajectories providing unreliable information.

If we want the system to float at a certain altitude and being transported by the flow in a passive way, it is important it maintains a constant weight and volume. Using a Mater-Bi^{©1} balloon enables us to satisfy this requirement due to the material's low elasticity. Our spherical balloon will have a maximum diameter of 30 cm. In order to float on an isopycnic surface, a surface characterized by equal density, its density must correspond to the target altitude (a maximum of 5 km altitude within the Atmospheric Boundary Layer).

In terms of the environment, the cloud system under study is characterized by small-scale geophysical turbulence, involving motion on a scale of order $\sim 10km$ or smaller. Given these dimensions, it is easy to see that the expected diameter of the balloon is much smaller than these values, meaning that its behaviour while being transported by the flux can be approximated to that of a fluid particle.

The object of our study is thermal convective clouds. Figure 2.3 shows a scheme representing the formation of convective clouds.

Firstly, solar radiation heats the ground. The ground's temperature then increases, generating heat fluxes that warm up the air layers directly above it.

¹Registered trademark of Novamont

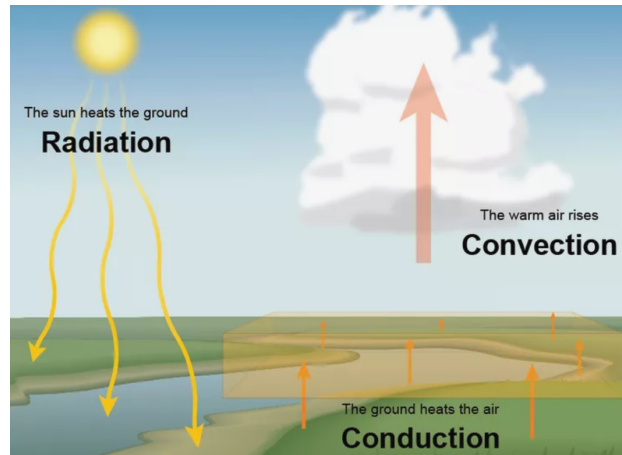


Figure 2.3: scheme representing convective clouds formation

Barren surfaces, such as sand and rock, tend to heat up more quickly than others like the surfaces covered by water or vegetation. Some air zones tend to warm up faster than others, resulting in patchy heating. Warmer air pockets have lower densities than the adjacent colder ones, they tend to rise vertically in a process known as "thermals". Heat and humidity are transported to higher altitudes. The convection process is stronger when the ground is heated more intensely, which is why this phenomenon tends to occur especially during spring and summer.



(a)



(b)

Figure 2.4: example of cumulus (a) and cumulonimbus (b) clouds

The air continues to rise, reaching zones of lower pressure and cools until the water vapour inside it condensates to create a cumulonimbus cloud (Figure 2.4a). If the air is particularly moist, a cumulonimbus cloud (Figure 2.4b) or towering cumulonimbus will form. In the latter case, there is a threat of severe weather.

Turbulence that characterizes these clouds is very fragmentated and tends to be anisotropic and intermittent in the zones of interface between clouds and subsaturated ambient air. This is why our radiosonde should have the appropriate sensors to measure these fluctuations. They are designed to measure eddies with a size range of between 0.5-1m, a maximum frequency of 0.5-1 Hz and a kinetic energy per unit mass of 0.001-0.01 $(m/s)^2$. It is also important to mention that the cost of the sondes should be as low as possible, not only because the sondes are expendable, but also because a large number of them are needed for each deployment.

Our system should be able to measure speed, acceleration, pressure, temperature, and relative humidity fluctuations. Some operational requirements were set considering the environment of warm clouds: temperature=0-30°C, external relative humidity (RH)=0-100%, external pressure=400-1100 mbar, trajectories=+/-100 mm accuracy and airflow fluctuations=5-6 m/s inside the clouds.

Finally, we must consider that the system collects data and sends it to a data-acquiring system via wireless technology until the radiosonde's battery runs out. Clearly, finding a transmission technology that enables us to reach longer distances without using too much power is crucial.

2.3 System architecture and design methodology

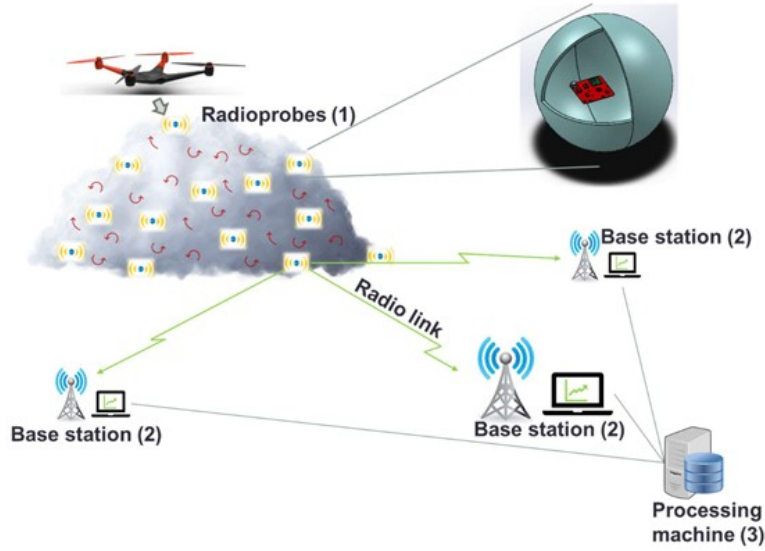


Figure 2.5: working principle and sonde's system architecture

Figure 2.5 shows the working principle of the system. The wireless sensor network (WSN) comprises the following elements: a system made of a round Mater-Bi balloon and a radiosonde (1), which is equipped with all the necessary sensors to measure atmospheric fluctuations. This system can transmit collected and preprocessed data to the base station (2), which is located on the ground. These ground stations can receive and gather data, which they send to the processing machine (3). This machine can perform some post-processing activities such as filtering and visualization.

Figure 2.6 shows the system described by its functional blocks:

1) data processing and control unit

This is the computational module of the system. It controls and executes different subsystems automatically. After receiving data from the sensors, the data processing and control unit interprets, processes and saves the data before sending them to ground stations via the transmission module.

2) radiocommunication system

This is a one-way wireless communication system with ground stations, and the LoRa is the preferred method. This module also contains two RF antennas: one transmits in-flight collected data to the ground stations, and

the other obtains positioning and timing data from satellites.

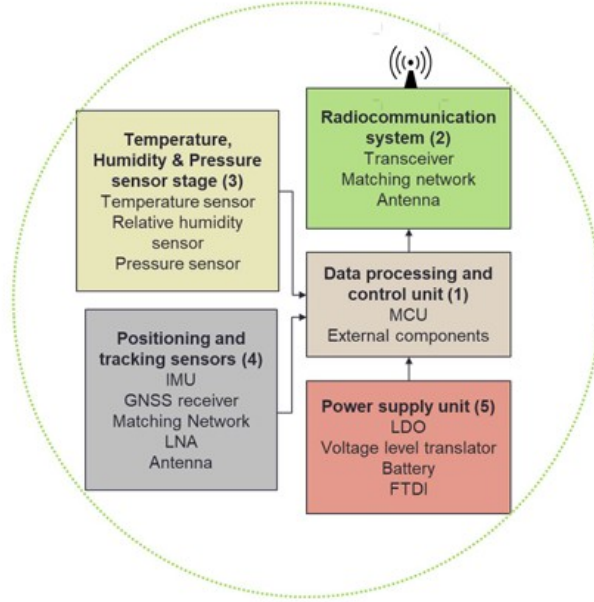


Figure 2.6: radiosonde's block diagram

3)temperature, pressure, humidity sensor stage

The BME280 sensor was chosen as it consumes a very low amount of current (μA), which is ideal for our battery-powered system.

4)positioning and tracking sensor stage

The properties of particles in a Lagrangian reference system are determined by measuring their properties while flying along a trajectory over time. Tracking data obtained from a large number of sondes simultaneously gives us the opportunity to determine the characteristics of the entire domain during the flight. An orientation filter is used to combine data obtained from the Inertial Measurement Unit (IMU) and a Kalman filter uses the orientation filter's output to fuse it with the data coming from the Global Navigation Satellite System (GNSS) receiver.

5)power supply unit

The system is currently powered by a single 4.0 V lithium metal oxide (LMO) non-rechargeable battery with a nominal capacity of 125 mAh and a pulse current capacity of 3.75A.

Chapter 3

Mater-Bi balloons



3.1 Introduction

The correct choice of size, shape and material of the balloons used to carry the radiosonde is a crucial issue.

First of all, our balloons should have a shape as close to spherical as possible, in order to behave as a particle following a Lagrangian trajectory within the flow: a different shape, such as an oblate or prolate one, would

introduce additional disturbances in the motion, leading to distorted measurements of atmospheric dynamics.

Another important aspect to consider is the target altitude and environment of our measurements. We are interested in studying turbulent dynamics within the Atmospheric Boundary Layer (ABL). Our balloons should therefore be able to carry radiosondes to altitudes within the boundary layer and withstand atmospheric humidity and potential rain. To achieve these goals, our balloons should have little wettability and maintain a constant volume. The balloon's volume should be chosen to allow it to float within a certain altitude range once a condition of neutral buoyancy is reached.

Last but not the least, environmental impact should be taken into account: at present, we do not have a systematic way to recover the balloons at the end of their flight, and it is fairly clear that this could negatively impact on the environment in terms of pollution.

Taking the aforementioned points into account, and also considering the importance of using material that is easily available on the market, the choice fell on Mater-Bi®[®], a material developed by Novamont and already familiar to us due to its use in the production of compostable shopping bags.

In this chapter, we will discuss all the reasons behind this choice and how to properly size and thermally seal balloons to give them a shape as spherical as possible. A retention test was also carried out to compare the performances of balloons hand-sealed by the Houseflies team with that of the balloons sealed industrially, which were produced by Grabo Srl.

3.2 Material choice

At the beginning of the Horizon 2020 Innovative Training Network Cloud-Microphysics-Turbulence-Telemetry (MSCA-ITN-COMPLETE) project, Basso et al. [7] had to identify the material that would guarantee the best performances while meeting the requirements we previously discussed. The reference materials are latex and Mylar, which are currently used for sounding balloons. However, these materials tend to change volume when ascending due to their elasticity.

The perfect material would guarantee that balloons maintain a constant volume and weight in order to be able to float on isopycnic surfaces. This can be achieved wby using a material with low wettability and low elasticity that has a very low Helium (He) permeability.

The two materials chosen to replace Mylar and Latex were Mater-Bi and

3.2. Material choice

Polylactic Acid (PLA). The effect of coatings was also studied. The coatings chosen for this study were selected based on their ability to decompose through bacteria, i.e. their biodegradability.

Experiments were conducted on 14 cm diameter balloons made of Mater-Bi[®], Mylar and PLA, with a thickness ranging from 30 to 60 μm .

Tensile strenght of different materials was the first investigated property.

Material	Young's modulus (MPa)	Tensile stress at yield (MPa)	Ultimate stress (MPa)	Elongation at break (mm/mm)	Energy (J/m ³)
Latex	4 $\pm$ 1	7 $\pm$ 1	27 $\pm$ 1	18 $\pm$ 0.3	125 $\pm$ 6
Mylar	1185 $\pm$ 33	30 $\pm$ 1	55 $\pm$ 3	0.8 $\pm$ 0.1	35 $\pm$ 4
Mater Bi	161 $\pm$ 13	8 $\pm$ 1	12 $\pm$ 1	3.2 $\pm$ 0.1	34 $\pm$ 2
Mater Bi+Cwax+Pine Resin	121 $\pm$ 10	6 $\pm$ 0.2	10 $\pm$ 1	3.1 $\pm$ 0.7	26 $\pm$ 6
Mater Bi+Cwax+SiO ₂ NPs	108 $\pm$ 11	4 $\pm$ 1	7 $\pm$ 0.5	1.1 $\pm$ 0.1	8 $\pm$ 1
PLA	1578 $\pm$ 93	18 $\pm$ 2	24 $\pm$ 4	0.09 $\pm$ 0.05	4 $\pm$ 2
PLA+Cwax+Pine Resin	925 $\pm$ 22	15 $\pm$ 1	17 $\pm$ 1	0.07 $\pm$ 0.04	6 $\pm$ 3
PLA+Cwax+SiO ₂ NPs	993 $\pm$ 112	14 $\pm$ 1	17 $\pm$ 1	0.06 $\pm$ 0.01	2 $\pm$ 1

Table 3.1: characteristic average values. These results were obtained after performing experiments with an INSTRON machine at a deformation rate of 1 mm⁻¹. [7]

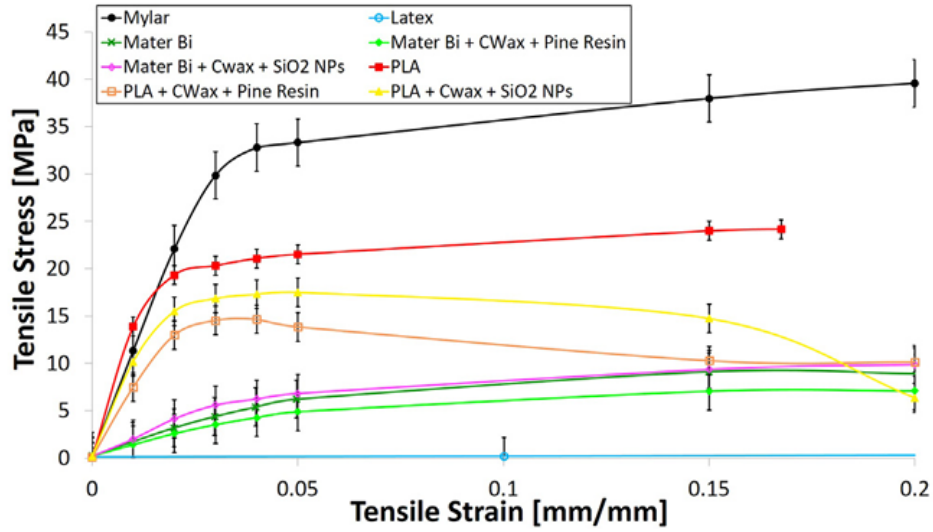


Figure 3.1: Tensile Stress-Strain curves for one test for each material used during tests. [7]

As can be seen in Table 3.1, PLA, is characterized by a high toughness, comparable to that of Mylar, independently of its coating. This toughness is around 1000MPa. This property enables the balloon to float at a convenient altitude without the entire system expanding. However, PLA has an

3.2. Material choice

elongation at break of $\sim 1 \text{ mm mm}^{-1}$, meaning the structure would not be able to support even slight expansion, resulting in the balloon bursting prematurely. Therefore, we concluded that PLA is not the best material for our needs.

Conversely, Mater-Bi has a lower Young Module (100-200 MPa), meaning it is more elastic and can withstand minor expansions, as confirmed by its elongation at break of $\sim 3 \text{ mm mm}^{-1}$.

Mater-Bi would still allow the balloon to float at a constant altitude, and its ability to expand around 300% of its initial size would not lead to a premature burst. It is clear why Mater-Bi was the best choice.

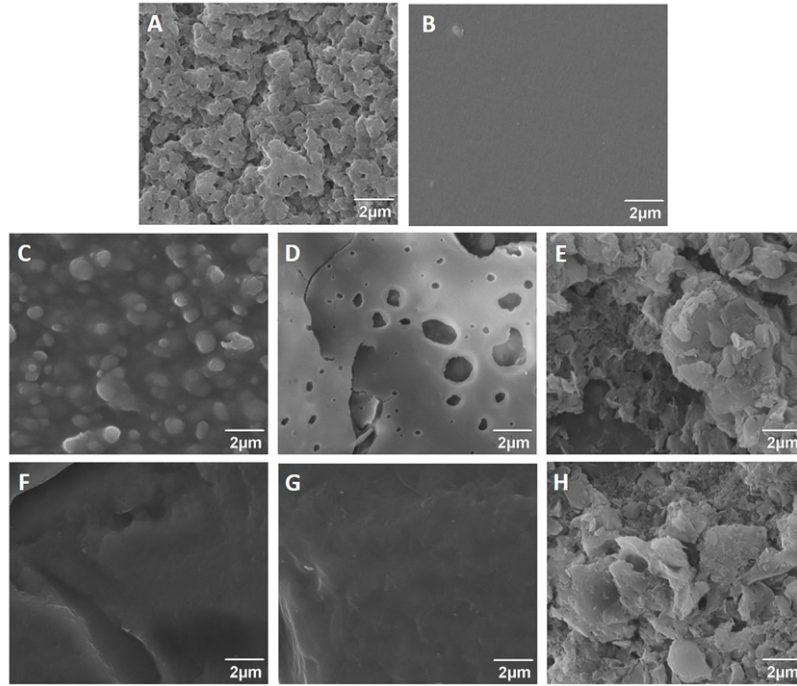


Figure 3.2: Images taken with a scanning electron microscope at magnification $\times 6000$. (A) Latex, (B) Mylar, (C) Mater-Bi[©] (D) Mater-Bi + carnauba Wax + Pine Resin, (E) Mater-Bi + Carnauba Wax + SiO_2 NPs, (F) PLA, (G) PLA + carnauba Wax + Pine Resin, (H) PLA + carnauba Wax + SiO_2 NPs [7]

Balloons float in and out of clouds, which indicated that this environment is certainly characterized by high humidity. This can lead to droplets condensing on the surface.

If balloons have a high wettability, their weight will certainly increase, in-

evitably decreasing the altitude they can reach.

A higher contact angle indicates that the material is more hydrophobic.

Super hydrophobicity is reached with contact angles around 150° .

Latex and Mylar have contact angles of around 95° , pristine Mater-Bi and PLA's have contact angles of around 90° , meaning they are more wettable. This hydrophobic property was achieved by spraying the surface with a polymery-based coating.

A $5\ \mu\text{l}$ droplet was deposited on the surface of the different materials to measure the contact angle and, consequently, the wettability of the material.

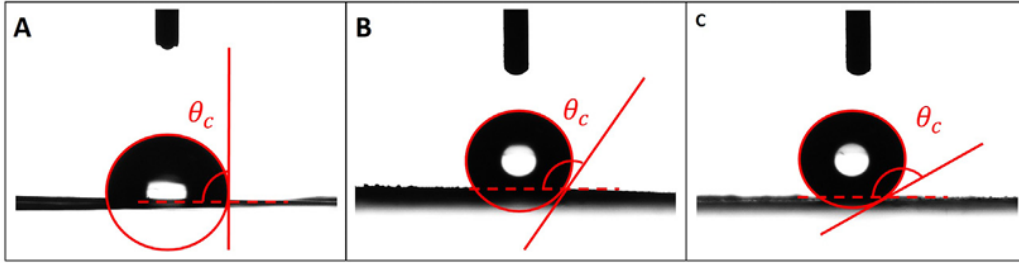


Figure 3.3: increase of contact angle (and so hydrophobicity) when a $5\ \mu\text{l}$ droplet is placed on (A) Mater-Bi, (B) Mater-Bi coated with carnuba wax and (C) Mater-Bi coated with carnuba wax+ SiO_2 [7]

The size of the droplet was chosen to provide an accurate measurement of the surface properties, independent of gravity phenomena. The latter is not negligible in the case of large droplets. In (C) a size of $12\ \mu\text{l}$ was chosen due to the extremely high hydrophobicity, which prevented the droplet from detaching from the needle. In this case, a contact angle of around 140° was measured, which can be considered a satisfactory result.

As discussed in [7], Mater-Bi also performed satisfactorily in terms of helium permeability.

3.3 Balloon Sizing

We will now discuss the process of correctly sizing the balloons to achieve the desired altitudes. This process is the same as that presented in [36] and it is based on Archimede's principle of buoyancy.

When a balloon is inflated with a gas that is less dense than air, an upward force is generated:

3.3. Balloon Sizing

$$F_b = (\rho_{air} - \rho_{He})V_b g \quad (3.1)$$

Where $\rho_{air}gV_b$ is Archimede's buoyancy force while $\rho_{He}gV_b$ is the weight of the gas inside the balloon and V_b is the ballon's volume. F_b is the effective buoyancy force.

It is also possible to write 3.1 in terms of masses:

$$M_t = (\rho_{air} - \rho_{He})V_b \quad (3.2)$$

where $M_t = m_{balloon} + m_{radiosonde}$.

By reversing the equation, we can obtain:

$$V_b = \frac{M_t}{\rho_{air} - \rho_{He}} = \frac{m_b + m_r}{\rho_{air} \left(1 - \frac{M_{He}}{M_{air}}\right)} \quad (3.3)$$

By considering the equations for sphere's volume and balloon's mass:

$$V_b = \frac{4}{3}\pi R_b^3 \quad (3.4)$$

$$m_b = \rho_m t S_b = 4\pi R_b^2 t \rho_m \quad (3.5)$$

It is possible to put equations 3.4 and 3.5 into 3.3 in order to obtain a third order equation in the unknown R_b .

Considering the molar masses of $M_{He} = 4.003g/mol$ and $M_{air} = 28.96g/mol$, a material thickness $t = 23\mu m$ and a material density of Mater-Bi of $\rho_m = 1.29g/cm^3$, we can describe some parametric curves as it was done in S. Abdunabiev et Al. [5]. One curve was described for each considered mass of radiosonde, while the density of air, ρ_{air} , was computed at different altitudes in accordance with ICAO standards.

For example, if we have a balloon with the above-mentioned characteristics and want it to reach an expected altitude of 5 km, and assuming that it is inflated optimally way, its radius should be slightly smaller than 30 cm.

3.3. Balloon Sizing

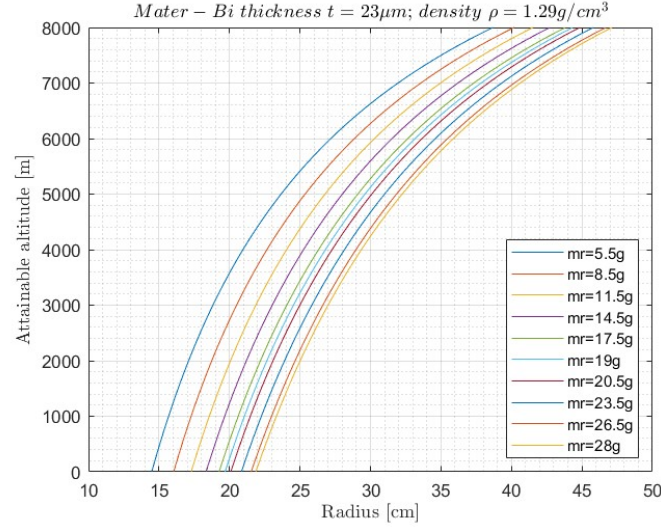


Figure 3.4: parametric curves showing expected attainable altitude based on the carried radiosonde's mass and balloon's radius

The same process was carried out using balloons made of Mylar and PA-LPDE. Figure 3.5 shows different curves obtained for the various materials and payloads. These were then compared with some experimental measurements, demonstrating the a good reliability of the proposed sizing method.

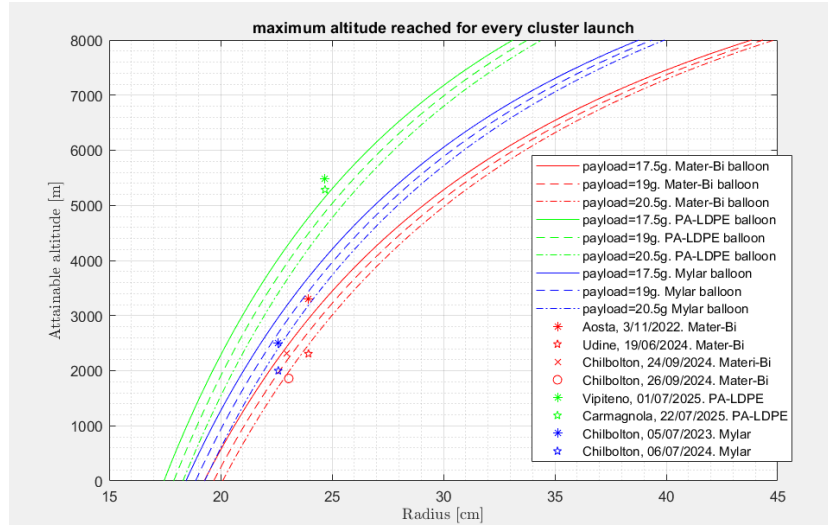


Figure 3.5: Parametric curves for different materials and payloads compared with experimental data obtained from different launches

3.4 Balloon production

In this section we will discuss the process required to produce a spherical balloon.

The production of balloons is one of the most crucial aspects of a successful experiment. The main challenges are creating a 3D shape from a flat one and the sensitivity of Mater-Bi to heat.

The current state of balloon production has also been achieved thanks to the work of past thesis students: Andrea Caporali [11], Giovanni Cipri [12], Pierpaolo Di Felice [15] and Chiara Geron [17]. They were the first to produce Mater-Bi balloons and the current shape of the petals and the balloons themselves is the result of their work.

Firstly, the approximate volume of the balloon must be calculated considering the weight of the attached radiosonde and the desired altitude.

The balloon will comprise four petals and a round top cover which will be thermally soldered together. The shape of the petals and the round cover is shown in Figure 3.6.

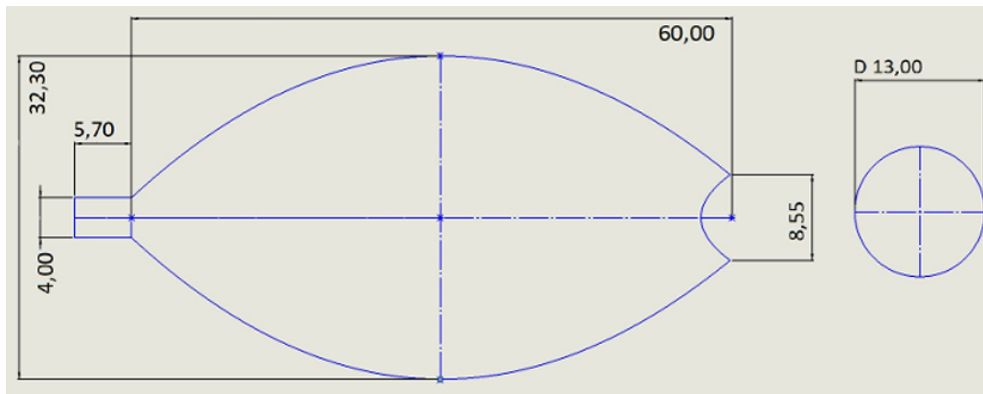


Figure 3.6: CAD model of balloon's parts which will be sealed together. Dimensions were changed in order to obtain a spherical balloon with an approximate diameter of 40 cm

The shapes were cutted from flat sheets of Mater-Bi and then, until recently they were to be thermally sealed together using a manual sealer like the one shown in Figure 3.7.

This method was really impractical as it was really easy to burn the material while soldering it due to a lack of pressure and speed regulation. It should also be noted that producing a single balloon used to take several hours, which is a considerable amount of time.



Figure 3.7: Manual thermal sealer used for balloon's production. It is provided with a temperature regulator.

For this reason Riccardo Villa [33] developed a welding machine during his thesis project. The Houseflies team used this machine to create the latest balloons for performing retention tests, which drastically reduced the production time from a few hours to one hour.

This prototype enables us to control the pressure and speed during soldering. Mater-Bi sheets pass through two wheels: the sealer's and a teflon wheel mounted at the bottom of the machine. The sealer's regulator can still be used to control temperature. Before welding the material, the Mater-Bi is covered with two Teflon sheets to allow the heat to diffuse better and prevent the material from burning.

Once all the petals have been soldered together, it is important to check any damage or holes in the material. If the quality check is passed, the upper cover can be soldered.

The balloons can then be inflated if we want to perform some experiments or store them for future use.

3.4. Balloon production

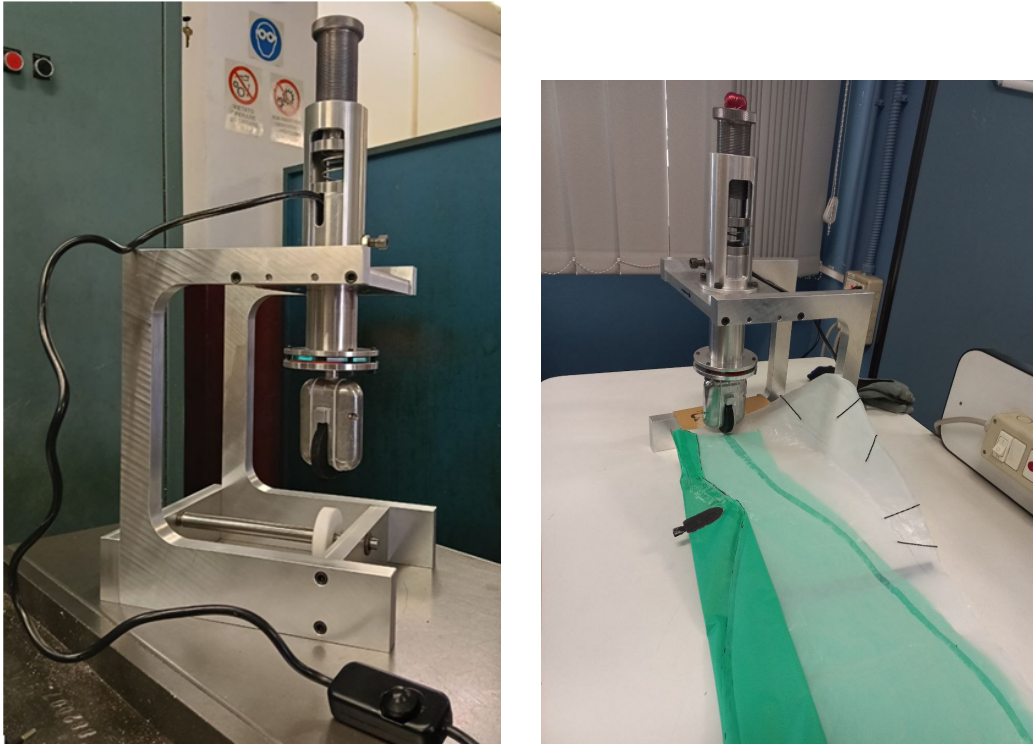


Figure 3.8: Thermal welding machine developed by Riccardo Villa [33]



Figure 3.9: Inflated balloons used for performing a retention test

3.5 Retention test: 24/25 September 2025

This experiment took place on the DISAT (Dipartimento di Scienza Applicata e Tecnologia) rooftop between 24 and 25 September 2025.

Mater-Bi balloons made using the welding machine developed by Riccardo Villa [33] were used during this experiment. The main goal of this experiment was to investigate how long the balloons could remain inflated in order to assess the quality of the welding. Two radiosondes were also attached to the balloons to measure environmental parameters.

Preparation

Before this experiment was carried out, a first attempt was made, but it ended up in failure because the welded balloons were too small to lift up the radiosondes. For this reason, new balloons were cut adding five centimeters of thickness to the entire design for each petal of the balloon. After the outline of each petal was drawn, the petals were welded to each other one by one.

Once all the petals had been welded, the tops of the balloons were closed in two different ways: the first balloon was closed with a rope and a welding, and the second with some rope and some electrician's tape.

After ensuring that all the holes in the balloons were properly closed, the two empty balloons were weighted.

Balloon	Weight [g]
1 (top welded)	41.23
2 (not welded on top)	45

Table 3.2: Empty weight of the balloons

After weighting the balloons, they were inflated with helium for a retention test.

During this test, we wanted to check out if the balloons would have enough lifting force to carry the radiosondes for an entire day. We also wanted to understand if they would be able to resist any mechanical stress due to rainy weather and wind throughout the radiosondes working time, until the batteries ran out.

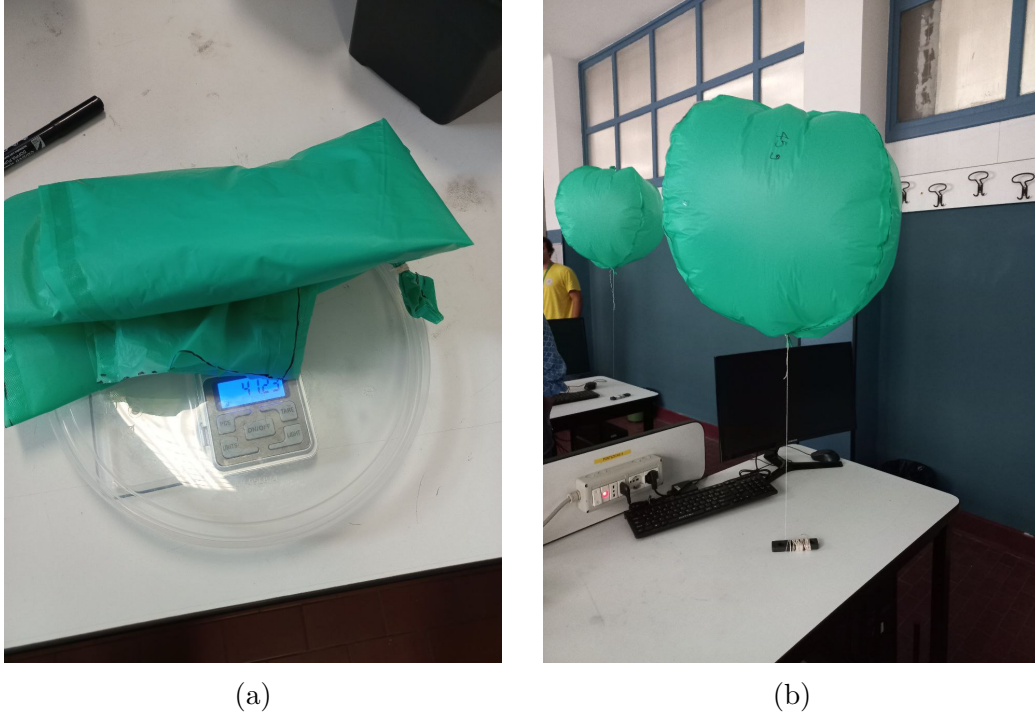


Figure 3.10: weighting phase (a) and filled balloons (b) used for retention test

After filling the balloons, they were weighted to calculate their lifting force. The balloons were attached to a $\sim 200g$ weight, so the lifting force was found by subtracting this value from the reading on the balance.

Balloon	Lifting Force [g]
1 (top welded)	200-169.8 $\sim$ 30.2
2 (not welded on top)	200-167.8 $\sim$ 32

Table 3.3: Lifting force before the experiment

The lifting force is the total weight that our system can lift. When considering a system, this includes the helium inside of it, the envelope and the rope attached to it. The final part of the preparation phase involved attaching the radiosondes to the balloons, setting up the equipment, and leaving the balloons on the roof of DISAT.

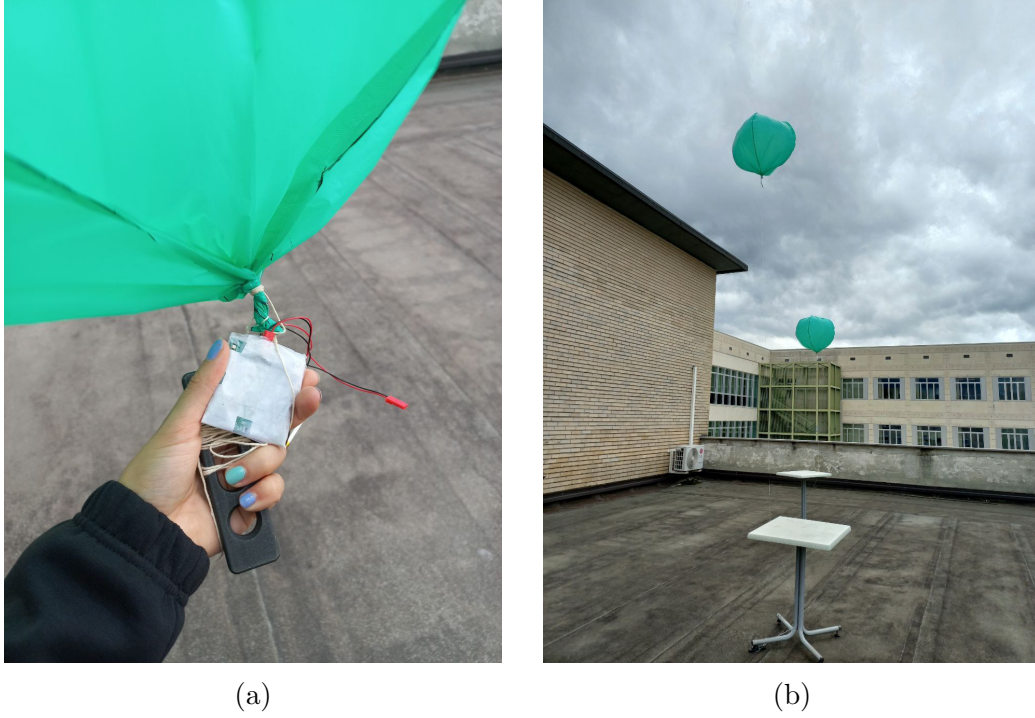


Figure 3.11: attached radiosonde (a) and completed setup (b)

Experiment and data

The entire experiment lasted just over one day.

	Start	End
Date	24/09/2025	25/09/2025
Retention Test	1.40 p.m.	11.30 a.m
Data collection	1.40 p.m.	1.50 a.m.

Table 3.4: Timetable

Data collection continued until the radiosonde's battery ran out. Even after being exposed to rain and wind, the balloons remained intact after the end of the experiment.

The balloons could no longer sustain the weight of the radiosonde, but the second balloon (which had the greatest lifting force) was still able to float. Considering the retention test a success, we proceeded to evaluate the remaining lifting force of the balloons, in order to make estimations for further tests.



Figure 3.12: weighting of second balloon after retention test

At the end of the retention test, the resulting lifting force was $\sim 3gr..$

Radius evaluation

After considering the retention test a success, we have to check if the system would respect the mission requirements.

One of the main requirements is that, in order to stay inside the Planetary Boundary layer, the balloons shouldn't fly above 5 km altitude.

Considering that the maximum reachable elevation is strictly connected to the balloon's radius, we will now evaluate an esteem of the balloon radius in two different ways: from the balloon's weight and from the buoyancy's law.

Considering the second balloon, we now evaluate the radius from its empty weight:

$$m = \rho_{mb} 4\pi r^2 t_{mb} \quad (3.6)$$

where:

density ρ_{mb}	1,24 – 1.29g/cm ³
thickness t_{mb}	30μm

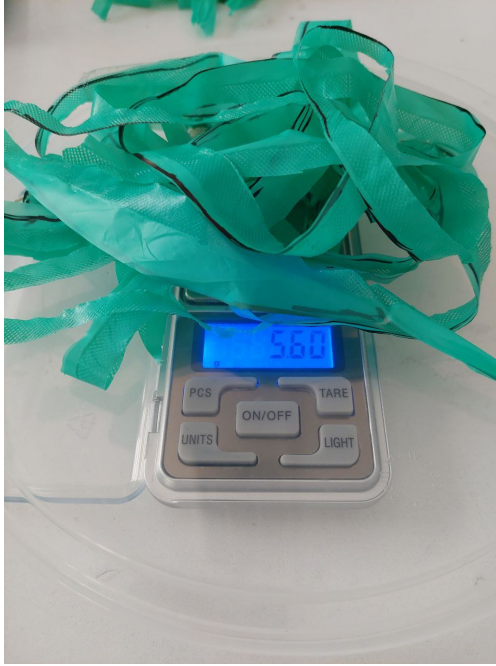
Table 3.5: Mater-Bi features

We will have:

$$r = \sqrt{\frac{m}{4\pi\rho_{mb}t_{mb}}} \quad (3.7)$$

We also noticed that this evaluation may overestimate the actual radius of the balloon due to the fact that we are assuming that all the weight will contribute to the balloon's volume, while the top and bottom parts, as well as the welded stripes, will just add extra weight to the system.

For this reason, we cut all the parts that will not contribute to the volume, weighted them and then weighted the remaining part of the balloon.



(a)



(b)

Figure 3.13: weighting of the cuttings discarded from second balloon (a) and final weight of the second balloon (b)

balloon	initial weight [g]	cuttings [g]	final weight [g]
1 (top welded)	41.23	5.72	32.99
2 (not welded on top)	45	5.60	38

Table 3.6: cuttings and final weight

Considering the two balloons and the different estimations of the total mass concurring to the volume, and the minimum and maximum Mater-Bi possible densities, we will have:

balloon	$\rho_{mb}[kg/m^3]$	radius (total mass) [cm]	radius (no cuttings) [cm]
1 (top welded)	1.24	29.70	26.57
1 (top welded)	1.29	29.11	26.05
2 (not welded on top)	1.24	31.03	28.51
2 (not welded on top)	1.29	30.42	27.95

Table 3.7: Radius experimental estimate

We can now proceed with a parametric esteem, which we will use to understand if the system satisfies the mission requirements. Considering the buoyancy equation 3.3, the sphere volume equation 3.4 and balloon's mass equation 3.5 and combining them we obtain the following:

$$\frac{4}{3}\pi R_b^3 = \frac{m_r + 4\pi R_b^3 t_{mb} \rho_{mb}}{\rho_{air} - \rho_{He}} \quad (3.8)$$

which is a third-order parametric equation having R_b as unknown and m_r and ρ_a as parameters.

We will consider the two different cases, one by one.

Supposing a Mater-Bi density $\rho_{mb} = 1.24kg/m^3$, and solving equation (3.8) for different radiosonde's masses, it is possible to obtain the following parametric curves:

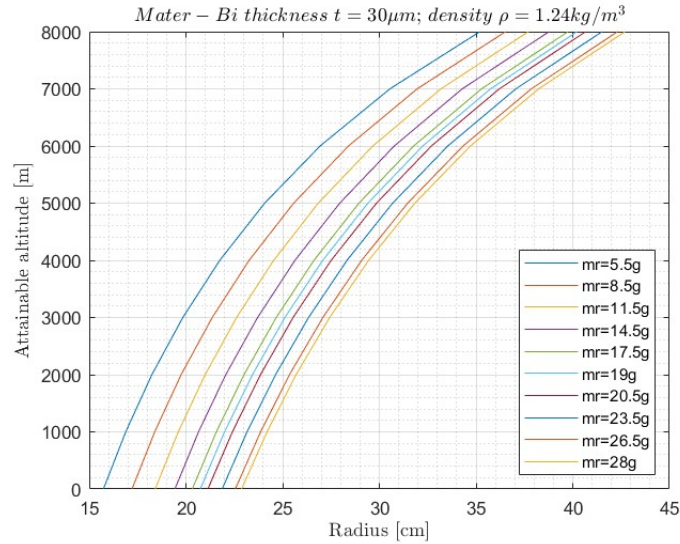


Figure 3.14: parametric curves for different radiosonde's masses

Considering a radiosonde's mass of 19 grams, it is possible to compare this results with the ones from Table 3.7.

For the first balloon (top welded):

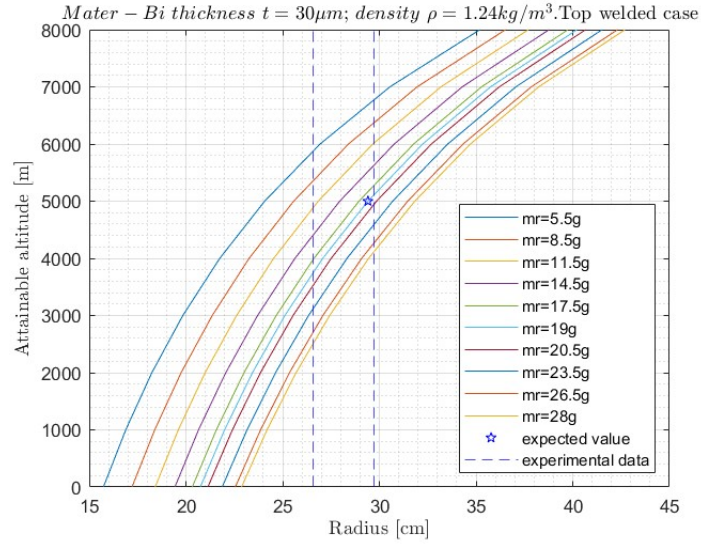


Figure 3.15: top welded balloon. First case

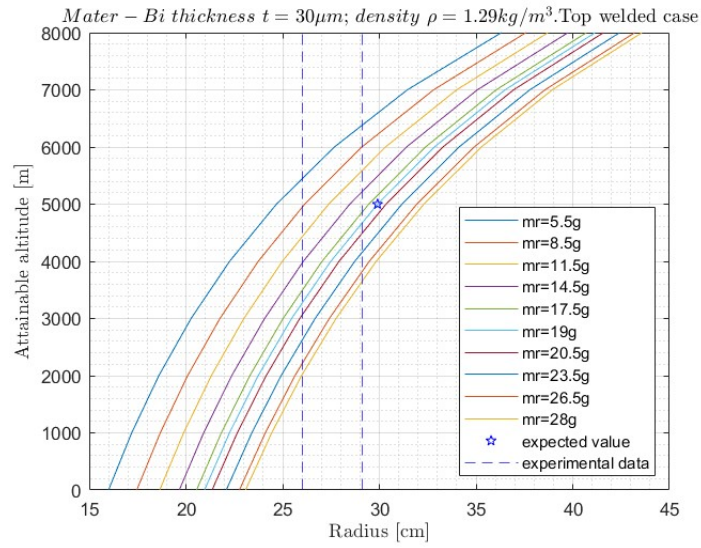


Figure 3.16: top welded balloon. Second case

And for the second balloon (not welded on top):

3.5. Retention test: 24/25 September 2025

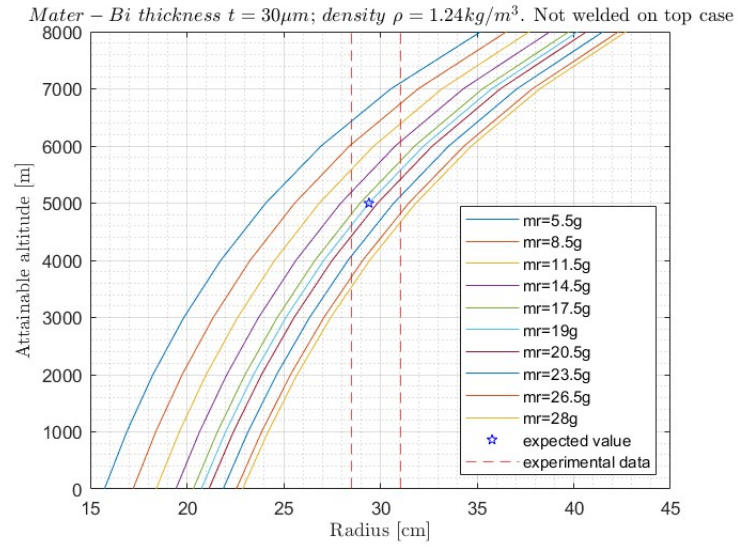


Figure 3.17: not welded on top balloon. First case

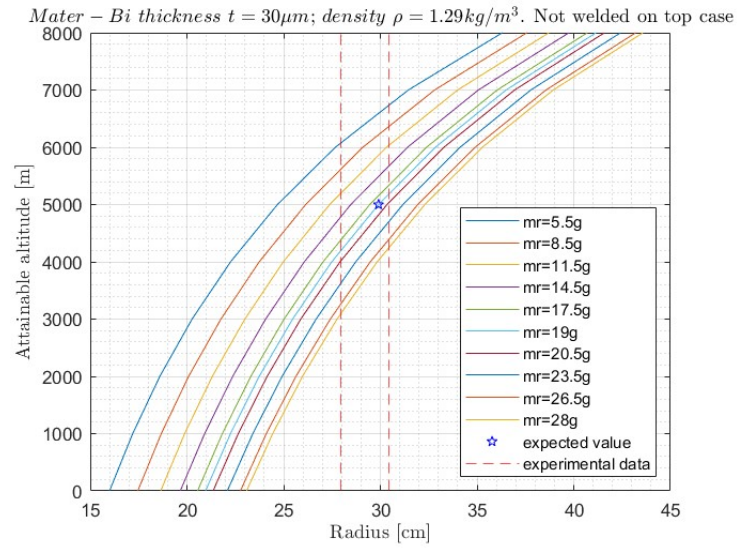


Figure 3.18: not welded on top balloon. Second case

Where, for all the shown cases, all the possible radius will be inside the two dotted lines.

Data analysis

We will now spend few lines describing the obtained results by analyzing our plots. We'd like to see if the sondes reported similar data during the experiment and then see, by a comparison with other data from different institutions, how reliable our dataset is.

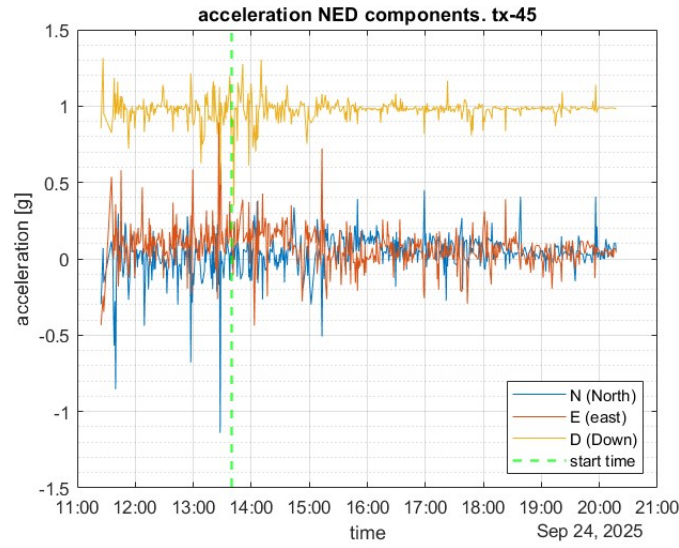


Figure 3.19: NED acceleration components of tx-45 sonde

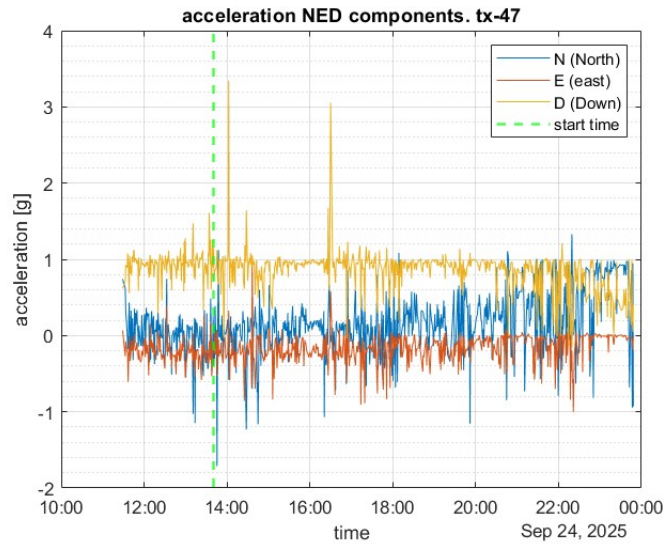


Figure 3.20: NED acceleration components of tx-47 sonde

3.5. Retention test: 24/25 September 2025

We can notice the presence of an offset of the acceleration component along the North direction.

This offset has a value of 1 g, which is consistent with the value of gravitational acceleration constant towards Earth's center. The other acceleration components are oscillating around zero, which is also consistent.

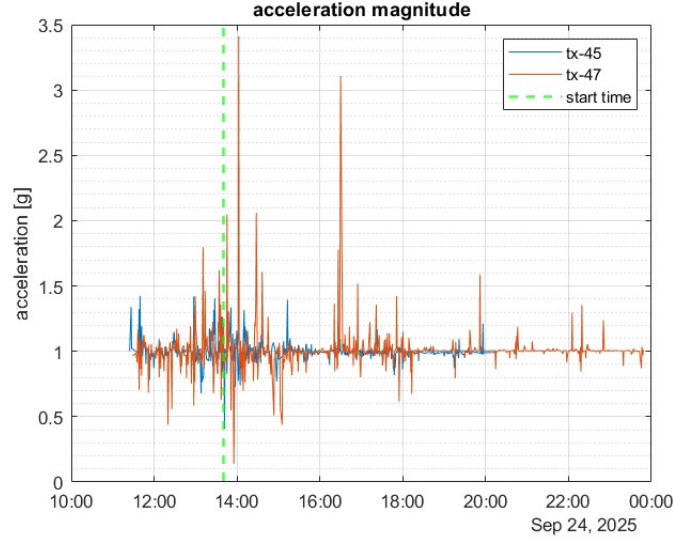


Figure 3.21: NED acceleration magnitudes

The dotted green line indicates the starting time of the experiment, that is when the sondes were placed in position.

We can notice some huge acceleration spikes, indicating the tension's action directed along the rope keeping the balloons in position.

The same was done with the magnetic field components and magnitudes, as shown below.

3.5. Retention test: 24/25 September 2025

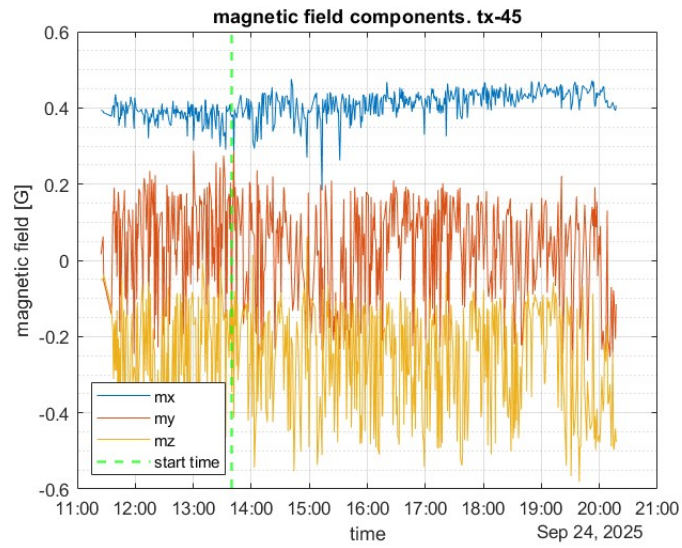


Figure 3.22: magnetic field components of tx-45 sonde

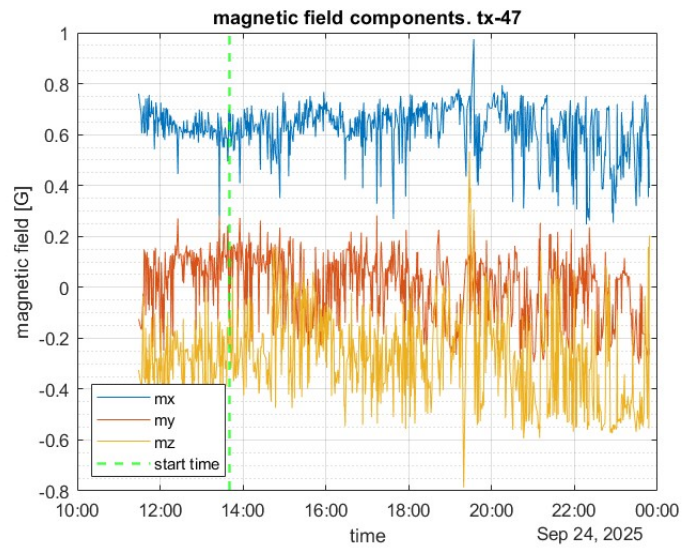


Figure 3.23: magnetic field components of tx-47 sonde

3.5. Retention test: 24/25 September 2025

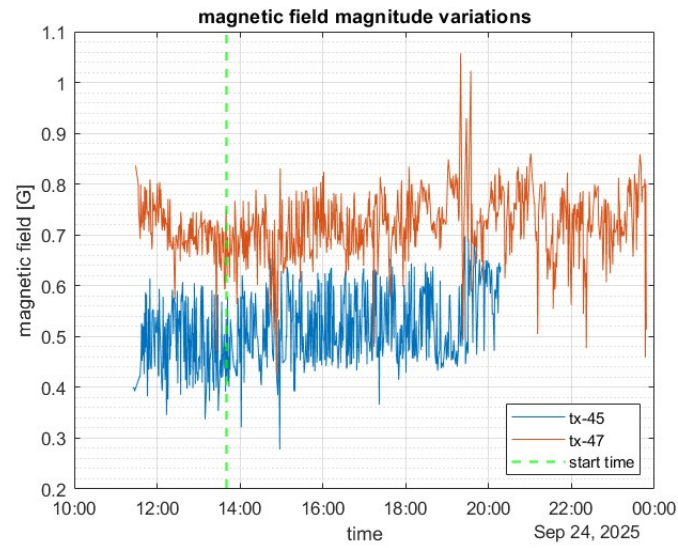


Figure 3.24: magnetic field module oscillations

We can now finish by analyzing pressure, temperature and humidity profiles tracked during the experiment.

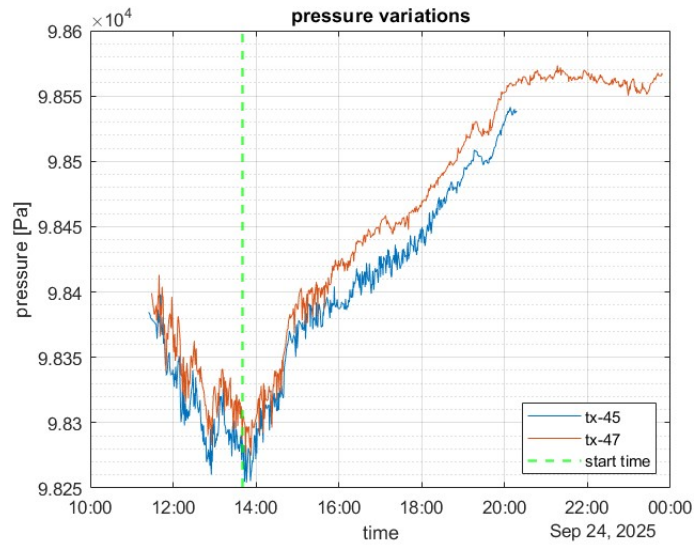


Figure 3.25: pressure variations

3.5. Retention test: 24/25 September 2025

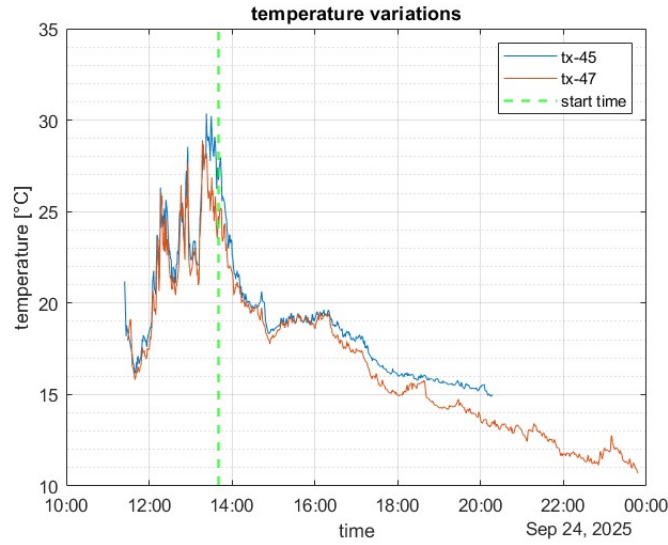


Figure 3.26: temperature variations

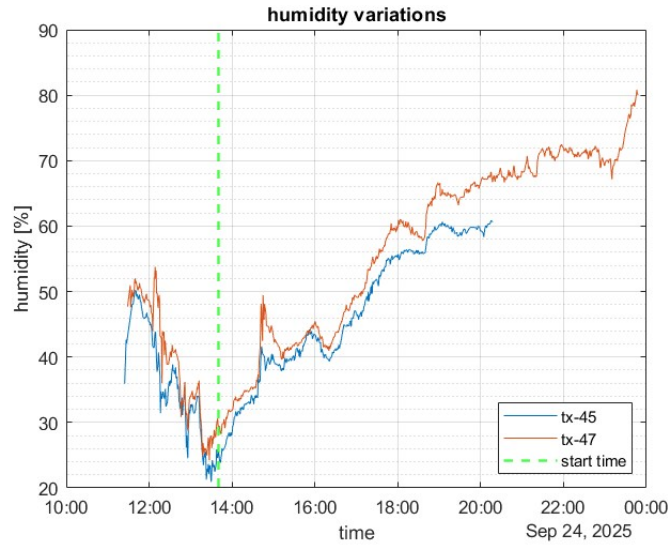


Figure 3.27: humidity variations

By observing the above plots we can notice that the profiles tracked by the two radiosondes are consistent with each other. Those profiles could eventually be used to compare the acquired results with the ones tracked by other organizations in order to validate them.

We now do this comparison by using data available at [3].

3.5. Retention test: 24/25 September 2025

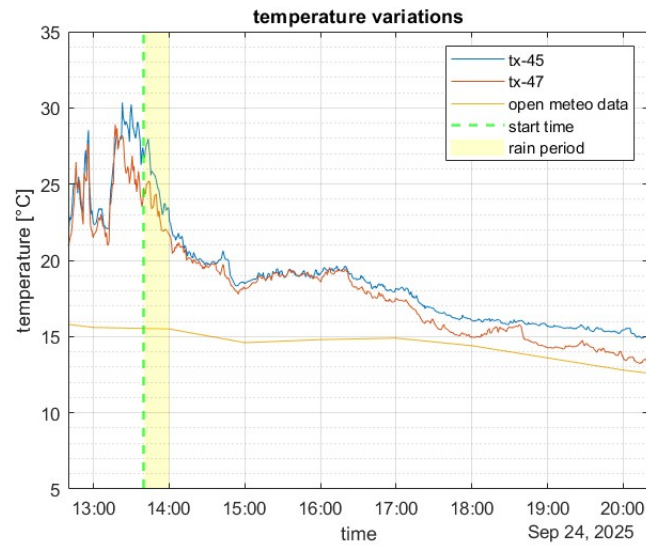


Figure 3.28: temperature variations comparison with Open Meteo data

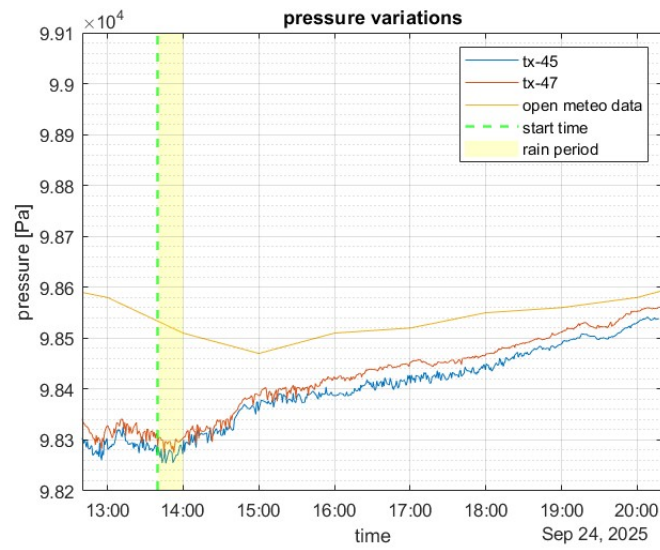


Figure 3.29: pressure variations comparison with Open Meteo data

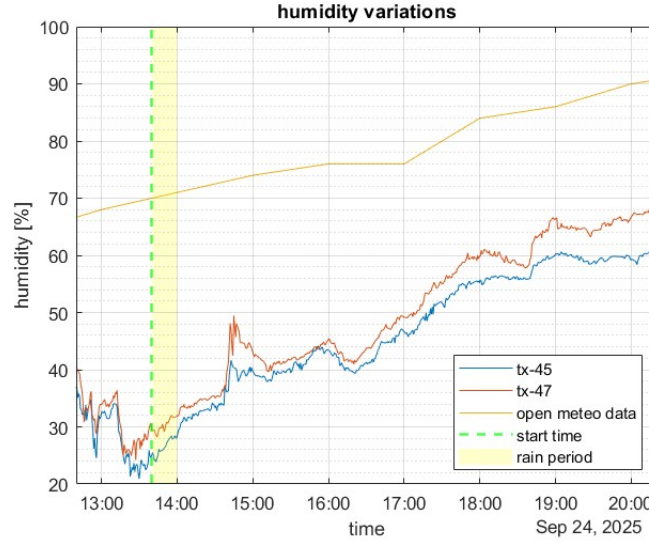


Figure 3.30: humidity variations comparison with Open Meteo data

By observing resulting graphs, we can notice how important it is to let the sondes stay exposed to outside environments for an amount of time close to one hour in order to obtain reliable data: as the time passes by, data becomes more consistent when analyzing temperature and pressure data. Unfortunately, we cannot say the same for humidity variations, as shown in Figure 28: recorded humidity appears to be too low. At the beginning, we supposed that recorded humidity was too low due to the fact that between 13:00 and 14:00 there was light rain. The comparison with data obtained for Open Meteo [3] confirmed our supposition.

In general, reported behaviour is consistent with what was found in Chapter 4 when comparison between Houseflies and Vaisala radiosonde was done.

Conclusions

In this section we will spend few lines to discuss the obtained results.

3.5. Retention test: 24/25 September 2025

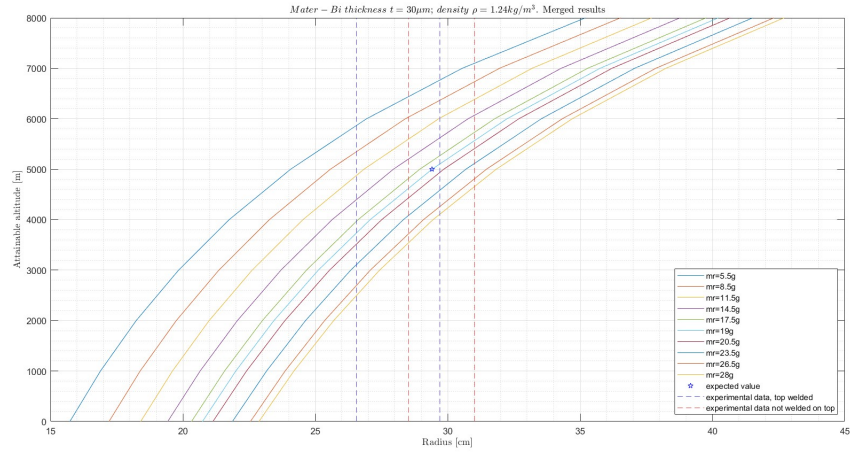


Figure 3.31: Merged results. First case

Balloon	$\rho_{mb}[\text{kg/m}^3]$	attainable altitude range [m]
1 (top welded)	1.24	3800-5100
2 (not welded on top)	1.24	4600-5600

Table 3.8: altitude range: first case

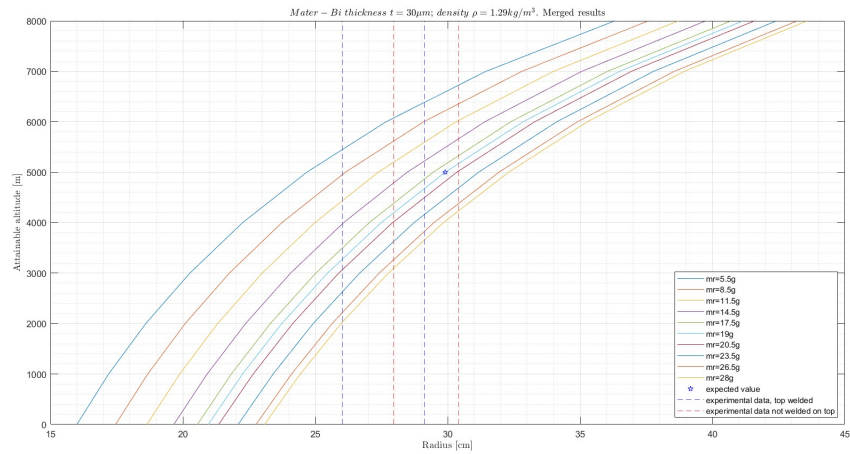


Figure 3.32: Merged results. Second case

3.5. Retention test: 24/25 September 2025

Balloon	$\rho_{mb}[kg/m^3]$	attainable altitude range [m]
1 (top welded)	1.29	$\sim 3300-4700$
2 (not welded on top)	1.29	$\sim 4200-5200$

Table 3.9: altitude range: second case

by merging all the data, we can have an idea of the biggest attainable altitude range, in which we consider minimum and maximum Mater-Bi densities:

Balloon	maximum altitude range [m]	radius range [cm]	weight range [g]
1 (top welded)	$\sim 3300-5100$	26.05-29.70	$\sim 32.99-41.23$
2 (not welded on top)	$\sim 4200-5600$	27.95-31.03	$\sim 38-45$

Table 3.10: Results summary

The not-welded-on-top balloon perfectly satisfies the mission requirements, while the top-welded one can be considered acceptable, but with the awareness that there is a big probability it would only reach lower altitudes. The perfect choice will depend on the purpose of the experiment: if is desirable to gather data from all over the boundary layer, having both of them would give more chances to collect data from a larger altitude range. On the other hand, if the main goal is to let the balloon float around 5 km altitude, it would be necessary to provide a design as similar as possible as the second balloon.

Chapter 4

Lagrangian Radiosonde Cluster Observations in a Narrow Alpine Valley during the TEAMx Observational Campaign: The Vipiteno/Sterzing Experiment



Figure 4.1: Released cluster during Vipiteno's experimental campaign

4.1 Introduction

From the 14th of June to the 11th of July 2025 I had the privilege to participate in TEAMx field campaign which took place in Vipiteno/Sterzing, Italy.

My work during the Extensive Observation Period (EOP) was deploying Radiosondes and collecting data. During this time I had the opportunity to understand better how atmospheric dynamics work with a focus on mountain areas, while working with atmospheric instrumentation and an international team of PhDs and researchers.

4.2 TEAMx

TEAMx (Multi-scale transport and exchange processes in the atmosphere over mountains) is an international research programme which was set up in order to improve the understanding of atmospheric exchange processes over mountains and advancing the parameterizations of the aforementioned processes inside numerical models [25].

Mountainous areas are extremely complex environments under a meteorological point of view. Mountain's orography considerably modifies atmospheric motions typical of multiple spatial scales, inducing the formation of gravity waves, convective motions, local circulations in valleys and hillsides, turbulent processes and vertical transport of warm, humidity, aerosols and pollutants.

Mountainous areas also constitute 30% of all emerged lands and play an important role in global cycles of water, energy and carbon.

Big progress was done so far by numerical simulations, but performing weather forecasts in the presence of complex terrain areas is still a big source of uncertainty due to the fact that atmospheric models still present some issues in the correct representation of exchange between surface, atmospheric boundary layer and free atmosphere, especially when there's the presence of big thermic gradients, turbulence, convection and complex tridimensional fluxes. All those limitations directly impact on the quality of weather forecasts in alpine areas.

The aforementioned are the reasons why TEAMx was designed as a big international programme, focused on both simulations activities and intense experimental campaigns. The main goal was to obtain atmospheric observations with high spatial and temporal resolution which could be useful to

better understand physical processes taking place in Mountain Boundary Layer (MoBL), the portion of atmosphere directly affected by mountain orography.

Alpine areas were chosen as the main study area for the project as they represent an ideal environment for observing complex atmospheric processes in strong topographic variability conditions, high humidity and strong interactions between phenomena from different scales.

Complete datasets useful for numerical models validations can be collected due to the presence of a dense observation system made of radar, lidars, ceilometers and sounding systems.

Vipiteno's experimental campaign was located inside this environment in order to study vertical transport processes, atmospheric ventilation and convective exchanges in alpine valleys. Experiments were specifically set up to analyze how the structure of the mountain boundary layer evolves during the whole day and how exchange processes between the valley and the free atmosphere influence temperature, humidity, wind and turbulence. This kind of phenomena are particularly important to understand orographic convection is triggered and how to improve the representation of sub-grid processes inside weather models at high resolution.

The whole campaign used different observation systems like soundings, remote sensing systems and in-situ measurements, with the goal to obtain a tridimensional description of alpine atmosphere and to build adequate datasets for physical analysis of phenomena and validation of numerical simulations. Sounding has a really important role in this context, as they allow to collect vertical profiles of temperature, humidity, pressure and wind which are fundamental to describe atmospheric stability and vertical transport processes inside MoBL.

In order to achieve these results, extensive observation period (EOP) were set up both in winter and summer 2024/2025, and I had the opportunity to participate in the summer one.

During EOPs, soundings were usually performed twice a day, at 11:00 and 23:00 UTC time (13:00 and 1:00 local time) but they were performed every three hours in case there was some alert (like for gravity waves or big storms).

Vipiteno's operational base was a campervan parked in a field in which all of our instrumentation was stored. Outside of it there was also an atmospheric station with ceilometers, lidars, radars and other useful instruments for tracking atmospheric data.

4.2.1 Sounding process

Here will be described the step-by-step process used to deploy a Vaisala radiosonde used for our experiments.

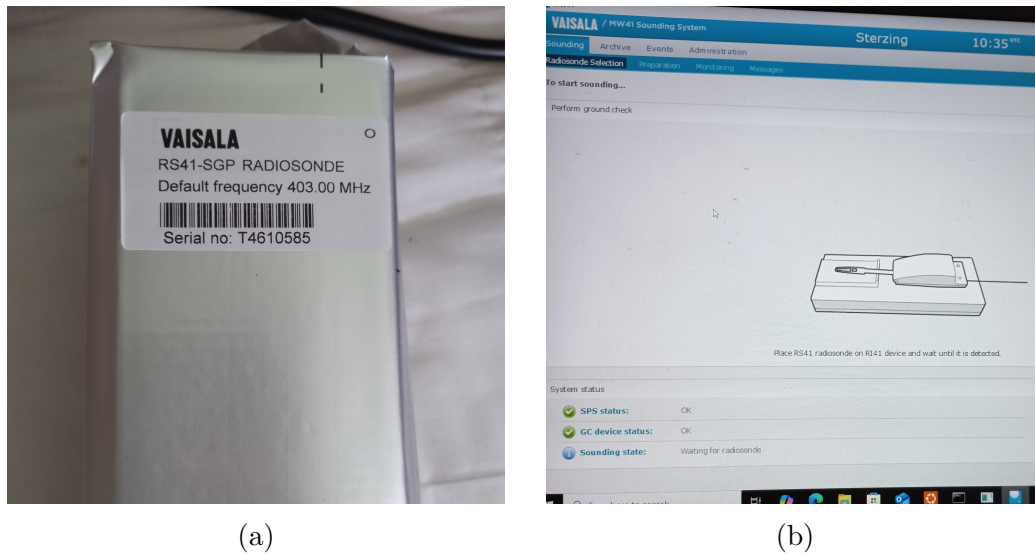


Figure 4.2

Fisrt thing to do is to take one still packed Vaisala's radiosonde as shown in Figure 4.2a. It is important to see the serial number and write it down in the excel file where all the main information about sounding are written down.

On the computer it is possible to see window in Figure 4.2b which tells us to put the radiosonde on the Vaisala Ground check device RI41, a device used fro ground check and calibration before performing the launch in order to guarantee a good accuracy of the data that will be gathered during the sounding.

4.2. TEAMx



Figure 4.3

After unpacking our radiosonde, we put it on RI41 (Figure 4.3). At this point ground check will be performed. During this step every kind of malfunctioning will be pointed out by the system: it was pretty rare, but +it happend that some radiosonde had a malfunction, for example, in the humidity sensor.

We then change the sounding frequency from default to the one that will be used during the sounding. We tick the selection to "countinue descending sounding": in this way our sonde will continue to collect data even after the burst of the balloon.

4.2. TEAMx

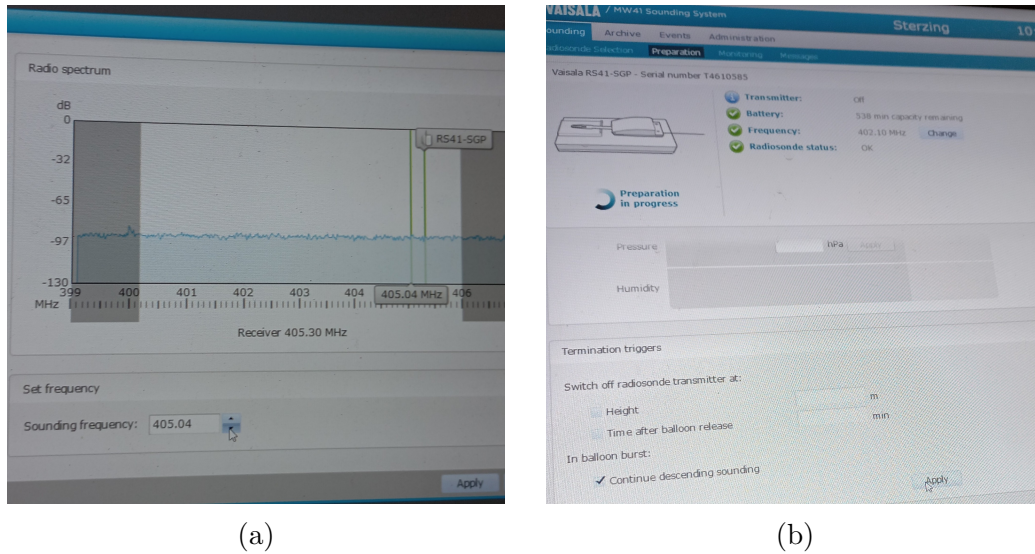


Figure 4.4

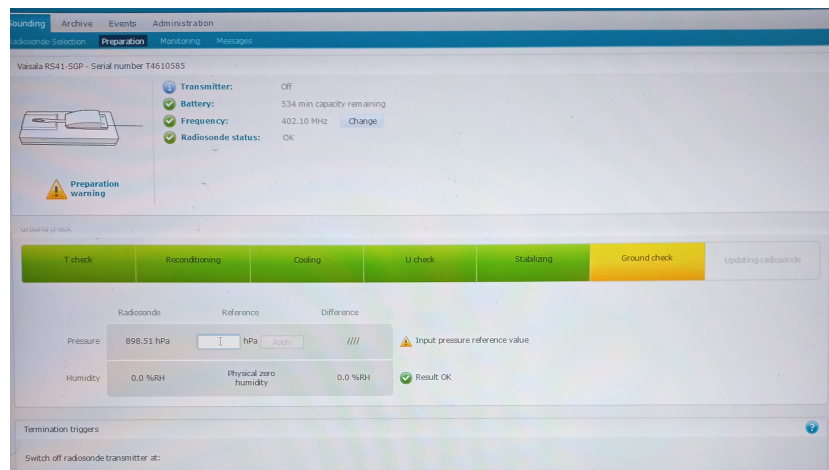


Figure 4.5

And, finally, we manually insert and apply the reference pressure, which has to be the same measured by the radiosonde at the moment of ground check: as an example, if the screen is the one shown in Figure 4.5, we will have to put in the reference tab the value of 898.51 hPa. We can now let the system do an updating of the radiosonde.

4.2. TEAMx



Figure 4.6

While RI41 updates the radiosonde, we go outside to inflate the balloon. As shown in Figure 4.6, we will need to pick up our balloon, a parachute, an unwinder, pliers and an electrician's band.

4.2. TEAMx



(a)



(b)

Figure 4.7



(a)



(b)

Figure 4.8

We can now go outside to the helium tanks. This step is a bit more artisanal, but very funny to perform: in order to inflate the balloon, we put the opening of the balloon around the nozzle shown in Figure 4.8a. Soundings require two persons to be present: one holds the balloon and the other gently opens the valve to let the helium flow through the balloon. As it is visible in Figure 4.7b, it is important that the person which is holding the balloon wears gloves: the latter is made of Latex and is full of powder. It is important not to touch it with bare hands in order to not contaminate it with hand's oils: this could eventually let the burst to happen faster than required. A bottle of water is attached to the balloon: when the latter has enough buoyancy force, it will start to pull slightly pull the bottle. When this happens, it is time to stop inflating the balloon. Right before closing the valve, we have to remember what is the remaining pressure inside the tank, shown in the quadrant in Figure 4.8b: this value has to be written in the excel file and will allow us to understand when it is time to replace the tanks.

After closing the valve, we attach the parachute to the balloon by placing its rope around the balloon's neck. We then fold the latter and properly close it with the electrician's band. It is important to carefully cut the band's excesses with pliers.



Figure 4.9: Tensile Stress-Strain curves for one test for each material used during tests. [7]

4.2. TEAMx

By the time the balloon is ready, also the updating of the radiosonde will be finished. At this point, while one person waits outside holding the balloon, the other goes inside to pick the radiosonde up.

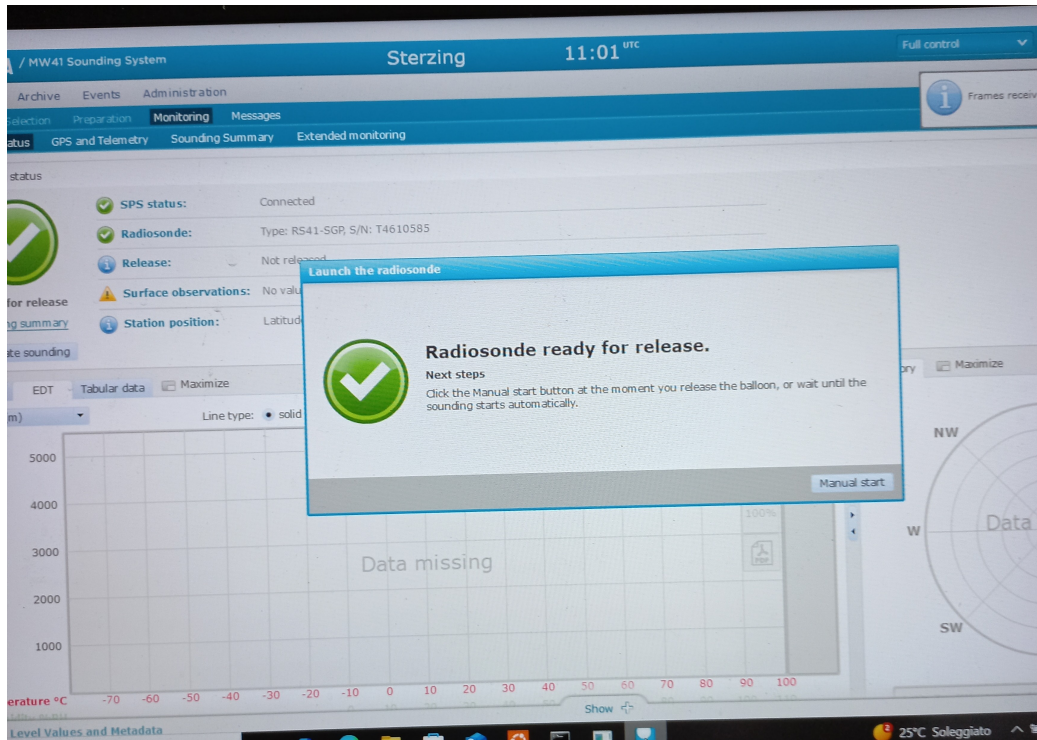


Figure 4.10

after attaching the radiosonde to the unwinder, the latter is connected to the parachute.

4.2. TEAMx



Figure 4.11



(a)



(b)

Figure 4.12

Everything is now ready to be deployed: we wait until release time and then... let it go!

4.3. Comparison between radiosondes

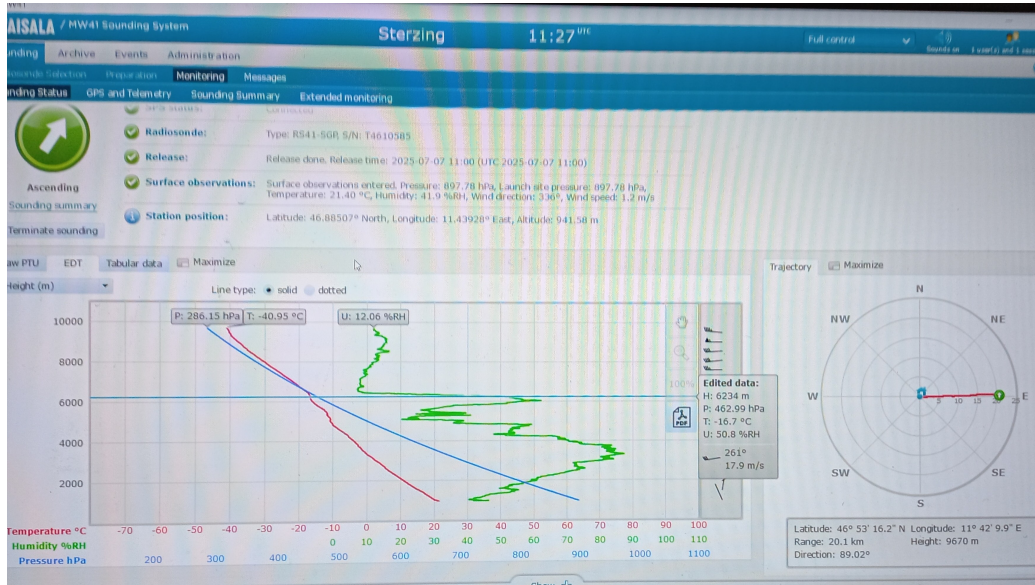


Figure 4.13

After having a look at the flying balloon, we have to go inside to be sure the system is receiving data from the radiosonde. If so, recorded pressure, humidity, temperature and wind profile will start to appear on screen as shown in Figure 4.13. It is now important to wait until the sonde reaches 5 km altitude: at that point the experiment is considered a success and it is possible to leave the station.

It will be then duty of the next group to check and write down in the excel file the reason of descend (usually burst of balloon) and the maximum reached altitude (usually around 30 km). All recorded data is then uploaded in a repository, ready to be user for simulation and data analysis after being converted from .bfr format to a readable one.

4.3 Comparison between radiosondes

4.3.1 Dual launch

On the 1st of July 2025, the same day a cluster launch was performed in Vipiteno, a dual launch was performed as well in order to evaluate the reliability of collected data.

One of Houseflies' radiosonde was attached to a Vaisala's one while it was launched in the context of the IOP measurements that were held by TEAMx. Both radiosondes were deployed at 17:00 UTC time, attached to a sounding balloon. The Houseflies' one was covered with a layer of tape in order to

4.3. Comparison between radiosondes

protect it from rain.

Vaisala's data was collected in BUFR format, which was then converted in order to plot pressure, temperature and humidity graphs for comparison. To be sure the conversion from BUFR to CSV format was performed correctly, I compared my results with the ones that were given by [1], confirming the conversion was done correctly.

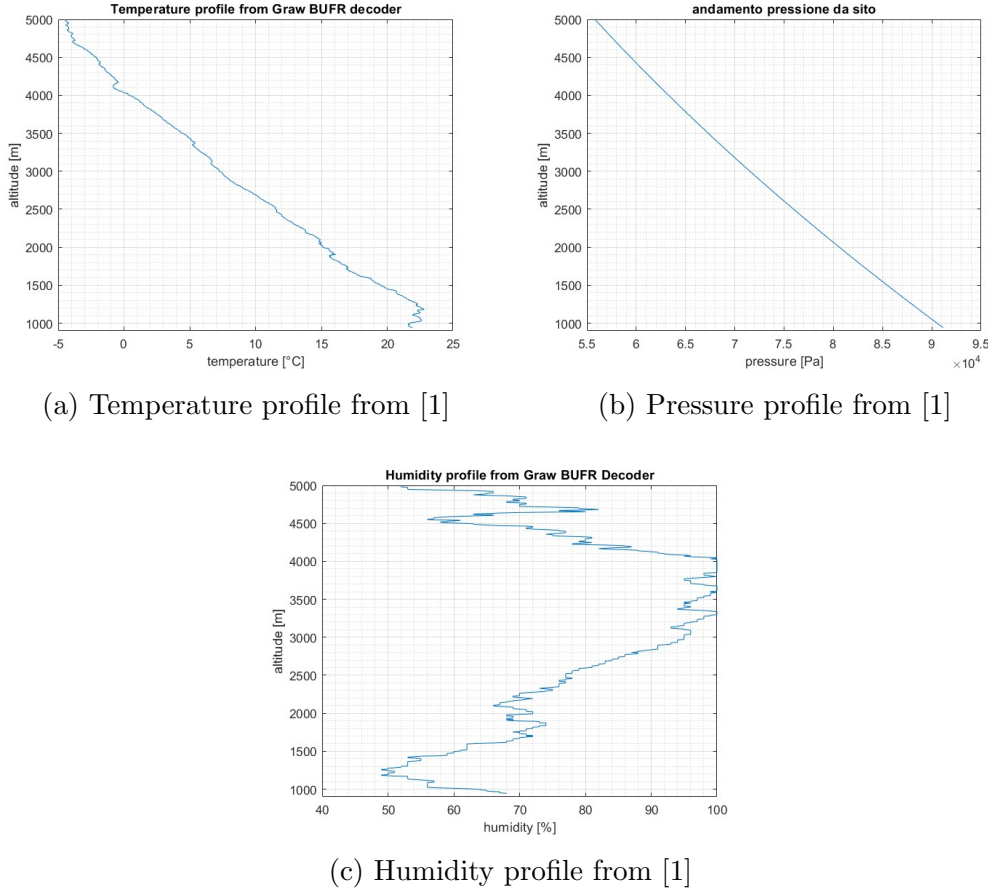


Figure 4.14: Atmospheric profiles obtained from [1]

After collecting all the data it was necessary to apply an offset to them in order to correct any kind of systematic errors that could take place during the measurements. This procedure was applied to both the datasets taken from the Houseflies' sonde and the Vaisala's one.

Data taken from Vipiteno's weather station [2] was taken as a reference.

All the values reported in Table 4.1, are referred to the ground.

After plotting data, it was visible that it was necessary to use microcontroller's internal reference time to plot data in order to consider also mil-

4.3. Comparison between radiosondes

Temperature	Pressure	Humidity
22.35 °C	1015.57 hPa	70.13 %

Table 4.1: Reference Values from Vipiteno’s station taken from [2] relative to 19:00 UTC time

liseconds: with the reconstructed datetime multiple packets of data arrived at the same time. Microcontroller’s time tracks the number of milliseconds elapsed from its accension. The main problem was to understand the exact reference time. To do so, pressure profiles had a crucial role: the time relative to the point at which pressure profile changed its slope was considered as the one at which the radiosondes were deployed. The timeshift was then applied to every point, as shown in Figures 4.15 4.16 and 4.17.

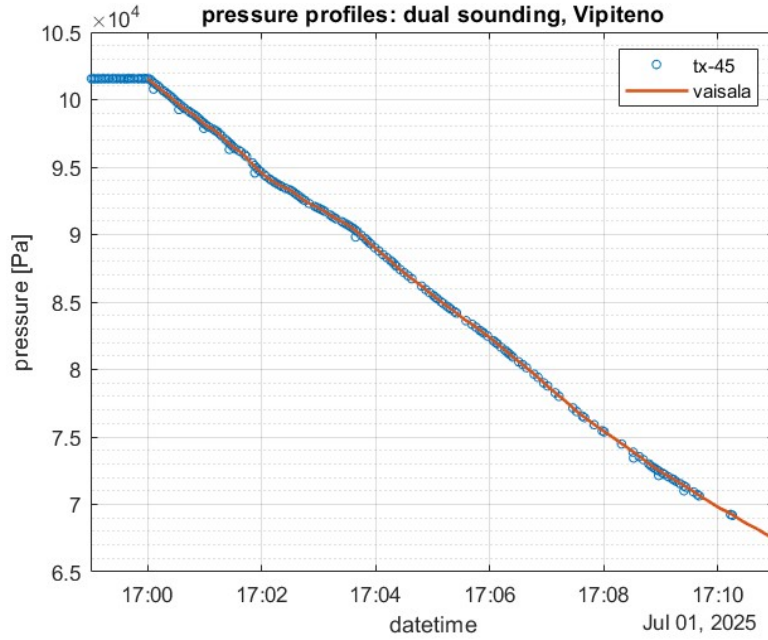


Figure 4.15: Comparison between pressure profiles

4.3. Comparison between radiosondes

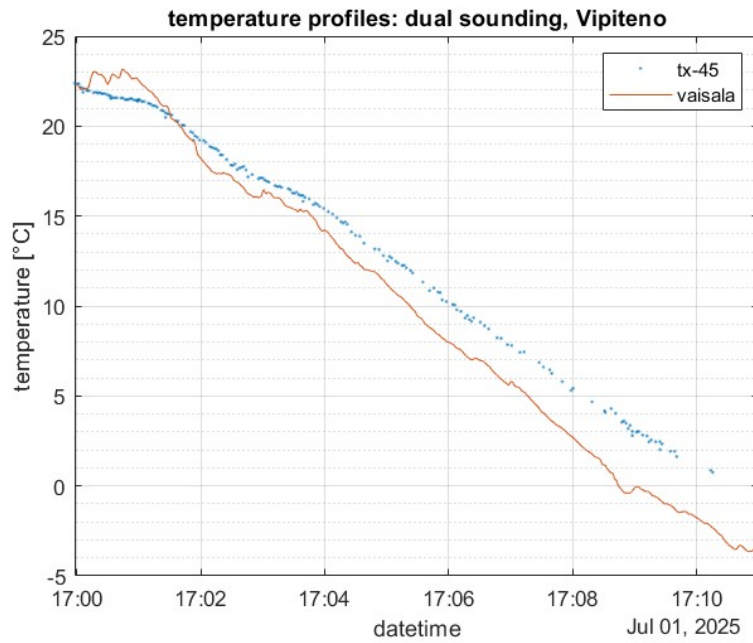


Figure 4.16: Comparison between temperature profiles

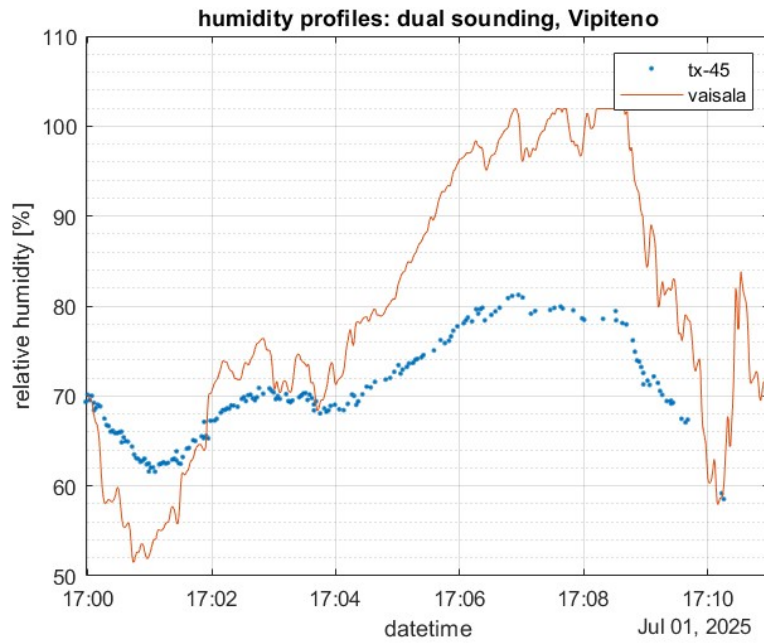


Figure 4.17: Comparison between humidity profiles

Figure 4.15 shows pressure profiles of the two radiosondes are consistent

4.3. Comparison between radiosondes

with each other, while Figures 4.16 and 4.17 show a discrepancy between the temperature and humidity profiles.

As reported in [10], humidity profiles are dependent upon temperature and pressure ones. We can deduce that the discrepancy is caused by a wrong tracking of the temperature profile, which propagates the error to the computation of the humidity profile as well: before 17:02 UTC time, Houseflies' radiosonde tracked a lower temperature than the Vaisala's one, and after 17:04 UTC the opposite happened with a significant discrepancy. In correspondence of these time intervals we can notice how between 17:00-17:02 UTC time tx-45 humidity is higher than the Vaisala's while from 17:04 on it is lower. Around 17:02-17:04 tracked humidity is similar but still lower than the actual value.

A similar behaviour was reported in Paredes' [23] PhD thesis. In [23], The radiosonde was directly attached to the Vaisala's one with some tape. This wasn't done during Vipiteno's dual launch because this could lead to some overheating caused by the proximity of the two sondes. It was also noticed that the tape partially occluded the EBM280 sensor, leading to an incorrect ventilation. This is what could have happened in the Vipiteno's measurement: even if we tried to carefully leave a hole for the sensor, the layer of tape could still have partially inhibited a correct ventilation and isolated the radiosonde creating a slightly hotter environment than the outer atmosphere.

Putting aside the aforementioned mismatches, we can notice how both the datasets show the same trends, which is still a satisfactory result. For further developments, finding a way to put the humidity sensor outside of the radiosonde could be crucial in order to obtain data of higher quality, increasing their reliability.

One final point has to be mentioned while considering relative humidity measurements collected by instrumentations.

Relative humidity measurements usually need to be post-processed with some algorithms in order to balance dry bias in humidity measurements and the presence of a time lag in the instrument's response. This applies to Vaisala's RS41 sondes as well, as mentioned in [18].

Due to the fact that some sensors are heated up to prevent condensation, relative humidity measurements tend to have a dry bias: this means that the sensor tends to record lower relative humidity values, with peaks of the bias reaching 3.1% of the total value. This behaviour tends to be more relevant for lower temperatures.

The second problem that has to be mentioned is time lag: sensor response time varies a lot with temperature, reaching a longer response time for

lower temperatures. This is a problem because atmosphere's humidity varies very quickly, so this means that measured humidity doesn't correspond to the real one at that exact time. Measurements for higher altitudes tend to be less reliable due to the fact that response time increases with decreasing temperatures.

Finally, ventilation has to be considered: sensors are heated up to prevent condensation but this will lead to an alteration of measurements. However, if ventilation is realistic, like for values $\sim 5m/s$, convective cooling is enough to compensate heating. On the other side, if ventilation is not ideal, temperature measured by the sensor can be altered and introduce some errors.

It is then understandable why performing a correct calibration is crucial also at low temperatures: calibration instrumentations at ambient conditions is not enough if the main challenges are found at lower temperatures. Performing correct calibrations allows on one side to obtain more reliable and accurate data and on the other to reduce any kind of negative influence on assimilation systems and numerical simulations.

In case this is not possible to obtain, some algorithms can be used to post-process data and compensate the humidity measurements time lag.

The use of this kind of algorithms can be applied also to data recorded by radiosondes, activity which is currently being carried out at the moment.

The evaluation of response time and measurements accuracy of radiosondes was evaluated by Paredes et Al. at INRiM, as explained in [21].

Concerning temperature, humidity and pressure measurements two different tests were performed.

In the first one, three radiosondes were put together in a climatic chamber to measure different conditions while also some reference sensors were put in the same place. Each measurement took 30 minutes to be performed. Under this conditions good measurement accuracy was found. Measured relative errors were slightly higher for smaller temperatures.

A second experiment was then performed by attaching a radiosonde to a Vaisala's one in order to perform a dual sounding as was done in Vipiteno. A similar behaviour to the one just mentioned before was found, with consistent pressure measurements and some discrepancies in temperature and humidity measurement highlighting the presence of a time lag in measurements.

Radiosonde's temperature, pressure and humidity sensor is Bosch BME280. This sensor is not actively heated up to prevent condensation as it is done for Vaisala's, but it can heat up while performing measurements. This is why a good trade-off in the acquisition rate is needed.

4.4 Cluster launch

On the 1st of July 2025 a cluster was launched in Vipiteno as a part of the Houseflies project. All data was then shared with TEAMx.



Figure 4.18: Cluster ready to be released

The experiment took place in the same field where the campervan that was used as a base for TEAMx's experiments was placed. For this experiment a total amount of 10 radiosonde was used and the availability of a public communication network (*The Things Network*, TTN), allowed the management of all this devices in parallel.

4.4.1 Experiment setup

The experiment was set up using the following instrumentation:

- 10 Radioprobes: current consolidated version of the radioprobee.
- 10 Mylar Globe 19" balloons: manufactured by Grabo S.r.l. and filled with 99% helium. Each balloon had a capacity of 63L and dimensions of 48×48×48 cm
- Laptop: used for collecting data and preparing the experiment
- LoRaWAN portable gateway: WisGate RAK7244 model
- 4 single-channel LoRa Gateways: Dragino LG01v2 model

Radiosonde's consolidated design is the one previously described in Chapter 2. Radiosondes are provided with a radiotransmission unit, GNSS receiver, IMU sensor (made of an accelerometer, gyroscope and magnetometer) and PHT sensor for pressure, humidity and temperature measurements.

In order to communicate with the radiosondes, two different protocols were used: the first one is the LoRaWAN protocol, which relies on the network of the public TTN gateways and the private RAK7244 station. The second one is the peer-to-peer protocol (P2P), which is implemented through the four Dragino LG01v2 receivers. P2P protocol was used to follow radiosondes in the first part of the experiment (45 minutes- 1 hour) and in order to use it a car was equipped with two Dragino LG01v2 receivers and a laptop. thanks to this instrumentation, it was possible to follow the trajectories of some of the radiosondes by following their coordinates.

Concerning the balloons, Mylar ones developed by Grabo S.r.l. were chosen to be used due to the fact that Mater-Bi ones are still under development.

4.4.2 Preparation

After arriving at the launch site, multiple step were necessary before starting the experiment. This procedure took few hours.

Initially, balloons were inflated with a gas mixture composed by 99% of helium and the rest 1% of air. In the meantime, receivers for peer-to-peer and LoRaWAN communication systems were configured.

Radiosondes are then powered up and some test are carried out in order to check if they can correctly connect to LoRaWAN gateways and Dragino receivers.

After all the sondes are checked out, the system can be assembled: the radiosonde is connected to a LiPO battery and the whole system is secured to the inflated balloon through a thread.

A final check to make sure that all the radiosondes are correctly working is done before being ready for the experiment.

4.4.3 Raw Data Analysis

We will now analyze raw data recorded during the experiment.

As it is shown in Figure 4.20a, all the radiosonde displayed a similar behaviour, travelling to the south, after they initially turned west as shown in Figure 4.20b. 3D trajectories were also reconstructed after converting geographical coordinates into NED reference frame, as shown in Figure 4.19. The cluster travelled across an area in which there wasn't a dense coverage

4.4. Cluster launch

of LORAWAN Gateway receiving stations: most of the data was collected during the first 20 minutes of flight, when all the sondes were still near the local RAK7244 receiving station and before we lost any kind of connection while following the cluster by car. Only six out of ten sondes continued to transfer data after the first half hour after the cluster release. This is why different plots will be shown for the whole launch and for the first 20 minutes, in order to understand better the tracked dynamics.

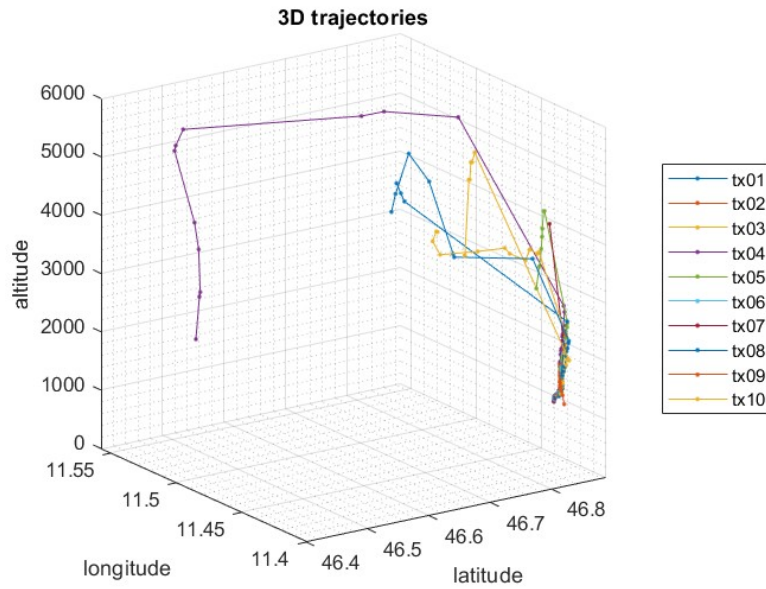
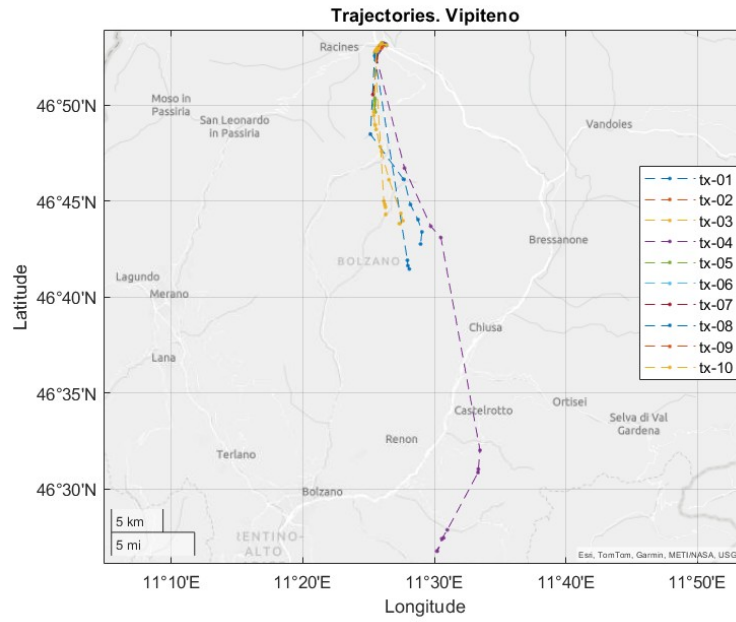
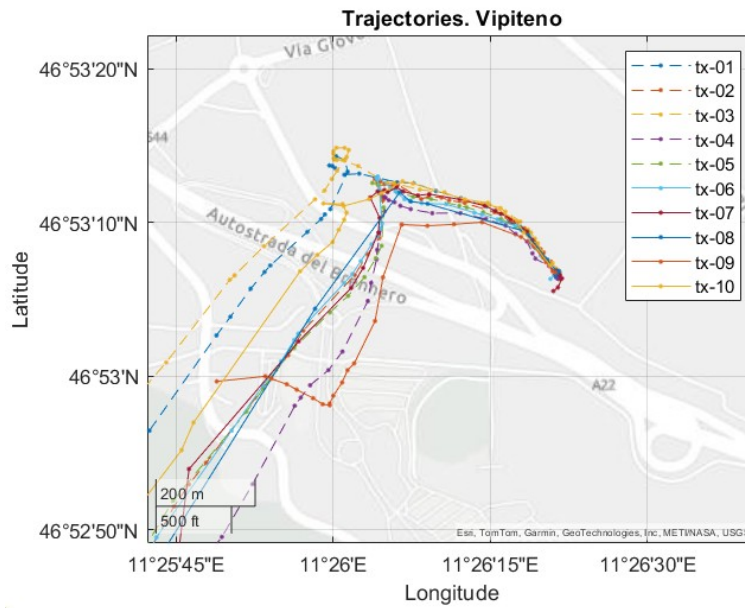


Figure 4.19: 3D Trajectories of Cluster launched in Vipiteno

4.4. Cluster launch



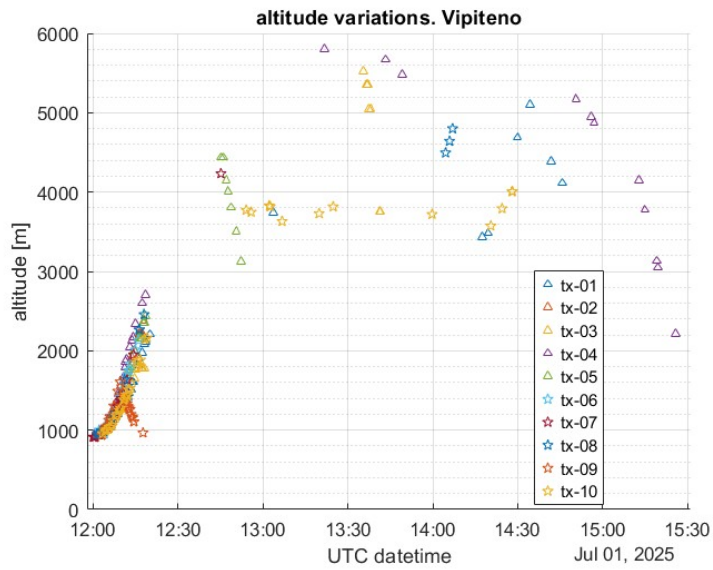
(a)



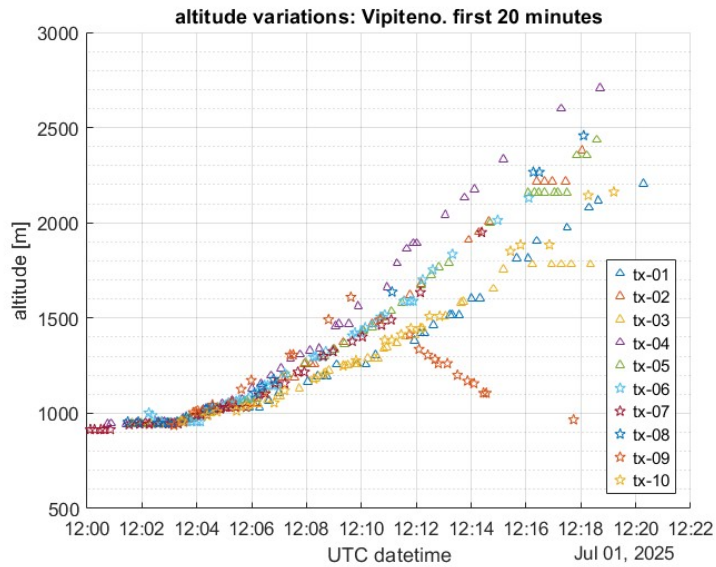
(b)

Figure 4.20: Trajectories of Cluster launched in Vipiteno

4.4. Cluster launch



(a)



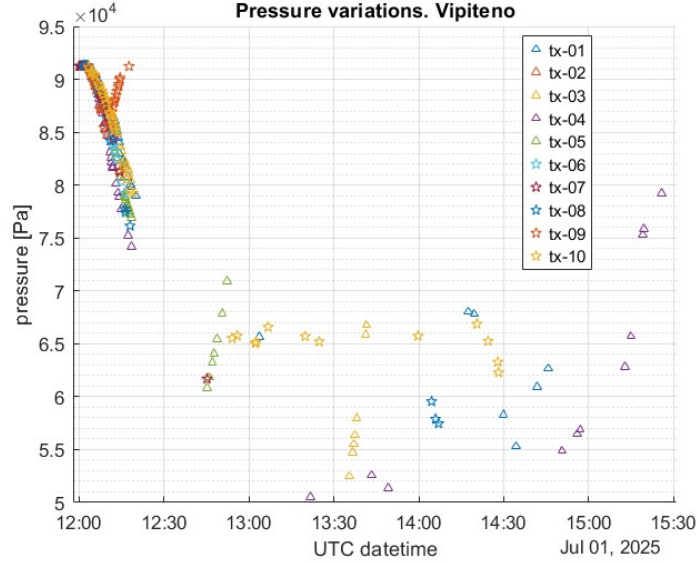
(b)

Figure 4.21: Altitudes reached by radiosondes

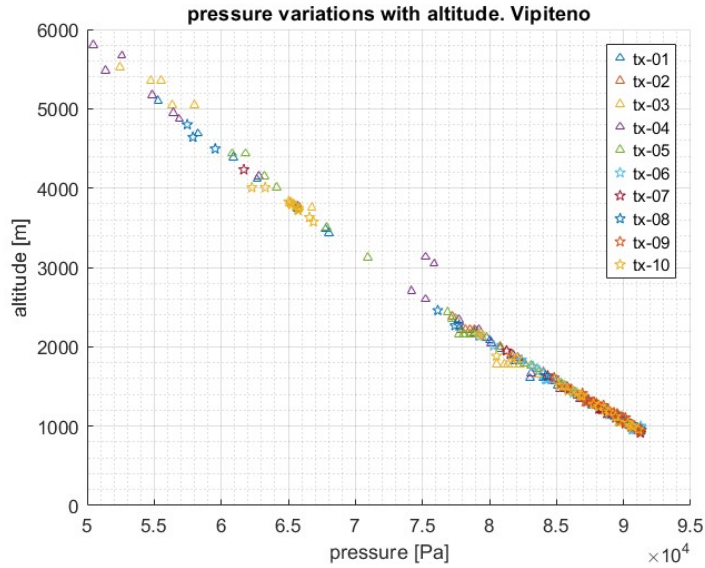
Radiosondes tx-02, tx-06, tx-07 and tx-09 didn't transmit any data in a timespan longer than 20 minutes after launch time. We can see that they were still ascending with the exception of tx-09, which lost height and landed shortly after its deployment. Tx-04 has covered the longest path and reached

4.4. Cluster launch

the highest altitude (6000 m altitude), reaching Bolzano's latitude.



(a)



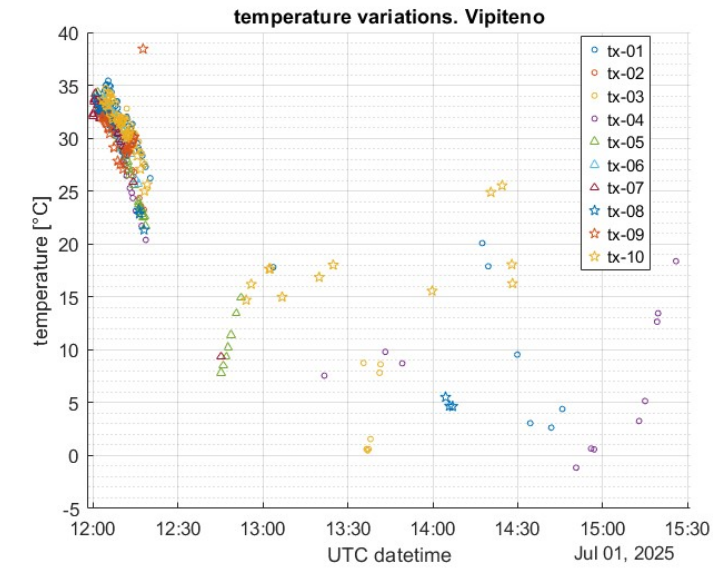
(b)

Figure 4.22: Pressure profiles

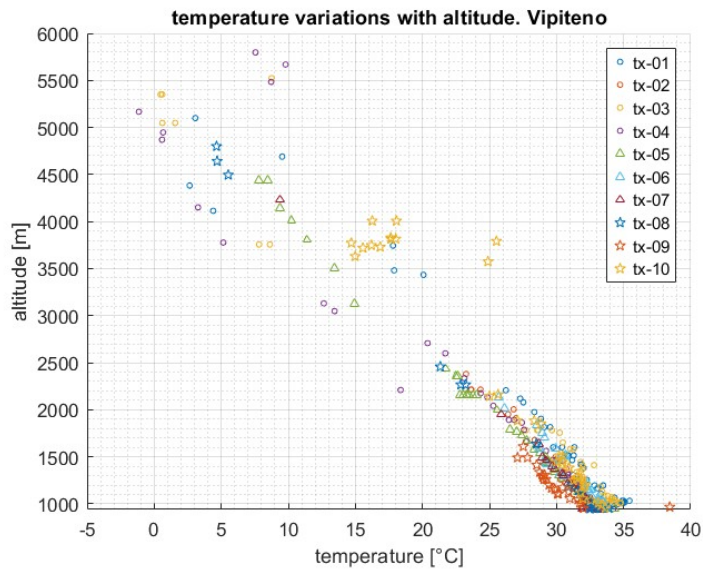
Observing Figure 4.22b, we can see how, as we expect, pressure tends to decrease with altitude. Local fluctuations of pressure that can be seen in Figure 4.22a are for sure related to relative local decrease or increase with

4.4. Cluster launch

altitude.



(a)



(b)

Figure 4.23: Temperature profiles

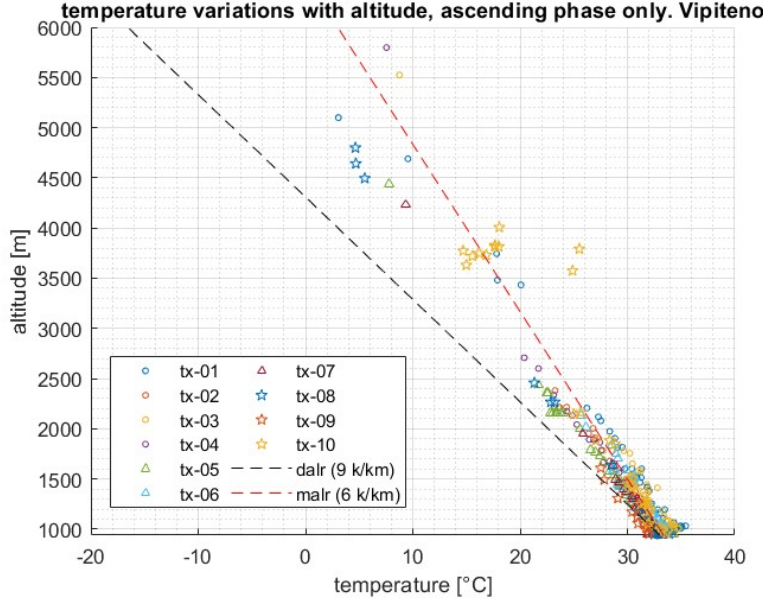


Figure 4.24: Temperature profiles during ascending phase and comparison with dry and moist adiabat

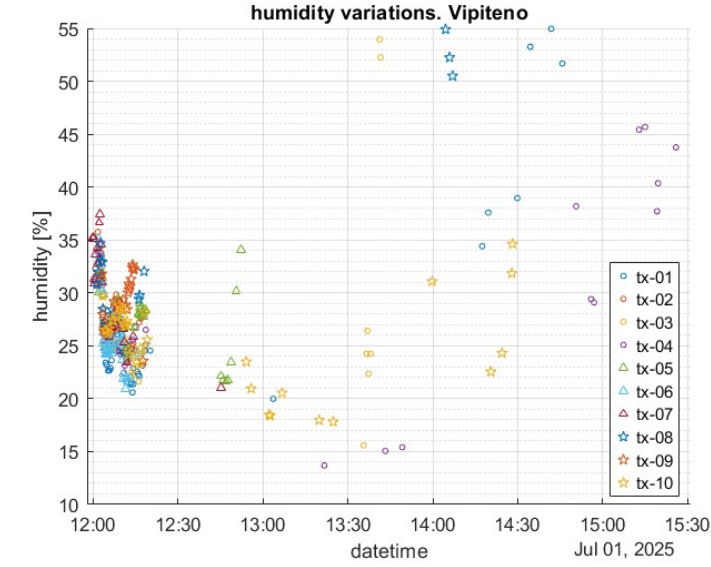
Temperature profiles present a behavior similar to the pressure ones. We can notice how temperature continuously decreases while altitude increases (Figure 4.23b).

In Figure 4.24, only data recorded during ascending phase are shown and it is possible to see a comparison with two lines, following the dry adiabatic lapse rate ("dalr", 9.8 K/km) and the moist adiabatic lapse rate (malr), which in this case was set to 6 k/km.

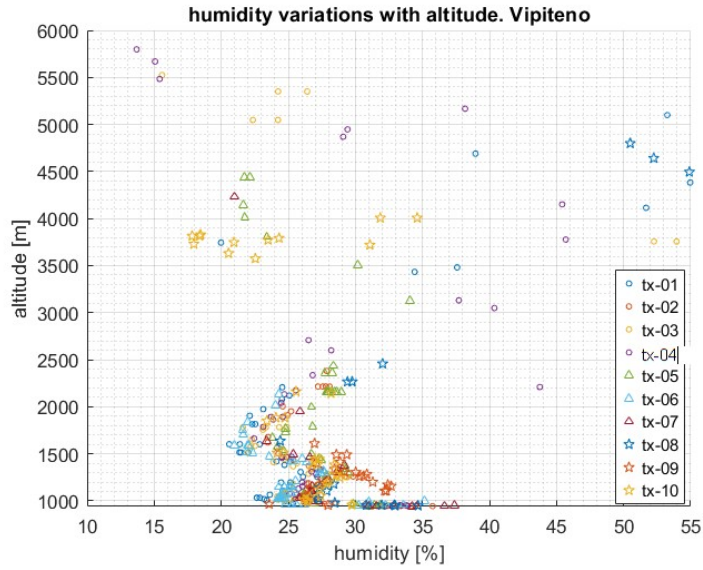
In the lower layers (until $\sim 1500m$ above sea level), data follows the slope of dry adiabatic lapse rate line, and it then tends to align to the slope of the moist adiabatic lapse rate ("malr").

Recorded behaviour is aligned with what expected: near the ground particles are heated by convective exchanges from the ground and tend to cool down while rising. Cooling takes place adiabatically, while the particle increases its dimensions. After reaching saturation point, water vapour starts to condensate, balancing the cooling mechanism and making the ascent slower.

4.4. Cluster launch



(a)



(b)

Figure 4.25: Humidity profiles

Unlike temperature, humidity profiles show considerable oscillations with altitude: this is likely associated with turbulent mixing and small-scale variability within the convective boundary layer. This oscillation could indicate that a mixing between dry and humid air masses. However, what is concerning about these data is the really low tracked values.

4.4. Cluster launch

In order to understand if those values are caused by some kind of bias error, reference values tracked by Vipiteno's weather station [2] are considered to make some comparisons to the ground level.

Temperature	Pressure	Humidity
27.73 °C	1013.45 hPa	57.53 %

Table 4.2: Reference Values from Vipiteno's station taken from [2] relative to 14:00 UTC time

The weather station tracked a higher humidity and a lower temperature. We have a difference of around 4-5 °C. This difference could be a reason why we have such low values of humidity. Unlike for dual launch, no tape was used to cover the sondes, so the ventilation hypotheses should be discarded. Due to the high irradiation, it is more likely that the sensor went under an overheating during the preparation procedure which lead to a overestimation of the actual value of the temperature.

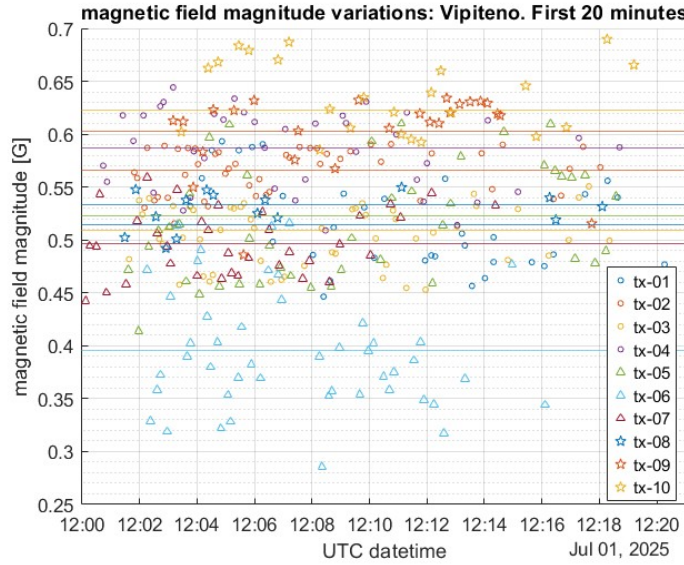


Figure 4.26: Magnetic field magnitude profiles. Solid lines represent mean values for each radiosonde

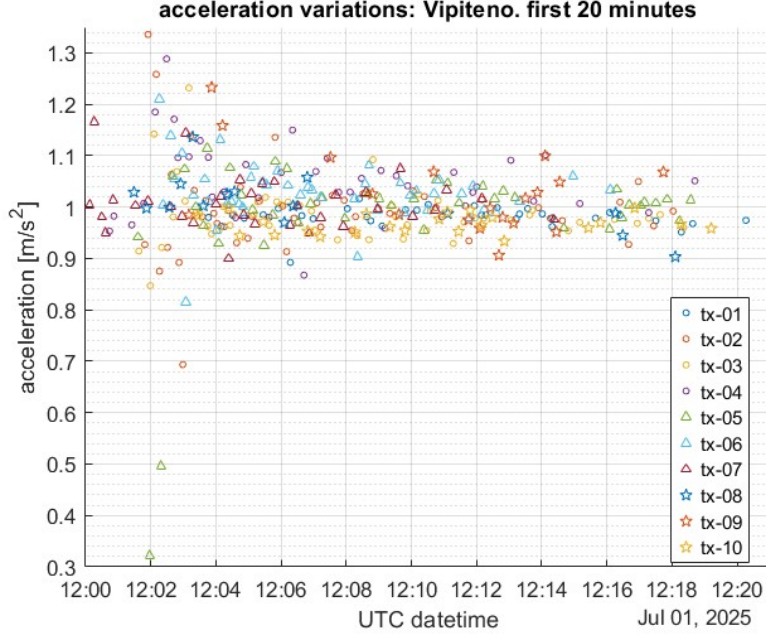


Figure 4.27: Acceleration magnitude profiles

For magnetic field and acceleration magnitudes we will now consider only the first 20 minutes of flight in order to easily interpret the behaviour. In Figure 4.26, we can notice that the magnetic field sensor wasn't properly calibrated: only tx-07 has a mean value inside the range 0.45-0.5 G, which is the expected value for the geographical location where the experiment took place.

On the other side, acceleration magnitudes oscillate around 1g for most of the flight, with an exception around 12:02 UTC time, where some spikes are present for some radiosondes: this behaviour could be justified by the fact that the cluster was in the first part of its ascending phase, which is likely associated with transient dynamics, including pendulum-like oscillations and stabilization of the balloon-payload system.

4.4.4 Spectral Analysis

In this section, we will analyze some results obtained after performing some post-processing on collected data from the radiosondes, in order to study atmospheric turbulent structures.

Results will be compared with well-known theories which are applied to isotropic turbulence case studies.

Packets of data were not collected at constant time intervals, this is why

4.4. Cluster launch

a resampling was necessary to obtain a uniform time grid and perform our analysis. Linear interpolation was applied to data as well at regular 30s intervals, which set the Nyquist frequency to:

$$f_N = \frac{1}{2\Delta t} = \frac{1}{2 \times 30 \text{ s}} \approx 0.0167 \text{ Hz} \quad (4.1)$$

Which limits the high-frequencies end of the spectra.

Data tracked from tx-01, tx-04 and tx-08 were chosen for analysis: the main reason is that these were the sondes which reported the longest flight path. A Fast Fourier Transformation (FFT) was applied to the aforementioned data and the Power Spectral Density (PSD) was subsequently evaluated and compared to the general behaviour of Kolmogorov's power law $S(f) \propto f^{-5/3}$. The Power Spectral Density (PSD) was estimated using Welch's method, which provides a smoother and more reliable spectral estimate by averaging multiple windowed segments of the signal.

In this first phase, we will discuss speed spectra behaviour. After converting geographical data into NEU reference frame, also speed was projected into its NEU components before performing spectral analysis.

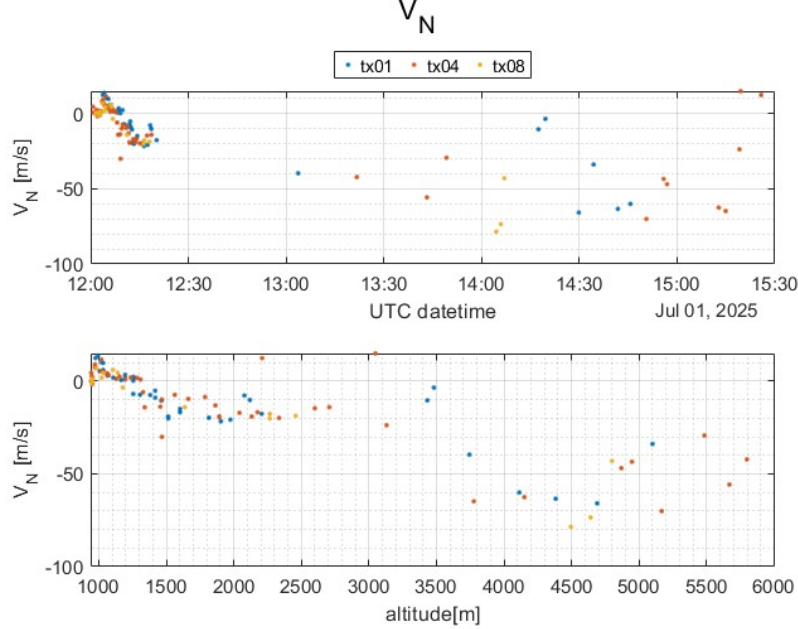


Figure 4.28: North speed component in the NEU reference frame as function of time and altitude

4.4. Cluster launch

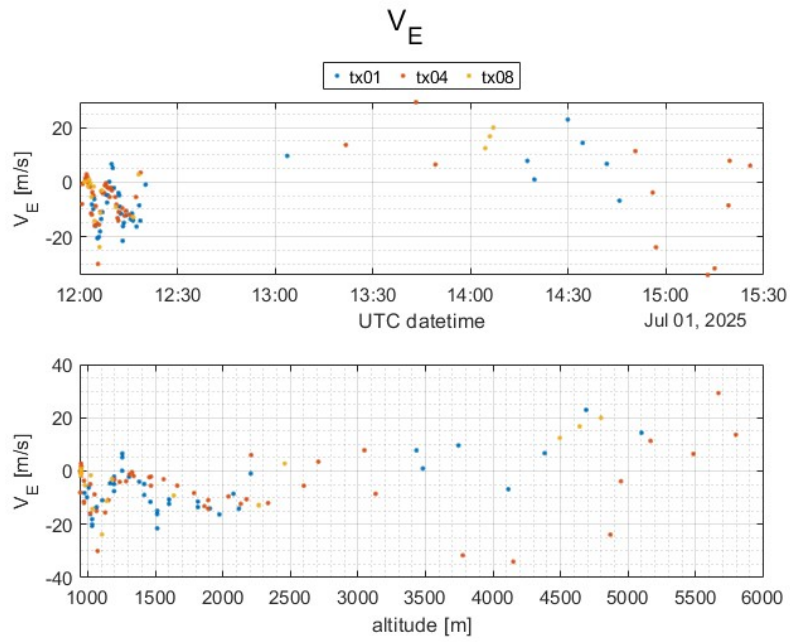


Figure 4.29: East speed component in the NEU reference frame as function of time and altitude

4.4. Cluster launch

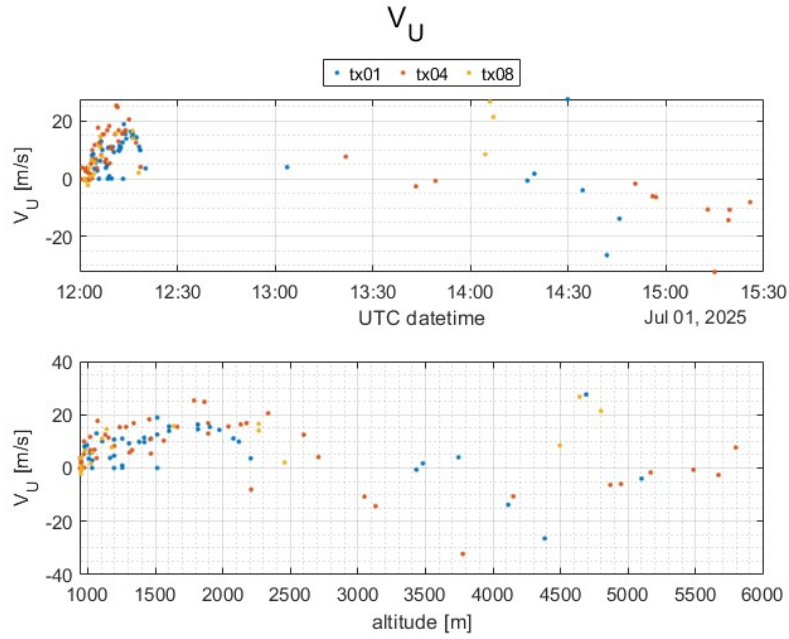


Figure 4.30: Up speed component in the NEU reference frame as function of time and altitude

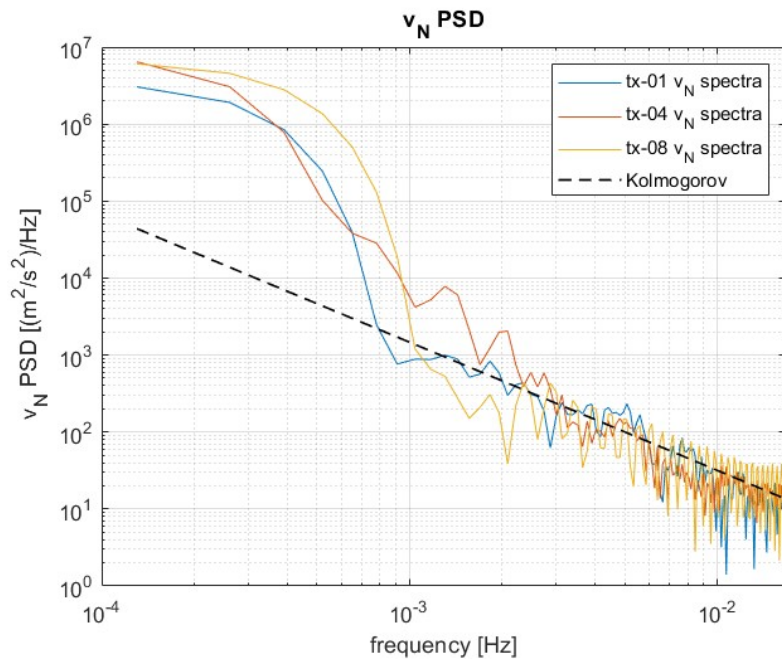


Figure 4.31: Spectral analysis for V_N

4.4. Cluster launch

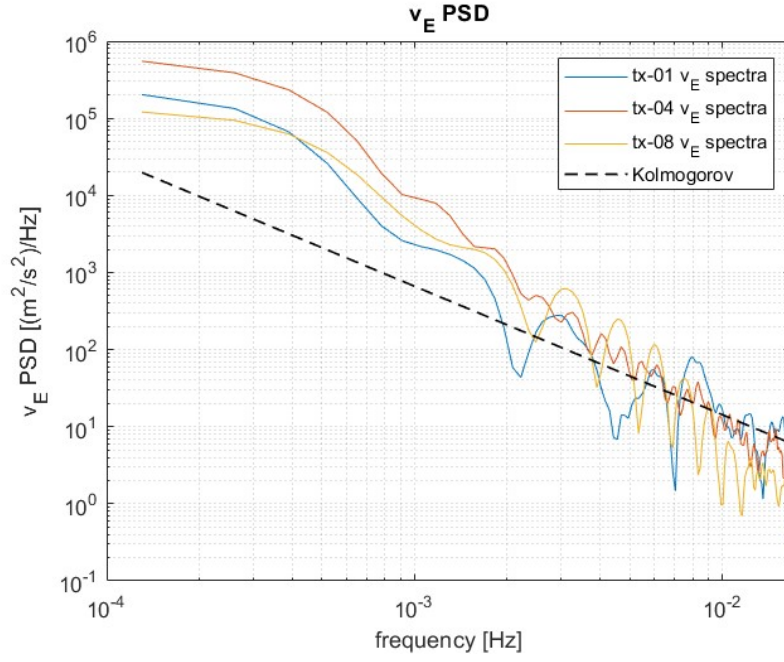


Figure 4.32: Spectral analysis for V_E

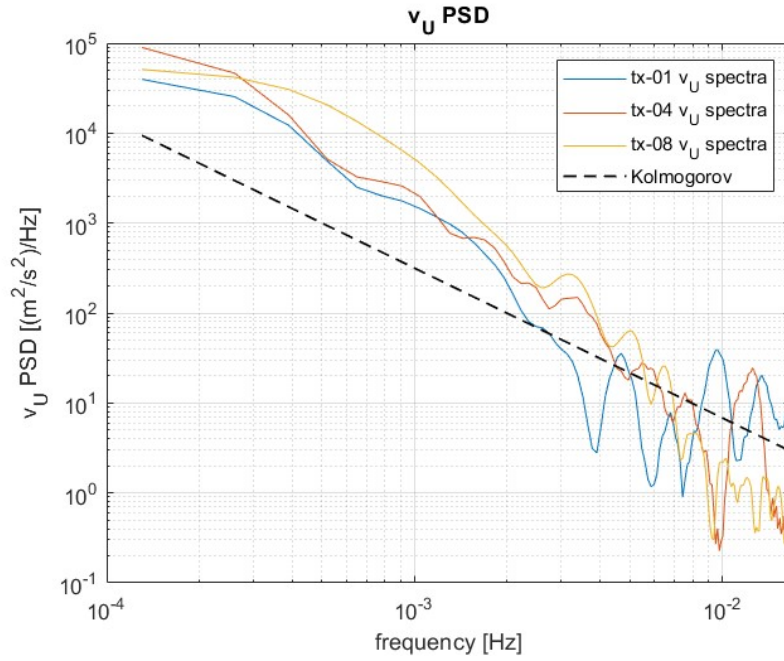


Figure 4.33: Spectral analysis for V_U

We can notice how, for low frequencies, spectra tends to flatten and then

becomes more noisy as the frequencies get higher. A comparison with Kolmogorov's theory is shown in the figures with a black dotted line. It is important to remember that Kolmogorov's theories only apply to the inertial subrange. Spectra tends to oscillate around this behaviour, but the inertial subrange is not pretty easy to be correctly identified as it is very small: sondes tracked real atmospheric data, so it is normal that dynamics tend to deviate from theories valid for isotropic turbulence. However, we could say that the inertial subrange can be identified for frequencies around $f = 2 - 6 * 10^{-3} Hz$ for V_N , $f = 4 - 8 * 10^{-3} Hz$ for V_E and $f = 4 - 8 * 10^{-3} Hz$ for V_U . For frequencies lower than this values, PSD tends to drop to lower values much faster as larger structures break down into smaller ones and energy dissipates.

Another interesting aspect that can be seen is that V_N spectra tends to be way more noisy than the other two. This behaviour could be justified by observing Figure 4.20a: it is evident how radiosondes where mainly travelling southwards, so it is likely that mean wind speed is aligned towards North-South direction. This is confirmed also by the fact that V_N spectra has higher levels of energy for lower frequencies: when energy levels for lower frequencies become higher, noise at lower frequencies increases as well.

At this point it is possible to investigate mean wind speed behaviour and spectra. Mean wind speed was computed starting from NEU speed components as:

$$ws_{mean} = \sqrt{V_N^2 + V_E^2} \quad (4.2)$$

Horizontal wind speed was chosen for analysis as a simplification due to the fact that radiosondes mostly travel along an horizontal path.

4.4. Cluster launch

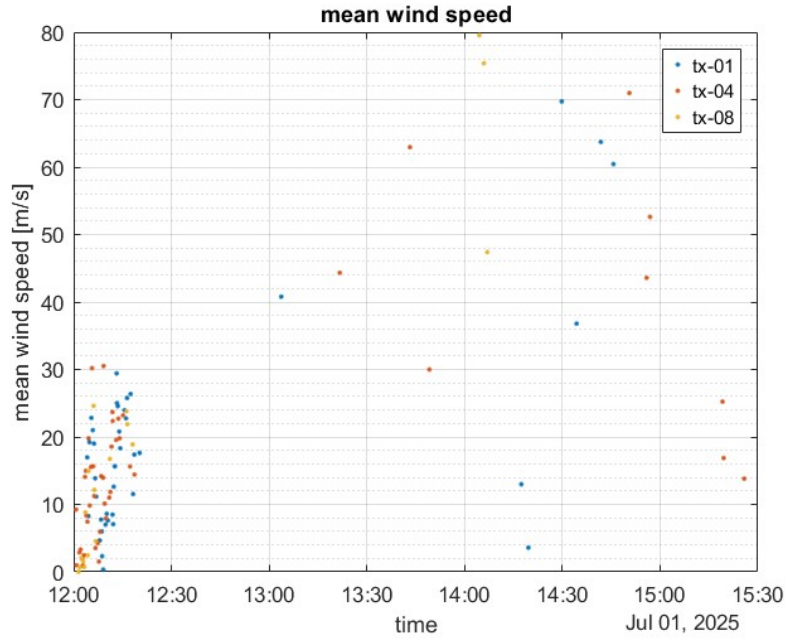


Figure 4.34: Mean wind speed profiles

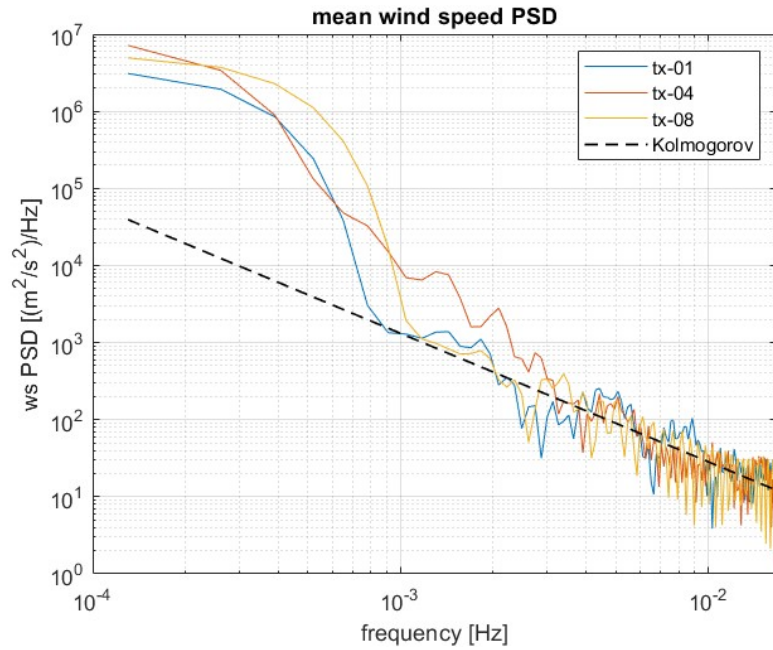


Figure 4.35: Spectral analysis for mean wind speed profiles

By observing Figure 4.35, we can see how also this spectra tends to have

very high energies at low frequencies and then becomes very noisy for lower ones.

Spectral analysis was performed also for pressure, temperature and humidity profiles.

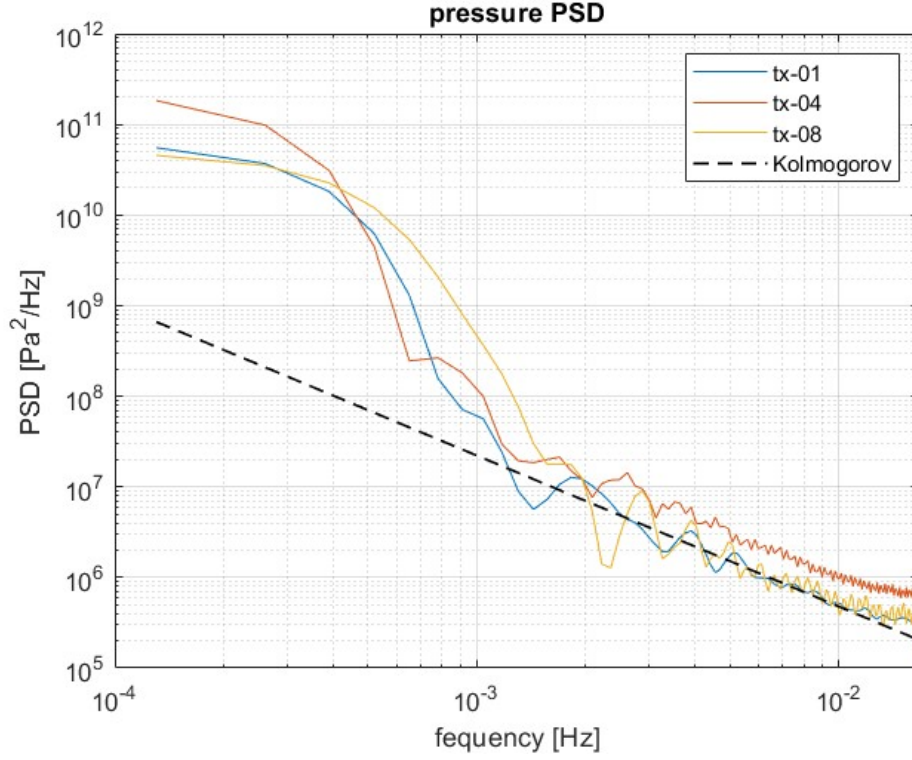


Figure 4.36: Spectral analysis for pressure profiles

In Figure 4.36, we can observe how energy is mostly stored into large structures. The inertial subrange can be identified between $f = 2 - 6 * 10^{-3} Hz$ and exhibits a plateau for lower frequencies. It is then less sensitive to smaller turbulence fluctuations.

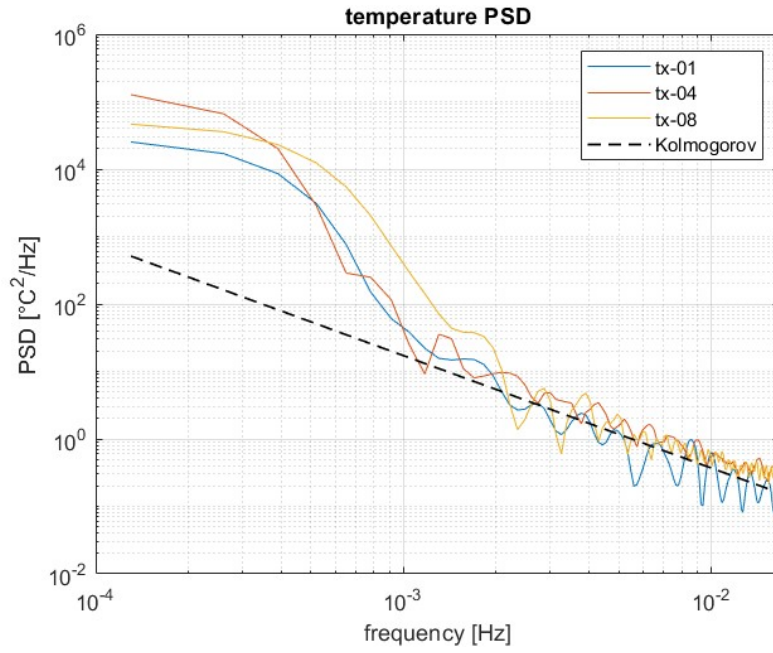


Figure 4.37: Spectral analysis for temperature profiles

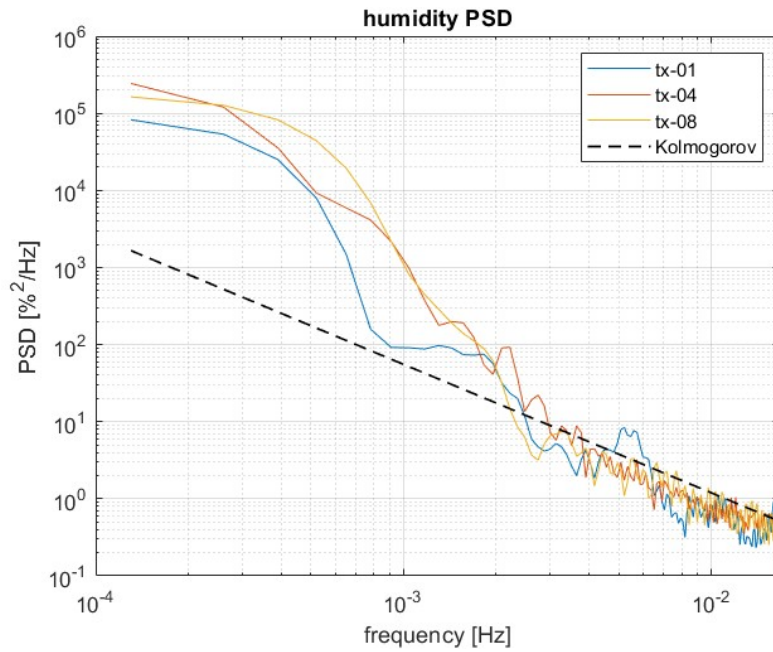


Figure 4.38: Spectral analysis for humidity profiles

In Figure 4.37, it is visible how Temperature spectra mostly follows Kol-

mogorov's laws: this means that Temperature behaves as a passive scalar, being advected and mixed by the turbulent flow without consistently affecting the flow itself.

Humidity spectra (Figure 4.38) appear more irregular than temperature ones, indicating a higher variability associated with moisture mixing processes.

To have an esteem of how fast turbulence loses its energy, Turbulent Kinetic Energy (TKE) dissipation rate was estimated, which is the rate at which turbulent kinetic energy is converted into internal energy through viscous effects (Stull, 1988 [27]).

For isotropic turbulence (for both wavenumber and frequency domain), the following relationship holds, as described by Batchelor [8] and already discussed in Chapter 1:

$$E(k) = C \varepsilon^{2/3} k^{-5/3} \quad (4.3)$$

and by applying Taylor's Hypothesis ($k = \frac{2\pi f}{U}$):

$$S(f) = \alpha \varepsilon^{2/3} \left(\frac{U}{2\pi} \right)^{2/3} f^{-5/3} \quad (4.4)$$

where k is the wavenumber, $F(k)$ the wavenumber spectrum, ε the mean energy dissipation rate, U the mean wind speed, f the frequency and $S(f)$ is the power spectral density in the frequency domain.

Considering measurements of $S(f)$ within the inertial subrange, the mean TKE dissipation rate $\bar{\varepsilon}$ can be computed as:

$$\bar{\varepsilon} = \frac{2\pi}{U} \left(\frac{f^{5/3} S(f)}{\alpha} \right)^{3/2} \quad (4.5)$$

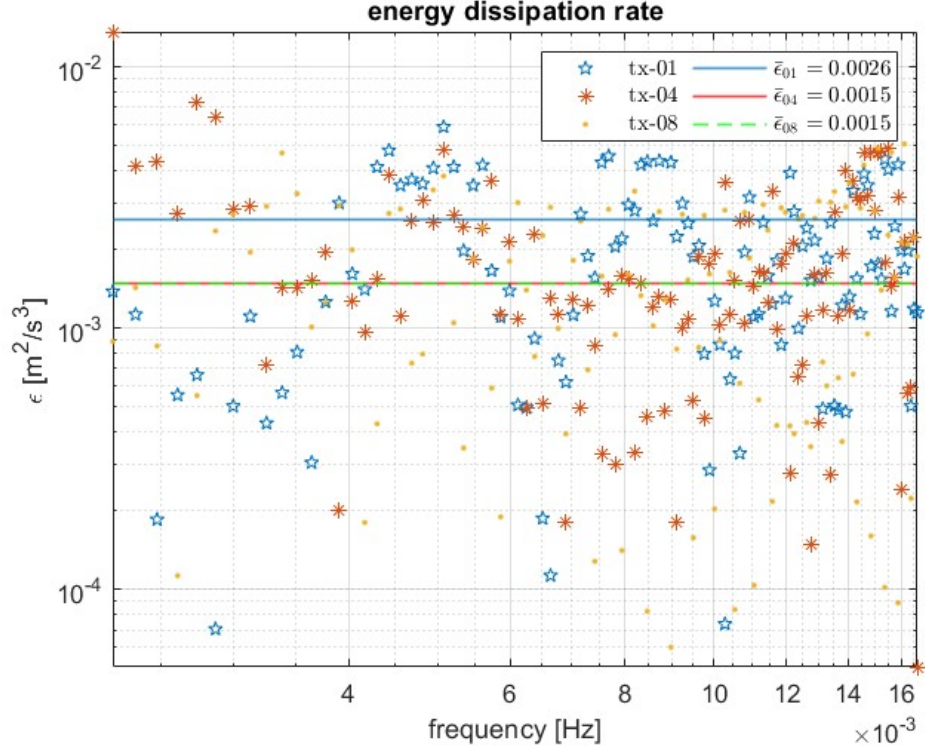


Figure 4.39: TKE dissipation rates. Mean values are highlighted with solid lines

Reported values which can be found in Figure 4.39 result to be consistent with values found in by Abdunabiev during his PhD thesis work [4] and O'Connor et Al [20]. Even if simplification assumption were made, obtained results still provide some valuable insights about atmospheric turbulence characteristics. For future detailed studies it will be crucial to incorporate anisotropy considerations and the broader wavenumber resolvable by radiosondes.

4.4.5 Stability parameters

In order to evaluate if considered atmosphere layers are stable or not, Brunt-Väisälä frequencies N^2 were evaluated using the procedure already explained in Chapter 1, Section 1.4.

It is recalled that positive values of the Brunt-Väisälä frequency ($N^2 > 0$), indicate stable stratification: this means vertical displacements of air particles are opposed by buoyancy forces; while on the other side negative values $N^2 < 0$ denote instability and the enhancement of vertical displace-

ment. Finally, values close to zero correspond to neutral conditions. It is not uncommon that stratification tends to change considerably while changing altitudes, alternating stable and unstable regions.

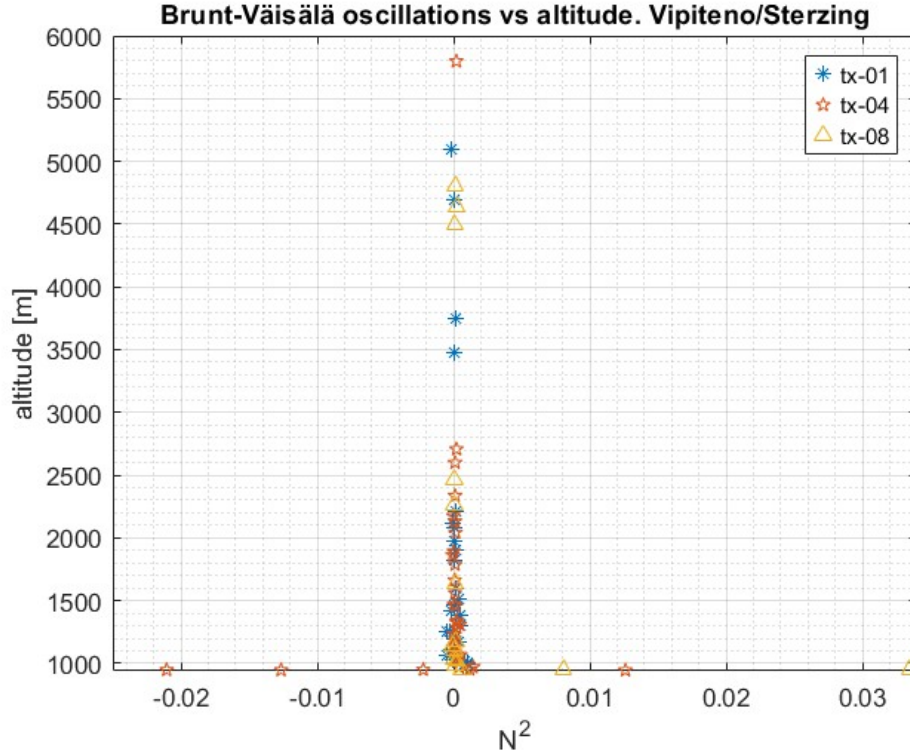


Figure 4.40: Brunt-Väisälä frequencies

Considering that Vipiteno is located at an altitude of 941m above sea level, we can notice how atmosphere's layers near the ground were more stratified with really unstable layers alternating with more stable ones. Considering the high temperatures recorded during the day, this is a typical behaviour of a convective boundary layer characterized by strong turbulent mixing and intermittent thermal plumes. With increasing altitudes, instead, atmosphere showed a more stable behaviour indicating a reduced turbulent activity: this is the perfect environment for the propagation of gravity waves, for which an intense observation campaign was set that day.

4.4.6 Dispersion Analysis

It is now possible to investigate relative motion of the cluster of radiosondes.

4.4. Cluster launch

Transmission was not continuous for all the radiosondes: 20 minutes after launch the first radiosondes started to stop transmitting data. The fact that the number of radiosondes changes in time must be considered also while performing analysis following Richardson [24] dispersion theories.

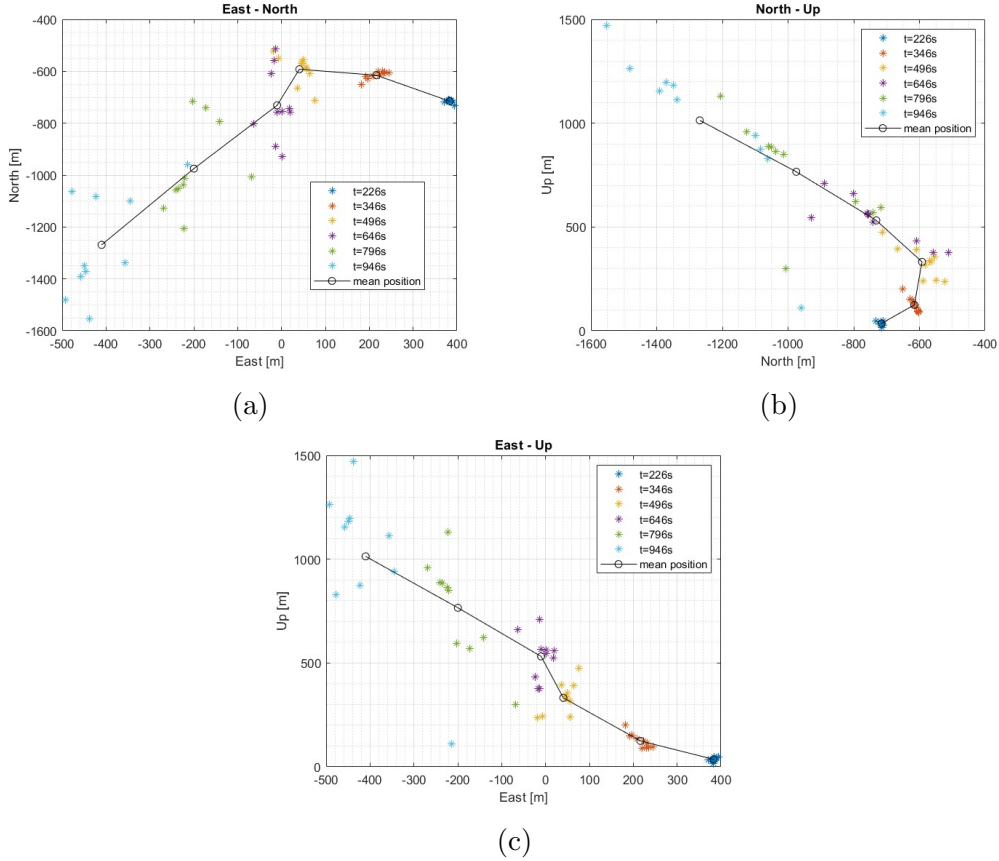


Figure 4.41: first 15 minutes cluster evolution in the planes: North-East (a), North-Up (b) and East-Up (c). Points were colored differently based on considered time, while black markers show the mean cluster position

Before proceeding with analysis following Richardson's theories [24], evolution of cluster in 2D planes at different time intervals was plotted, as shown in Figure 4.41. Plots show the cluster evolution for an amount of time slightly longer than 15 minutes, during which no transmission was lost from any radionde of the cluster. It is possible to notice how the cluster was initially compact during the first minutes of the ascending phase. It travelled towards south, as shown also in Figure 4.20a and started to spread in both horizontal and vertical directions.

It is now possible to continue with the classical Richardson (1926) framework for turbulent dispersion, where relative motion of radiosondes can be analyzed by using the distribution of their separation distances. For this purpose, Distance-Neighbour-Graph (DNG) function, denoted by Q , was used as already explained in Section 1.3.1. For the sake of completeness, we remind that this function identifies the mean number of neighbours which can be found inside a specified space interval.

$$Q_{n,n+1} = \frac{1}{N} (P_{n,n+1}^1 + P_{n,n+1}^2 + P_{n,n+1}^3 + \cdots + P_{n,n+1}^N) \quad (4.6)$$

It is straightforward to understand that Richardson's theories only considered the case of a cluster made of a constant number of points. This has to be taken into account while performing analysis.

Another important point to consider is that in [24] the theory was developed considering a one-dimensional space. It is obvious that the radiosondes travel in a three-dimensional space: Richardson's formulation [24] has been adapted to this configuration.

As the first stage, only the time interval where all the sondes were transmitting at the same time was considered, as shown in Figure 4.42. Due to the fact that at the beginning of the flight sondes were still pretty close to each other, a small distance interval $h = 30m$ was considered.

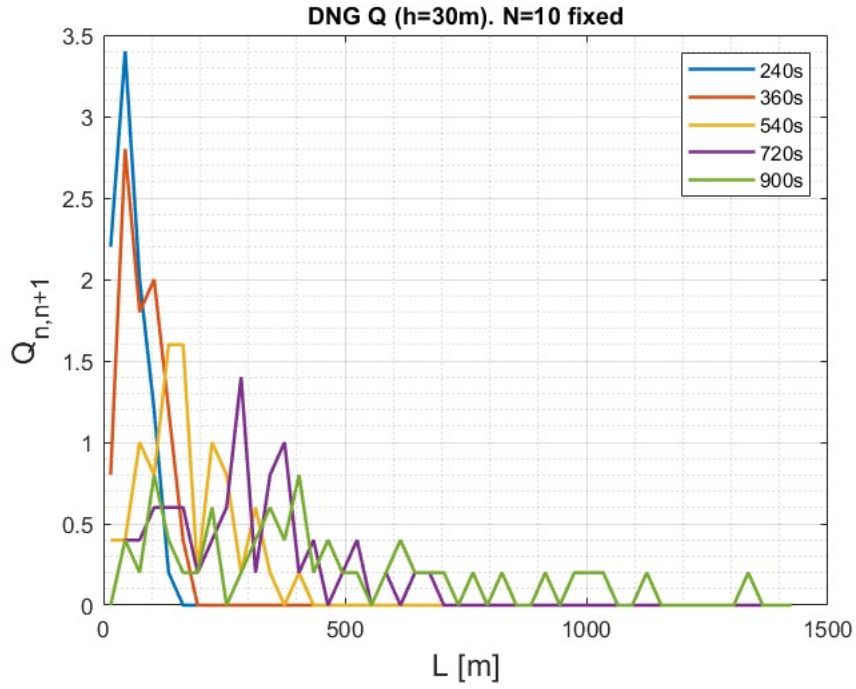


Figure 4.42: Distance-Neighbour-Graph for a fixed number of radiosondes.

By observing Figure 4.42, it is possible to notice how the number of sondes in the neighbourhood tends to decrease as time passes by.

The same analysis was then performed for a broader time interval. In this case a bigger distance interval $h = 200m$ was chosen.

4.4. Cluster launch

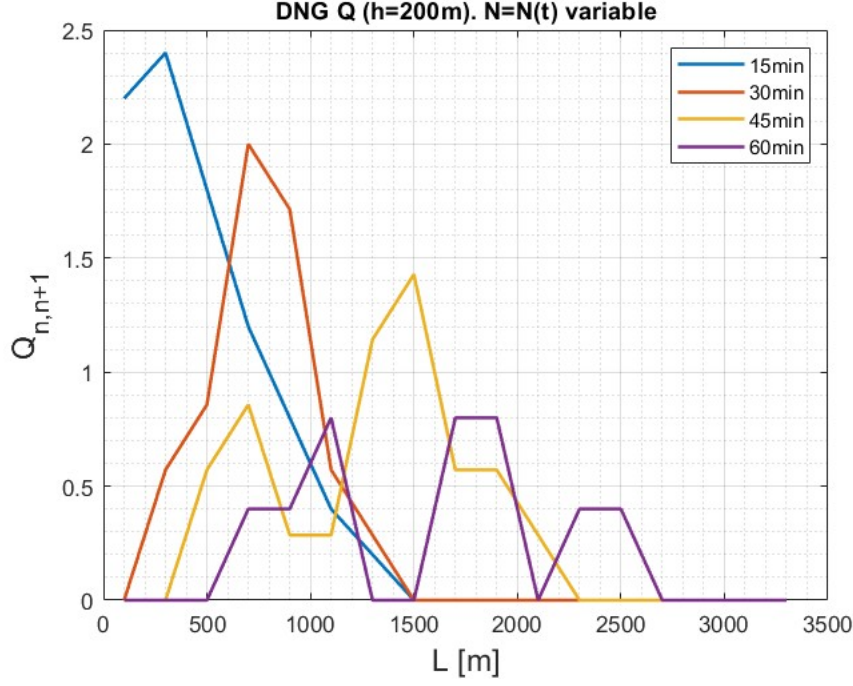


Figure 4.43: Distance-Neighbour-Graph considering a variable number of radiosondes.

It is important to remember that, in this case, the number of transmitting radiosondes was con mantained constant in time. This change was considered during computation and is reported in Table 4.3.

time after launch	transmitting sondes $N = N(t)$
15 min	10
30 min	7
45 min	7
60 min	5

Table 4.3: Number of transmitting sondes as a function of time after launch

The same analysis was then performed again for different fixed space intervals but this time considering the maximum values Q_{max} over time. The aforementioned two different case studies were considered also this time.

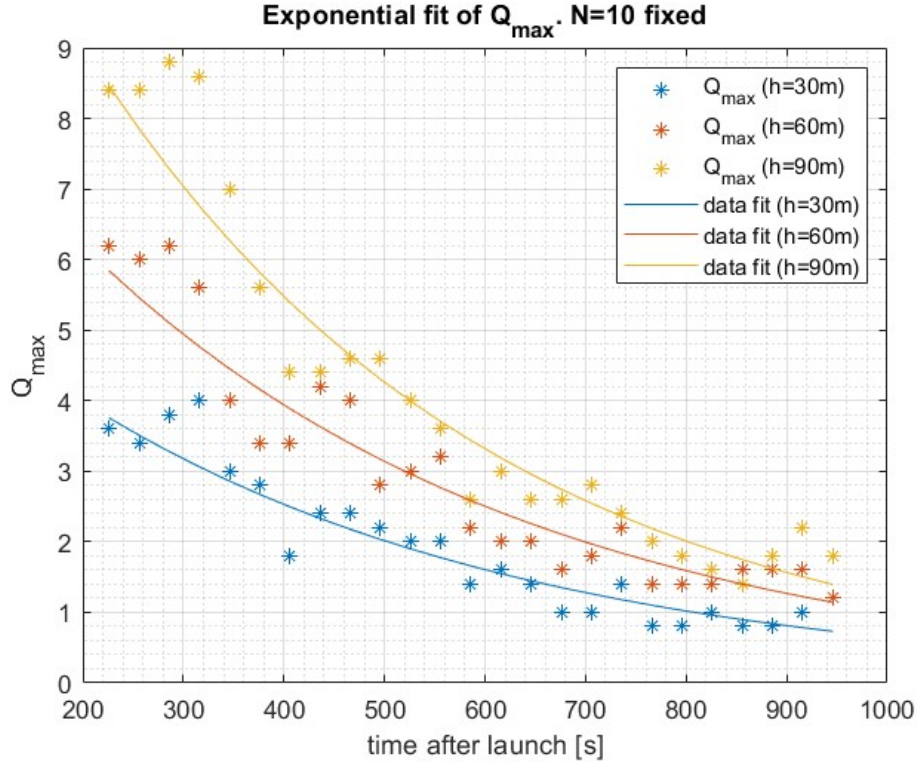


Figure 4.44: Q_{max} values over time for a fixed number of radiosondes

	A	α	equation
$h = 30 \text{ m}$	6.2793	-0.0023	$6.2793 + e^{-0.0023 t}$
$h = 60 \text{ m}$	9.7512	-0.0023	$9.7512 + e^{-0.0023 t}$
$h = 90 \text{ m}$	14.9097	-0.0025	$14.9097 + e^{-0.0025 t}$

Table 4.4: Fitted parameters and corresponding exponential models at different heights

Considering a constant number of radiosondes, as shown in Figure 4.44, a higher number of sondes is found in the neighbourhood when considering a bigger value of h . Values tend to decrease in time with an exponential behaviour of the type $Q(t) = A + e^{-\alpha t}$, as reported in Table 4.4.

The same was then made once again considering the variability of the number of radiosondes over time, as shown in Figure 4.45. In this case considering the exponential decay of Q_{max} for the entire time of the experiment could be misleading due to the fact that $N = N(t)$. To check if the decay behaves in the same way as seen in Table 4.4, it would be better to just consider time intervals where $N = \text{constant}$.

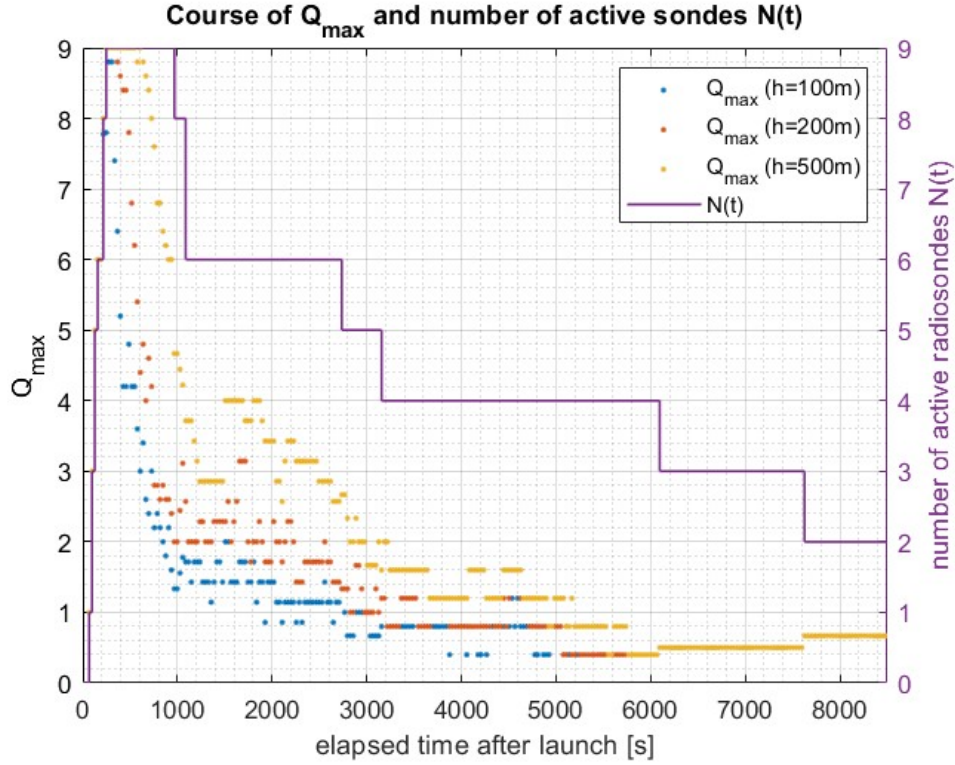


Figure 4.45: Q_{max} values over time considering a variable number of radiosondes. The number of active radiosondes at that time is tracked with a purple solid line.

4.4.7 Mean square separation distance analysis

A mean square separation distance analysis can be useful under the assumption of omogeneous isotropic turbulence, as it is described by [19]. As already discussed in Section 1.3.2, the Richardson-Obukhov (R-O) formulation is described as:

$$l^2 = l_0^2 + g_l \varepsilon t^3 \quad (4.7)$$

This analysis provides a measure of the dispersion of the radiosonde cluster, indicating how rapidly the probes diverge over time.

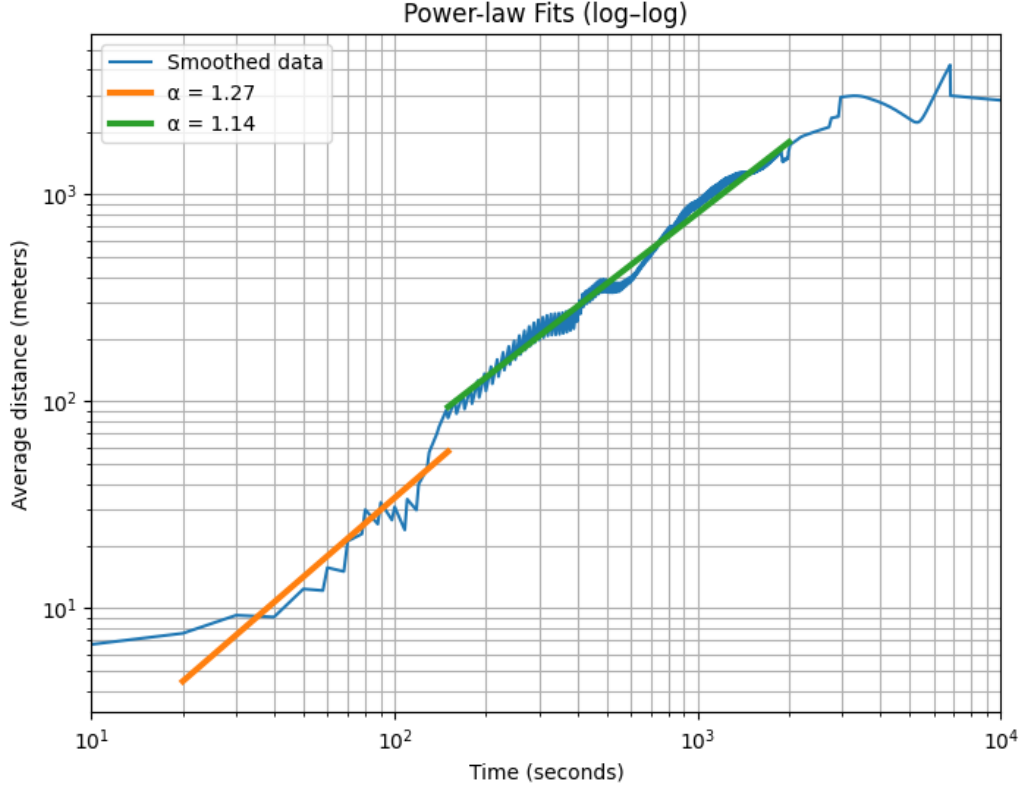


Figure 4.46: mean separation distance for Vipiteno's cluster

In Figure 4.46, a plot of mean separation distance is presented. Solid lines approximate the slope of data. By comparing our data with the expected behaviour by R-O theories, we notice that our data have a smaller exponential dependency than what expected ($\alpha=1.5$): this means that dispersion is not pretty much boosted in this area. This is actually coherent with what shown in Figure 4.20a.

4.4. Cluster launch

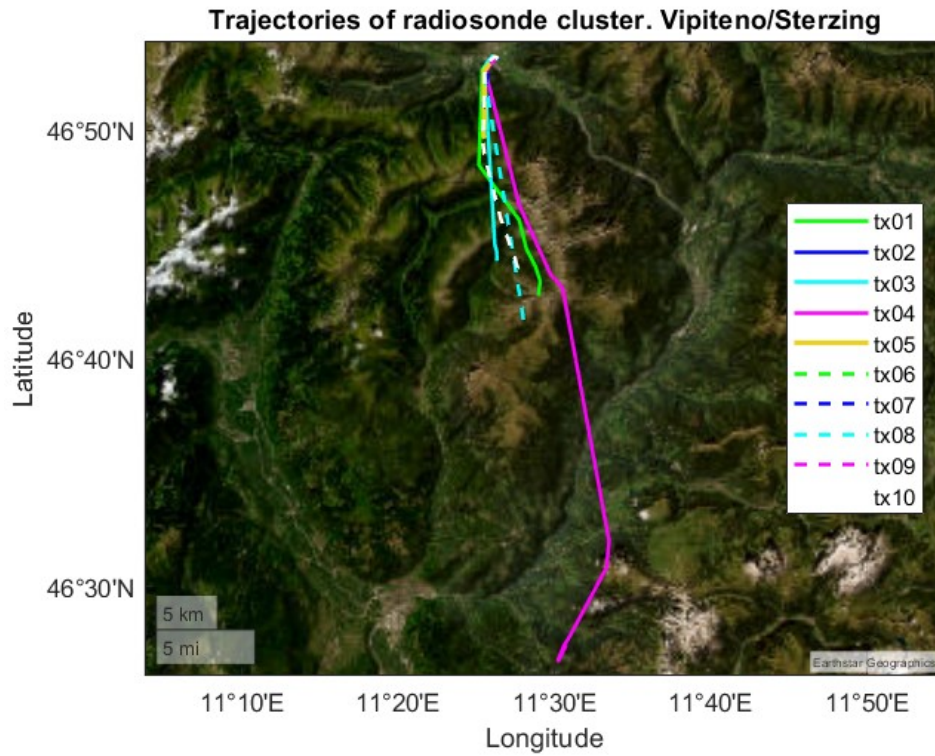


Figure 4.47: mean separation distance for Vipiteno's cluster

By also considering local orography, (Figure 4.47), we can notice how sonde's motion was affected by the presence of a mountainous environment, which canalized the whole flow. Only one radiosonde managed to continue to transmit data after passing the mountain range.

Chapter 5

Long-Range Lagrangian Radiosonde Cluster Observations from the Po Plain to Croatia: The Carmagnola Experiment



Figure 5.1: Balloons ready to be deployed during Carmagnola's experiment

5.1 Introduction

On the 22nd of July 2025, a second experiment was carried out.

This time a cluster made of 20 radiosondes was released from Centro di Agrozootecnica tetto Frati in Carmagnola (TO).

This was the launch with the highest number of released radiosondes, doubling the last maximum number of radiosondes.

The facility chosen for this experiment is a research facility of the University of Turin where agricultural and zootechnical studies are carried out.

This facility was chosen due to the presence of a meteorological and piezometric station operated by ARPA Piemonte.

Instrumentation used for the experiment and preparation process was the same for Vipiteno's launch, the only difference was in the number of used radiosondes and Mylar balloons.



Figure 5.2: View of Centro di Agrozootecnica Tetto Frati, Carmagnola (TO) where meteorological and piezometric instrumentation operated by ARPA Piemonte are shown

The whole cluster was launched around 10:20 UTC. After the release, sondes were chased by car following coordinates sent by some of the radiosondes as it was done in Vipiteno. This chasing allowed to collect as much data as possible in the first part of the experiment.

5.2 Raw Data analysis

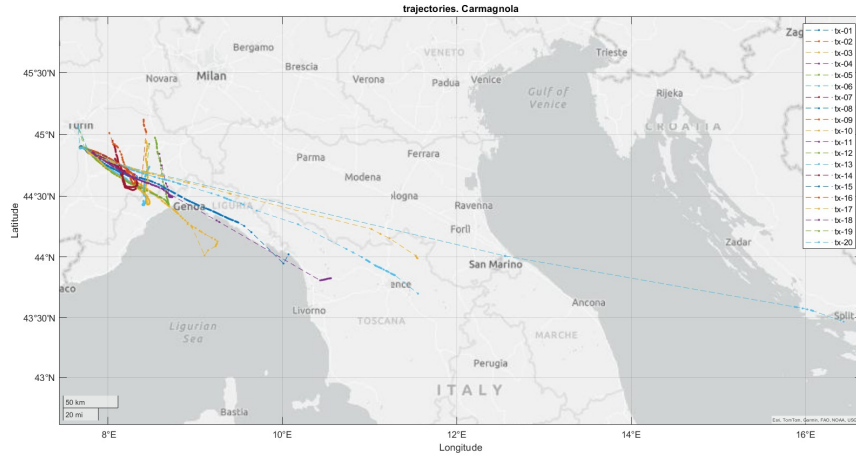


Figure 5.3: Trajectories of Cluster launched in Carmagnola

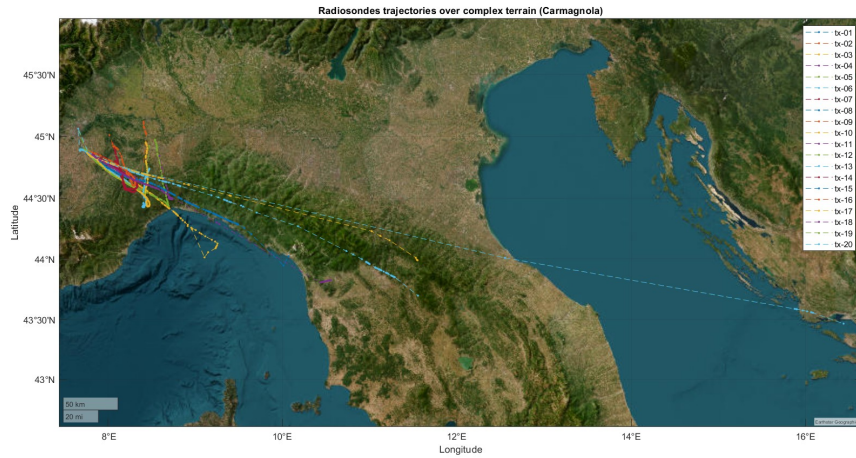


Figure 5.4: Trajectories of Cluster launched in Carmagnola considering local orography

As it is shown in Figures 5.3 and 5.4, radiosondes in the cluster divided into three different groups during the flight.

Radiosondes tx-07, tx-14, tx-16 and tx-19 probably encountered a vortex and turned back to Piemonte, heading for Turin. The group made of radiosondes tx-05, tx-06, tx-09, tx-10, tx-12 and tx-18 turned back to

5.2. Raw Data analysis

Piemonte like the first one, but instead of Turin headed towards Novara, so they were directed more to the North. Finally, the rest of the radiosonde had a linear path to the southeast: the majority of the radisondes inside this sub-cluster landed in Tuscany, while tx-03 followed the group until it probably encountered another vortex which made it turn back to Genoa and land in the Ligurian Sea. Tx-20 managed to reach Split, to the coast-line of Croatia, tracing in this way the longest path traveled by a House-flies' radiosonde so far.

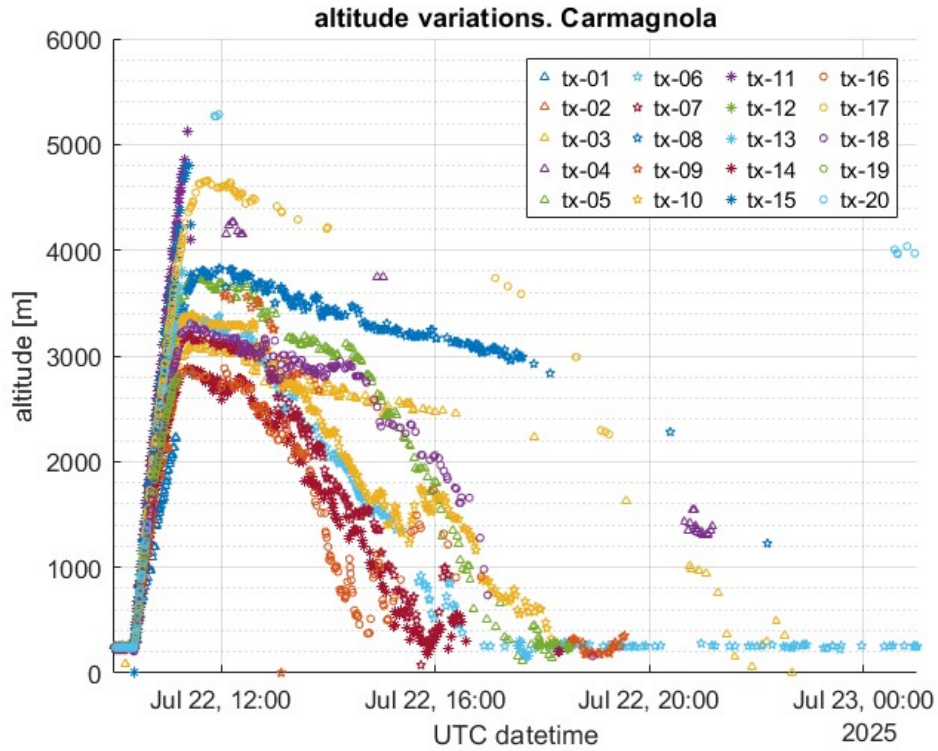
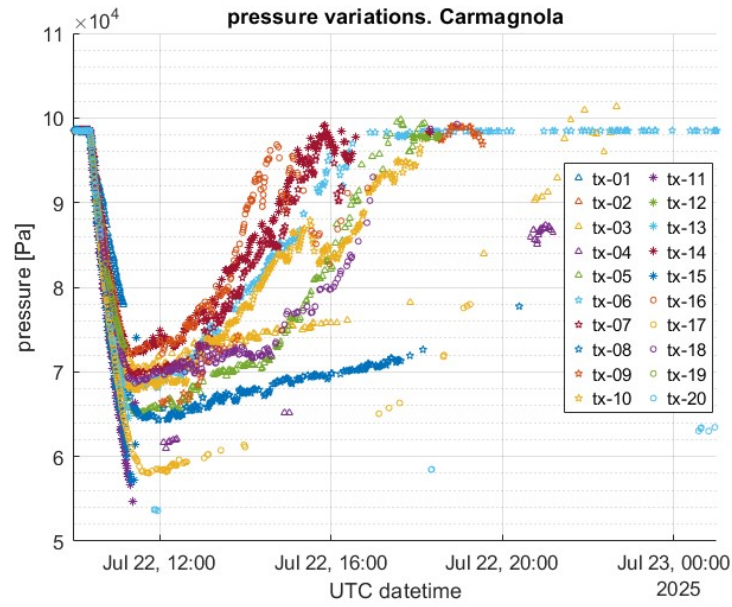
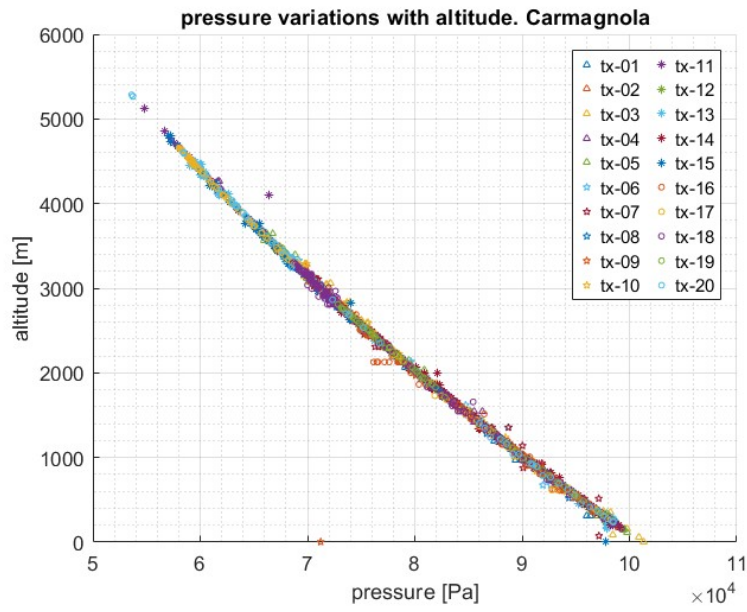


Figure 5.5: Altitudes reached by radiosondes

5.2. Raw Data analysis



(a)



(b)

Figure 5.6: Pressure profiles

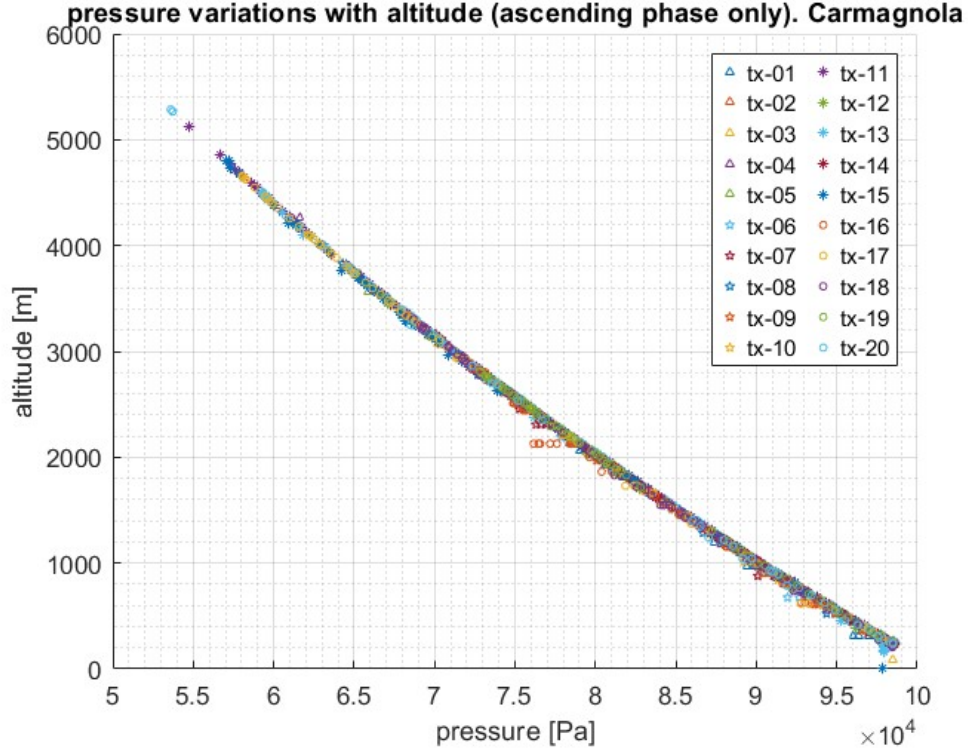


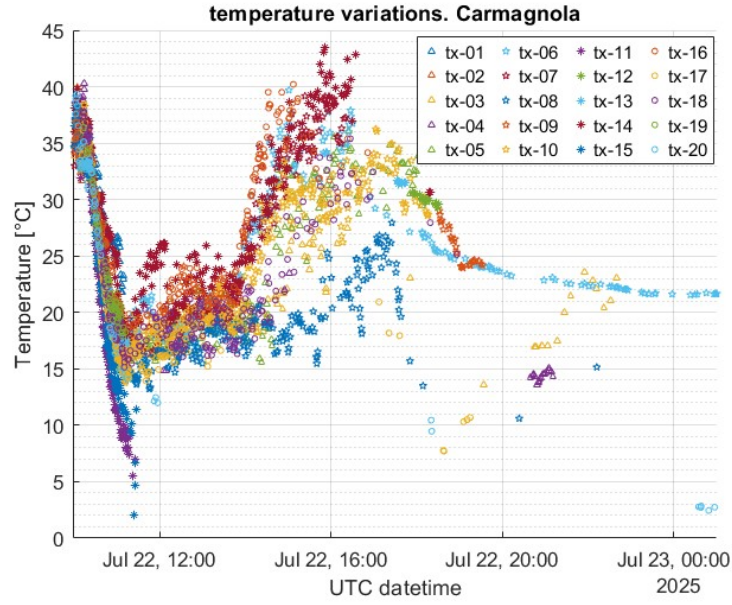
Figure 5.7: Pressure profiles during ascending phase

Observing pressure profiles shown in Figures 5.6b and 5.7, we can notice how they are perfectly coherent with expected results as pressure decreases with altitude. It is also possible to notice how pressure behaviour is perfectly coherent with the one recorded during Vipiteno's experiment, which is shown in Figure 4.20a. Only some recordings in Figure 5.6b are considerably out of the expected range (it is referred to two values recorded by sondes tx-09), but observing only the ascending phase (Figure 5.7) it is obvious that these points were recorded during descending phase, and finding the correspondent points in Figure 5.5, it is obvious that those were from the last packet of data recorded by the sondes before losing any kind of transmission. Considering also the fact that they were both near some LORAWAN Gateway station and last transmission was not after 3-4 hours after launch, it is unlikely that they run out of battery. Radiosonde tx-09 touched the ground around 14:00 UTC and then trasmitted few more data around 18-19 UTC, always while being not far from the ground. On the other hand, tx-11 data was the last transmitted one.

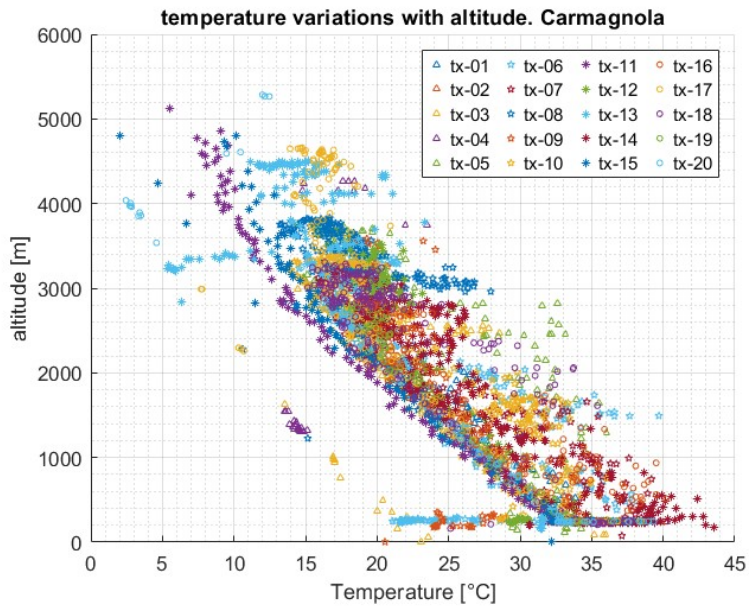
In Figure 5.6a some pressure fluctuations are related to corresponding altitudes fluctuations. It is also possible to notice how tx-06, after falling to

5.2. Raw Data analysis

the ground, continued to record the same pressure level for multiple hours.



(a)



(b)

Figure 5.8: Temperature profiles

5.2. Raw Data analysis

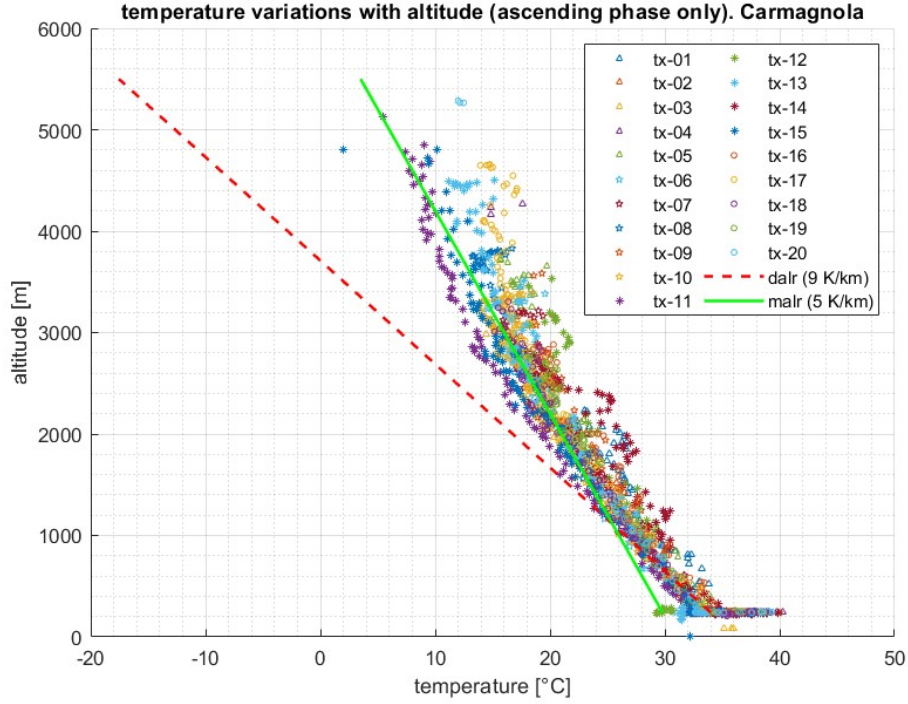
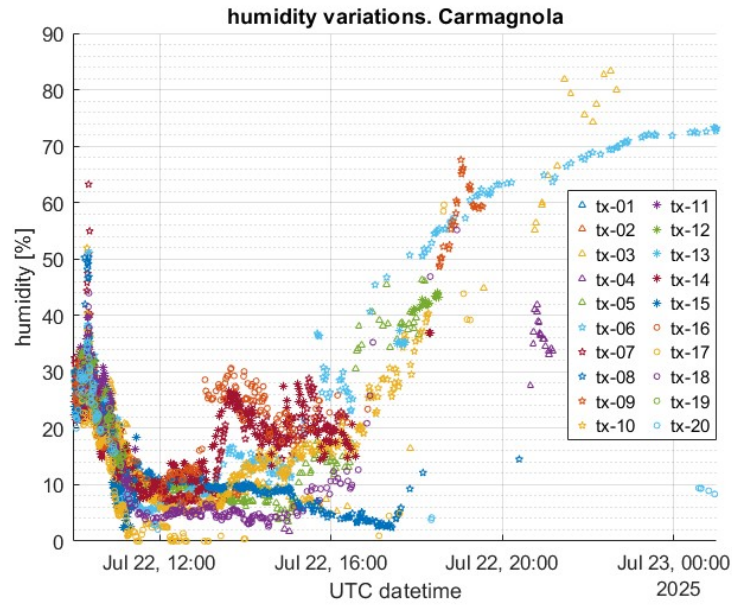


Figure 5.9: Temperature profiles during ascending phase and comparison with dry and moist adiabat

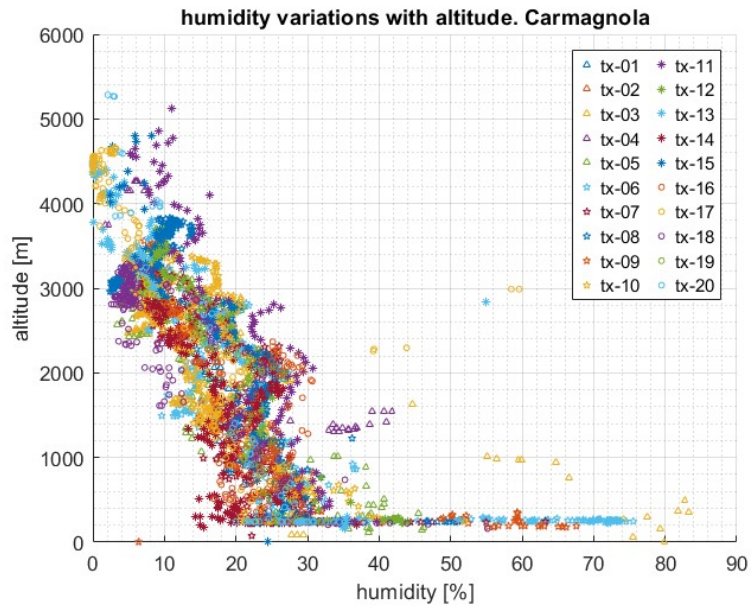
Profiles shown in Figure 5.8a show a behaviour similar to pressure ones: temperature oscillations can be related to corresponding altitudes ones. It is interesting to notice how, due to the fact that data was recorded during a long time interval, temperature tends to decrease not only due to the ascending phase but also for the cooling process of atmosphere boundary layer which takes place when evening comes. This process is evident observing tx-06 recordings: it was already mentioned that this sonde continued to record after touching the ground, and in Figure 5.8a it is possible to notice that, for a constant position, temperature tends to decrease as the sun starts to set down.

As it was previously done in Subsection 4.4.3, a comparison between temperature recorded data during ascending phase and moist and dry adiabatic lapse rate was made, as shown in Figure 5.9. Temperature data followed dry adiabat lapse rate's slope until $\sim 1500 - 1600m$ above sea level and fully aligned with moist adiabat lapse rate's slope for altitudes from 2000m on.

5.2. Raw Data analysis



(a)



(b)

Figure 5.10: Humidity profiles

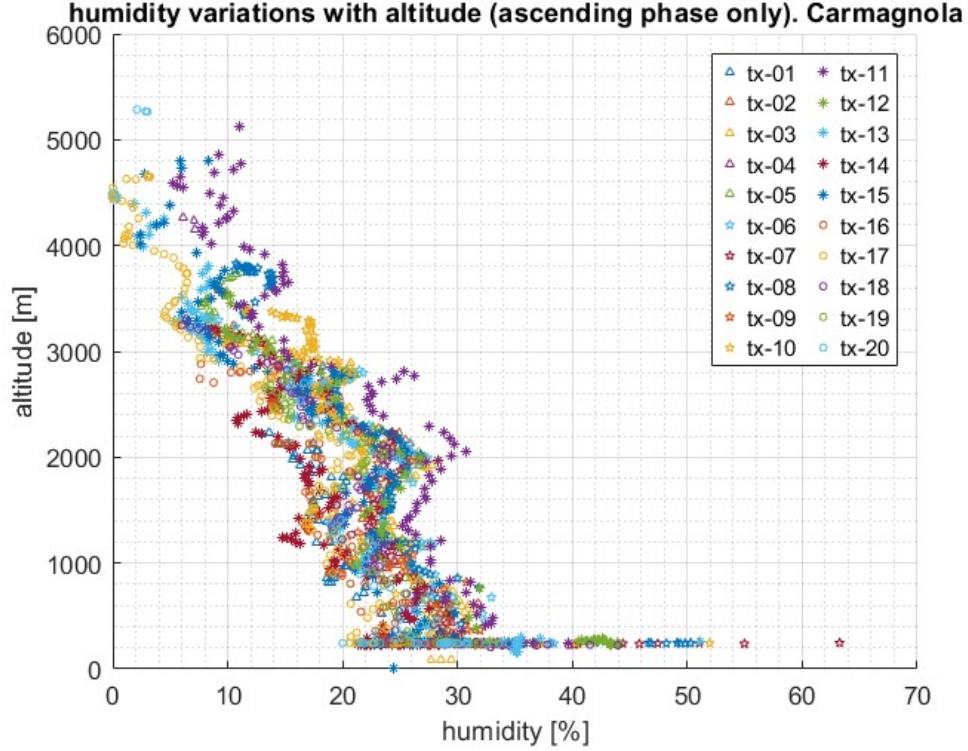


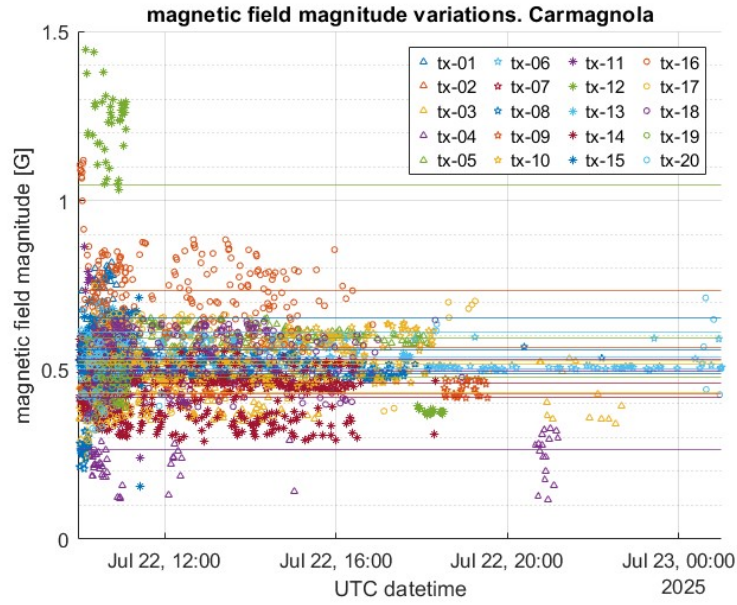
Figure 5.11: Humidity profiles considering only ascending phase

Recorded humidity shows more fluctuations than temperature and pressure profiles. This behaviour is consistent with what found in Vipiteno's data and is coherent with what is expected. Always observing tx-06 recordings, it is possible to notice how humidity tends to increase as the atmosphere starts to cool down.

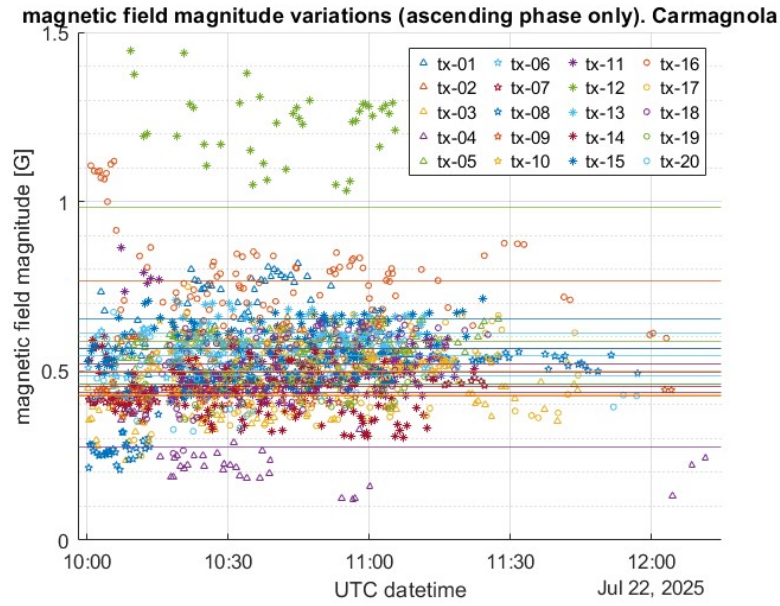
What is interesting to notice is that, as shown in Figure 5.11, mean humidity tends to decrease with increasing altitude, reaching also values near to zero. This behaviour was highlighted also in Riccardo Villa's thesis [33]. This behaviour has to be investigated more in detail in order to understand if recordings were affected by some bias errors or if atmosphere had such a peculiar behaviour that day.

We already know, as discussed in Subsection 4.3.1, where comparison between Väisälä and Houseflies' radiosonde behaviour was made, sondes are really sensitive to outer environment influence, and it is not unlikely that they have undergone overheating during preparation phase considering that it was a really hot July morning. Further analysis, also using some models like ICON will be conducted in the future in order to give more insights about this behaviour.

5.2. Raw Data analysis



(a)



(b)

Figure 5.12: Magnetic field magnitude profiles considering the whole flight (a) and only the ascending phase (b). The solid lines represent mean values for each radiosonde in the cluster.

As for Vipiteno's experiment, by observing Figure 5.12, the same obser-

variations made for Vipiteno in Figure 4.26 can be done: only some of the mean magnetic field magnitude values are in the expected range between 0.45-0.5G, meaning that a consistent way to properly calibrate the instrumentations still has to be found.

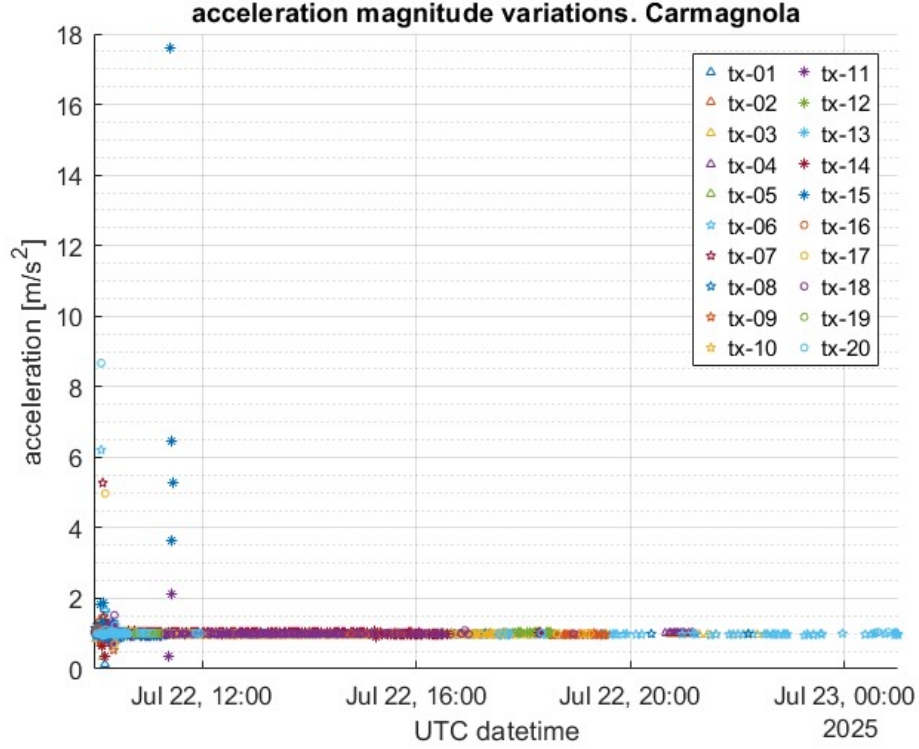


Figure 5.13: Acceleration magnitude profiles

As shown in Figure 5.13, with exception made for some points, acceleration magnitude stands in the expected values.

5.3 Spectral Analysis

In this section, results obtained from some post-processing analysis of collected data from radiosondes will be analyzed and compared with well-known theories from literature as it was done in Subsection 4.4.4.

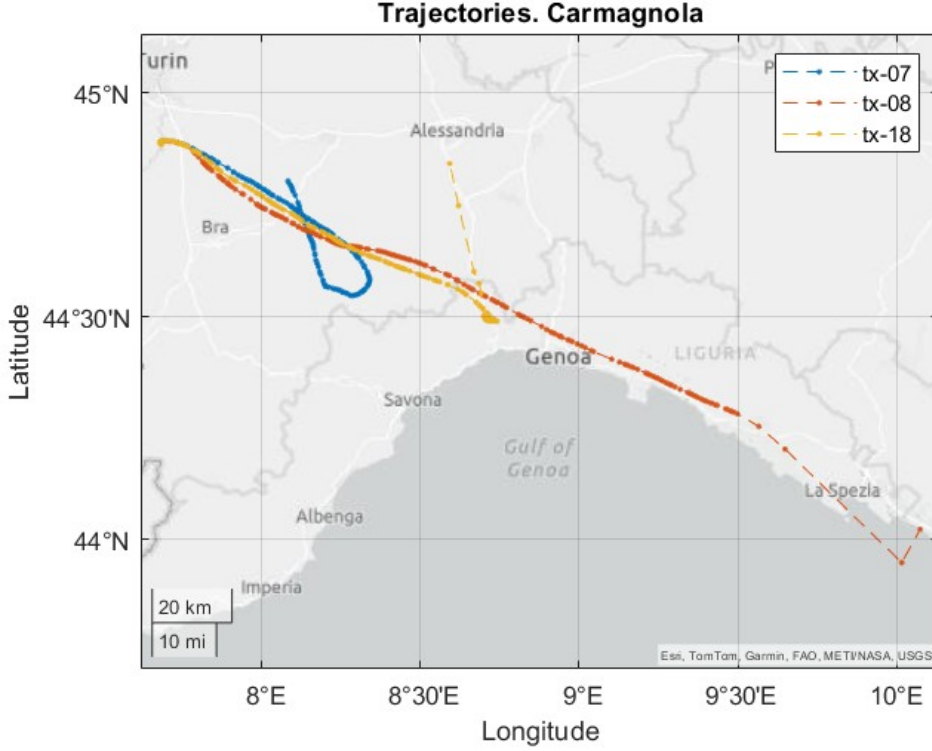


Figure 5.14: Trajectories of radiosondes tx-07, tx-08, tx-18

As it was previously done, packets of data were resampled in order to obtain a uniform time grid and perform our analysis. Linear interpolation was applied to data as well at regular 30s intervals, which set the Nyquist frequency to:

$$f_N = \frac{1}{2\Delta t} = \frac{1}{2 \times 30 \text{ s}} \approx 0.0167 \text{ Hz} \quad (5.1)$$

For this investigation three sondes were chosen: tx-07, tx-08 and tx-18. This decision was made in order to analyze different data from what analyzed by Riccardo Villa [33], all while comparing results coming from sondes belonging to different subcluster which branched from the main one as discussed before.

As it was done in Subsection 4.4.4, this investigation will start by analyzing NEU speed components spectra behaviour.

After collecting the coordinates for each recorded position, speed magnitude was projected into NEU coordinate frame.

5.3. Spectral Analysis

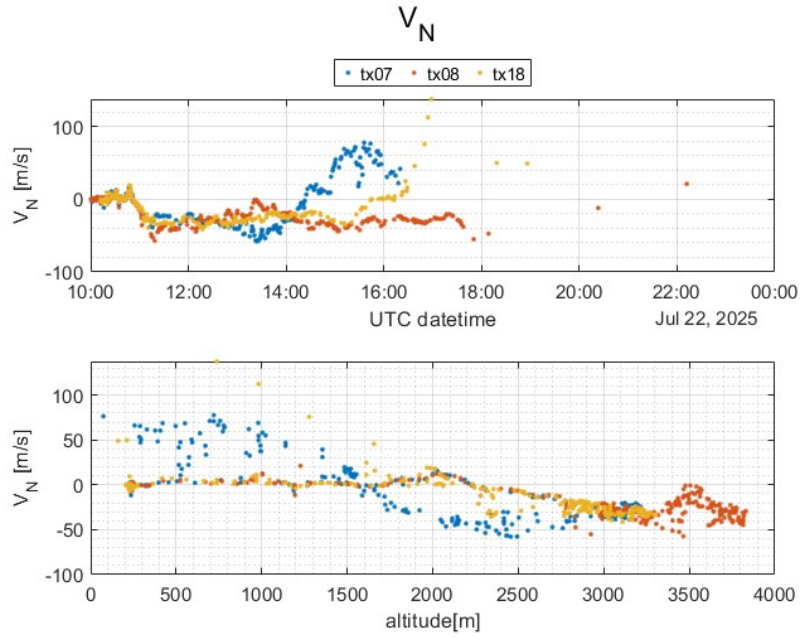


Figure 5.15: North speed component in the NEU reference frame as function of time and altitude

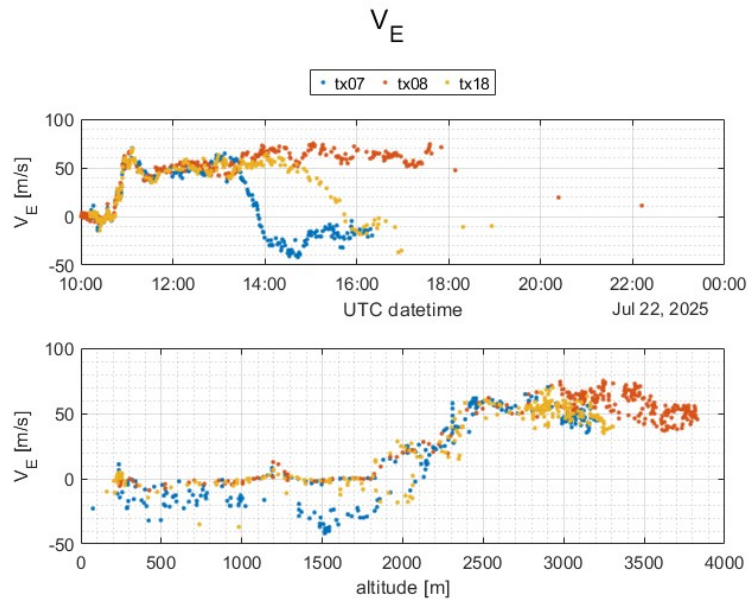


Figure 5.16: East speed component in the NEU reference frame as function of time and altitude

5.3. Spectral Analysis

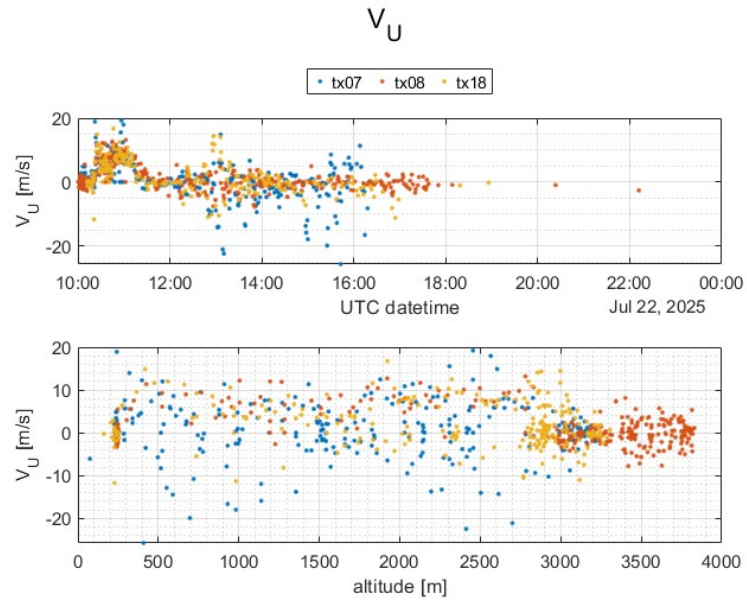


Figure 5.17: Up speed component in the NEU reference frame as function of time and altitude

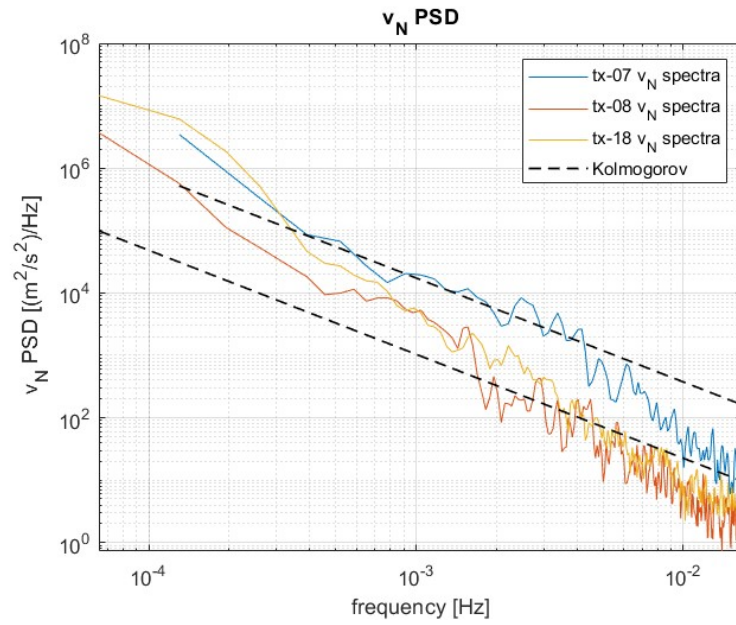


Figure 5.18: Spectral analysis for V_N

5.3. Spectral Analysis

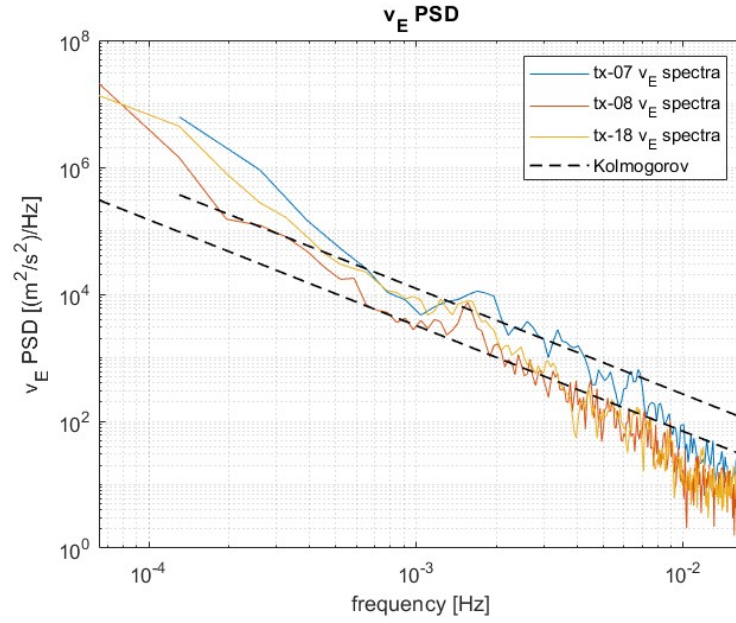


Figure 5.19: Spectral analysis for V_E

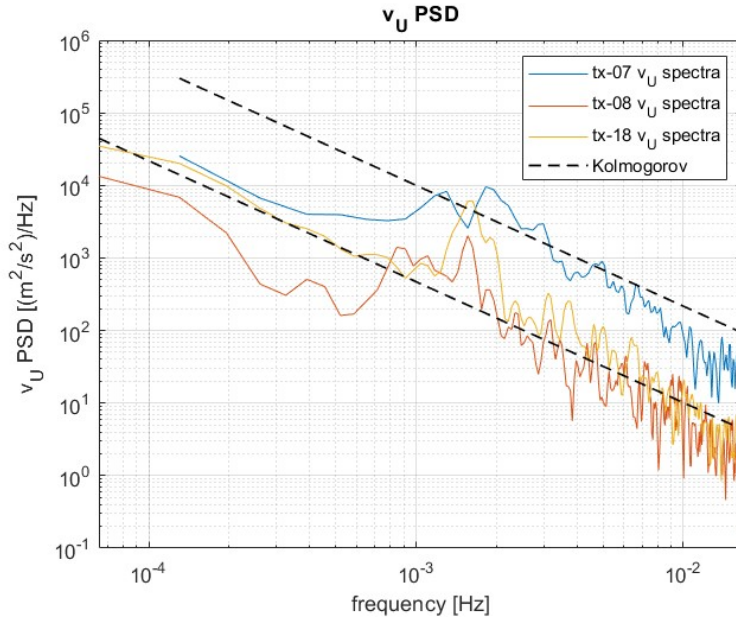


Figure 5.20: Spectral analysis for V_U

As it is shown in Figures 5.18, 5.19 and 5.20, energy levels of tx-07 energy levels are higher than tx-08 and tx-18 ones. This is consistent with tx-07

5.3. Spectral Analysis

trajectory, which exhibits a recirculation pattern suggestive of a localized vortex or strong shear region: it is then likely that this path is characterized by higher kinetic energy levels. Tx-08 exhibits a slightly more energetic behaviour than tx-18, which is characterized by a mostly linear trajectory, probably due to the fact that it does a little turn at a certain point of its trajectory.

As a comparison, black dotted lines are shown in figures to represent the energy cascade behaviour expected by Kolmogorov's theory, where $S(f) \propto f^{-5/3}$. It is possible to identify, by doing a comparison, the inertial subrange for certain frequencies.

Tx-07 inertial subrange is identified for frequencies around $f = 10^{-3} - 5 * 10^{-3} Hz$ for V_N , $f = 1.5 * 10^{-3} - 7 * 10^{-3} Hz$ for V_E and $f = 1.5 * 10^{-3} - 7 * 10^{-3} Hz$ for V_U . Tx-08 and tx-18 have a similar behaviour and their inertial subrange is identified for frequencies around $f = 1.5 * 10^{-3} - 6 * 10^{-3} Hz$ for V_N , $f = 10^{-3} - 7 * 10^{-3} Hz$ for V_E and $f = 2 * 10^{-3} - 10^{-2} Hz$ for V_U .

It is also possible to notice how energy levels of V_N and V_E are higher than V_U : it is true that there are multiple fluctuations upwards, but from NEU reference frame point of view, trajectories were mainly in North-East direction.

Lastly, in Figure 5.20 an interesting behaviour of the energy spectra is shown: after an initial decrease of energy typical of the expected energy cascade, instead of proceeding with this trend there is an increase in the energy density before the energy cascade starts again. This behaviour is more evident for tx-07, but also the others show a similar trend, even if less evident. The sudden increase of energy is located at relative low frequencies: this probably indicates the presence of an atmospheric structure which provided energy to the whole system.

It is now possible to analyze mean horizontal wind speed behaviour.

Horizontal mean wind speed was then computed as it was done in Subsection 4.4.4, which we write here again for the sake of completeness:

$$ws_{mean} = \sqrt{V_N^2 + V_E^2} \quad (5.2)$$

By observing Figure 5.22, it is possible to see how the energy level of tx-07 is still higher than the ones from tx-08 and tx-18, but way much less than what happens for only V_N : it is probably due to the effect of V_E , where the energy level of tx-07 is just slightly higher than the others.

5.3. Spectral Analysis

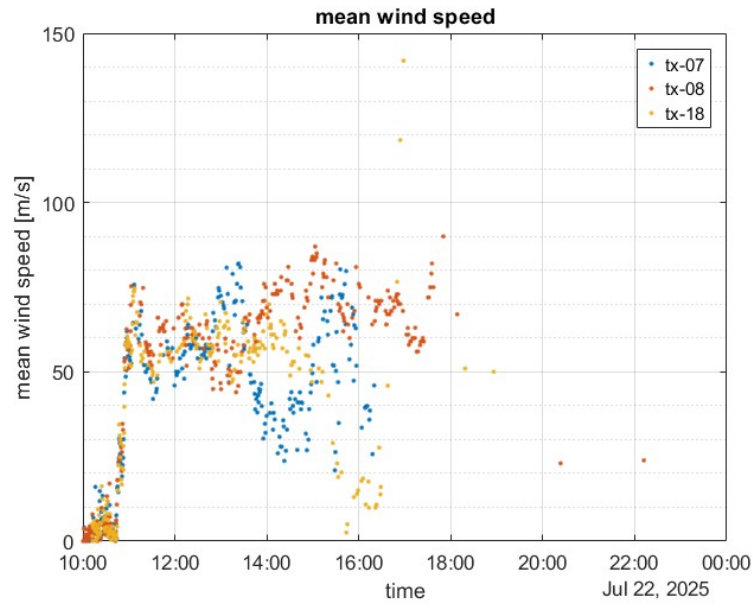


Figure 5.21: Mean wind speed profiles

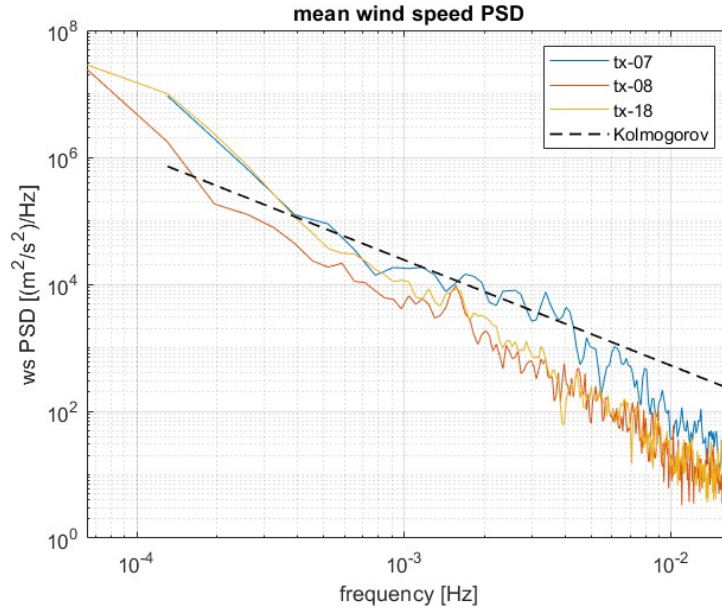


Figure 5.22: Spectral analysis for mean wind speed profiles

Spectral analysis were then performed for pressure, temperature and humidity profiles.

5.3. Spectral Analysis

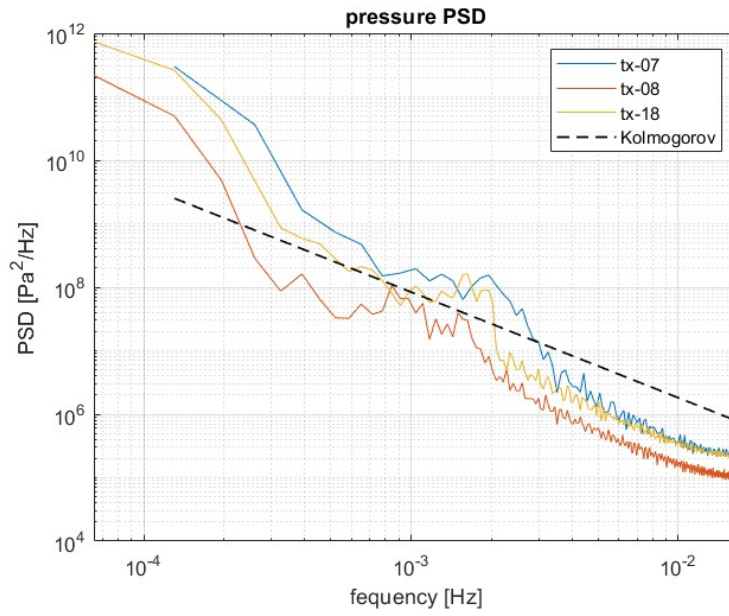


Figure 5.23: Spectral analysis for pressure profiles

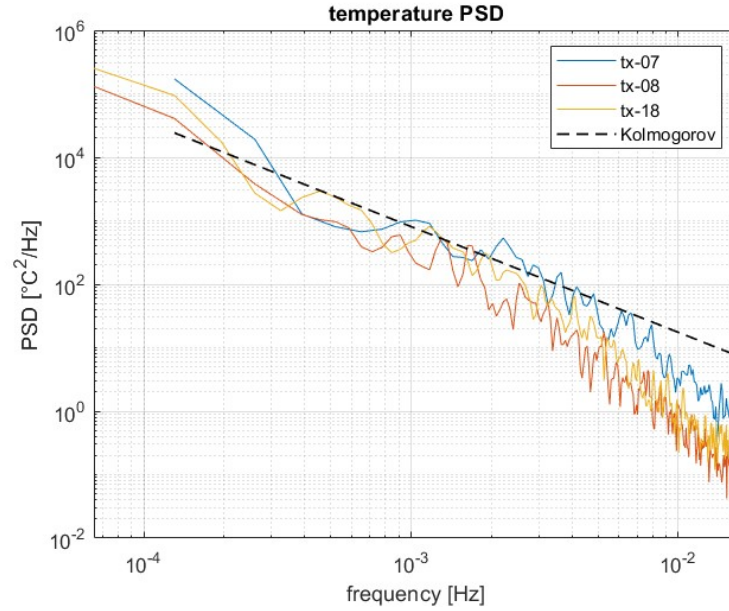


Figure 5.24: Spectral analysis for temperature profiles

5.3. Spectral Analysis

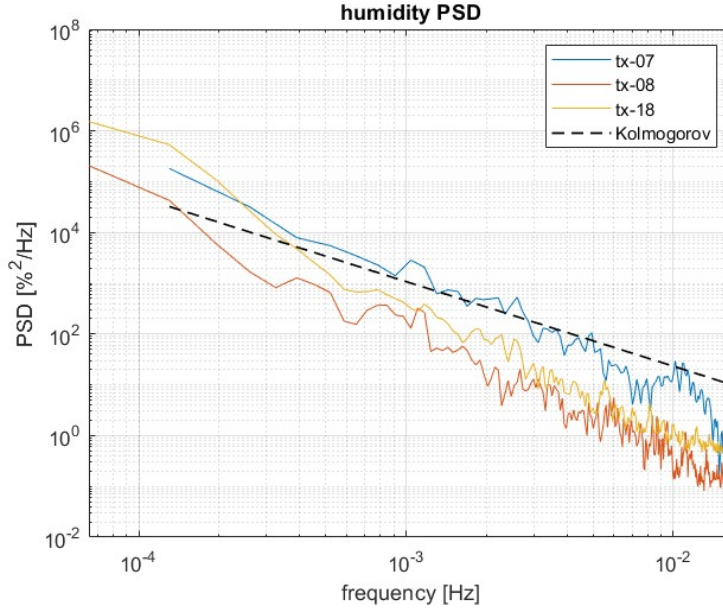


Figure 5.25: Spectral analysis for humidity profiles

Pressure spectra (Figure 5.23), exhibit a behaviour similar to the one found in Subsection 4.4.4: most of the energy is store at lower frequencies, then spectra follows Kolmogorov's law for inertial subrange for frequencies between $f = 2 * 10^{-3} - 10^{-2}$ and finally has a plateau for higher frequencies. Discussions made in Subsection 4.4.4 seem to apply also to temperature and humidity profiles (Figures 5.24 and 5.25): spectra mostly follow Kolmogorov's trend and tend to exhibit a plateau for higher frequencies, indicating the end of the energy cascade. This means they behave as passive scalars advected by the turbulent flow without affecting it.

To esteem how fast turbulent kinetc energy was dissipated, turbulent kinetc energy (TKE) dissipation rate was computed as it was previously done un Subsection 4.4.4, following the relashionhipt descibed by Batchelor [20] and then applying Taylor's hypothesys:

$$\bar{\varepsilon} = \frac{2\pi}{U} \left(\frac{f^{5/3} S(f)}{\alpha} \right)^{3/2} \quad (5.3)$$

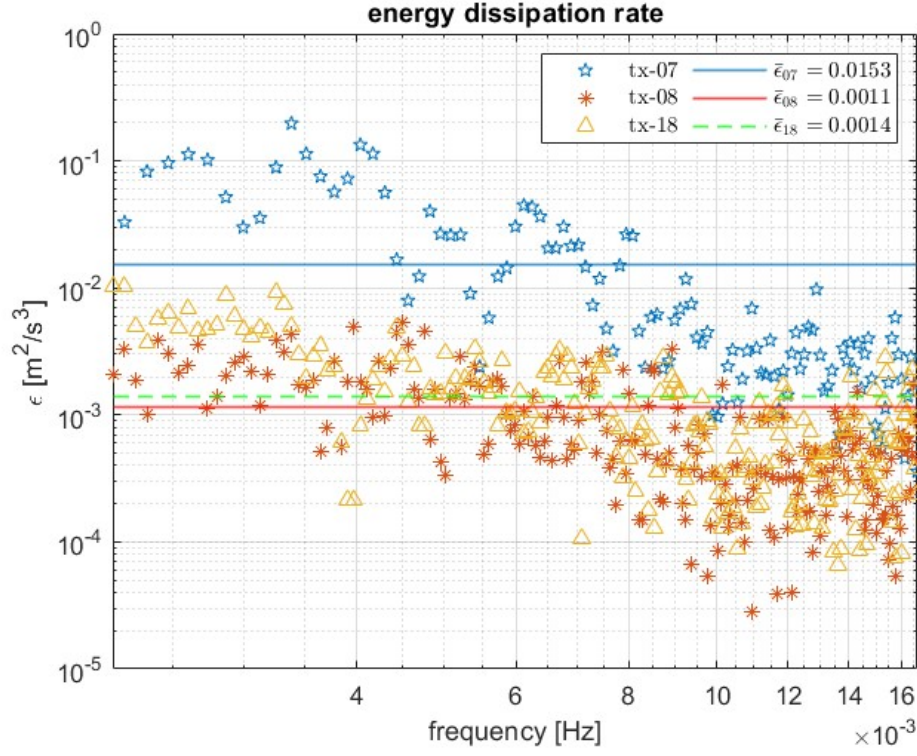


Figure 5.26: TKE dissipation rates. Mean values are highlighted with solid lines

The value of the mean energy dissipation rate, $\bar{\epsilon}$, gives us an esteem of how fast energy is transferred into smaller scales.

As shown in Figure 5.26, tx-08 and tx-18 have similar mean values, which are also consistent with the ones found in Subsection 4.4.4, while the mean value relative to tx-07 measurements is one order of magnitude higher than the others. Having a bigger value of $\bar{\epsilon}$ means that the sonde was in aerea characterized by a more intense turbulence cascade: this enhanced level of turbulent activity is consistent with the trajectory of tx-07, which exhibits a recirculation pattern suggestive of a localized vortex or strong shear region, while tx-08, tx-18 and Vipiteno's sondes trajectories reported a mostly linear behaviour.

5.4 stability parameters

As it was previously done in Subsection 4.4.5, Brunt-Väisälä frequencies were computed in order to evaluate the stability of the atmospheric layer

5.4. stability parameters

passed by the sonde. We remember that positive values of the Brunt–Väisälä frequency ($N^2 > 0$), indicate stable stratification, meaning that vertical displacements of air particles are opposed by buoyancy forces; while negative values $N^2 < 0$ denote instability and the enhancement of vertical displacement and values close to zero correspond to neutral conditions.

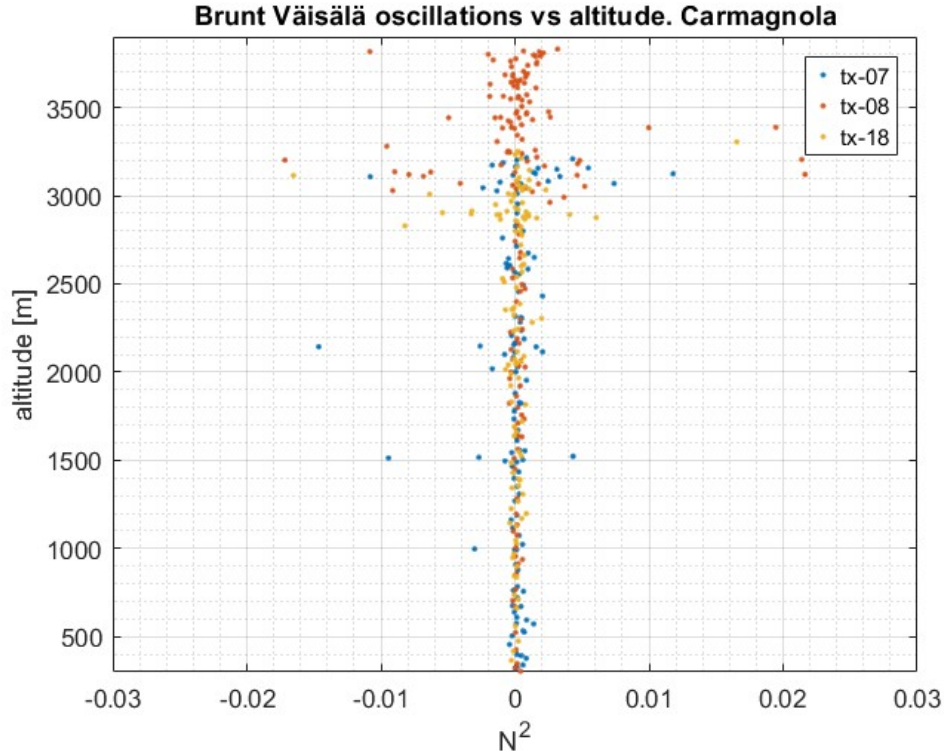


Figure 5.27: Brunt Väisälä frequencies

Figure 5.27 shows how N^2 values tend to oscillate around near-zero values. This means that a condition of weakly stable or near-neutral stability is found. As the altitude starts to increase, also the amplitude of oscillations does the same, especially around 3000 m altitude: this highlights the presence of an alternation between stable and unstable atmosphere layers.

5.5 Dispersion Analysis

Before proceeding with a deeper dispersion analysis, position of the radiosondes in the cluster at different time intervals were plotted. In the following graphs positions of the radiosondes during ascending phase, while all the radiosondes were recording all together, are shown.

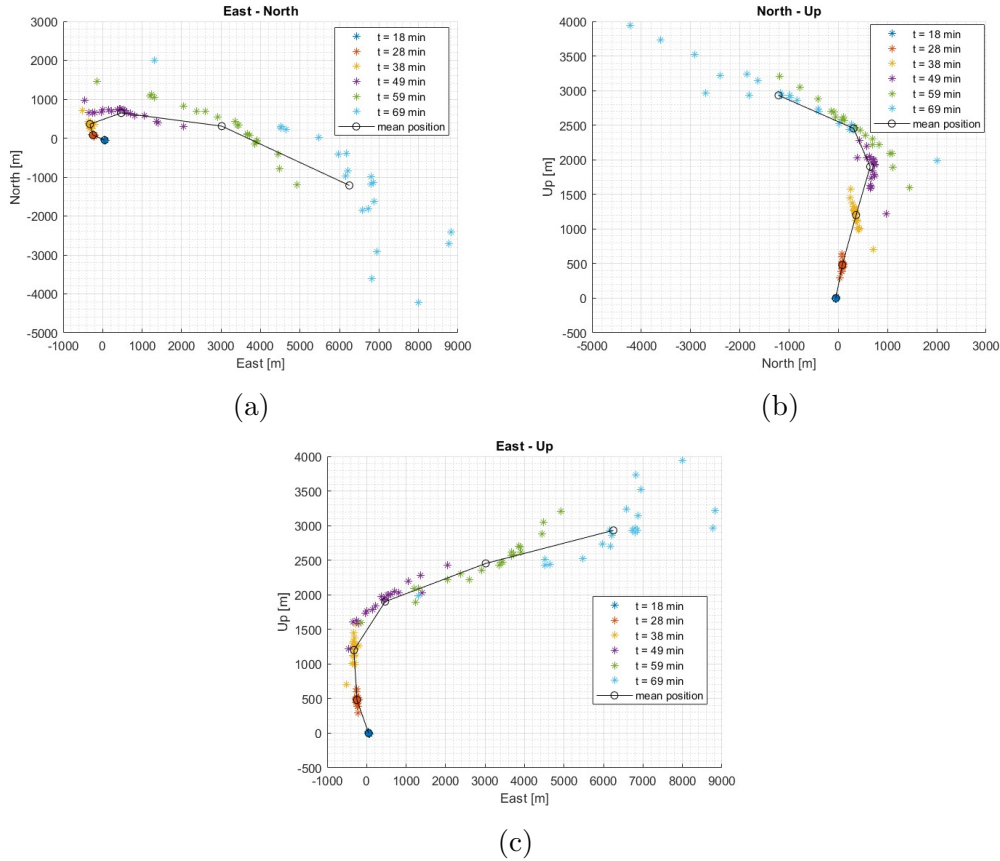


Figure 5.28: cluster evolution in the planes: East-North (a), North-Up (b) and East-Up (c). Points were coloured differently based on considered time, while black markers show the mean cluster position

In the first 20 minutes of the experiment the sondes were closer to each other. What is interesting is that, while ascending, they started to spread along a linear direction. Just in the last time interval displayed, after one hour from the launch, they started to spread also horizontally.

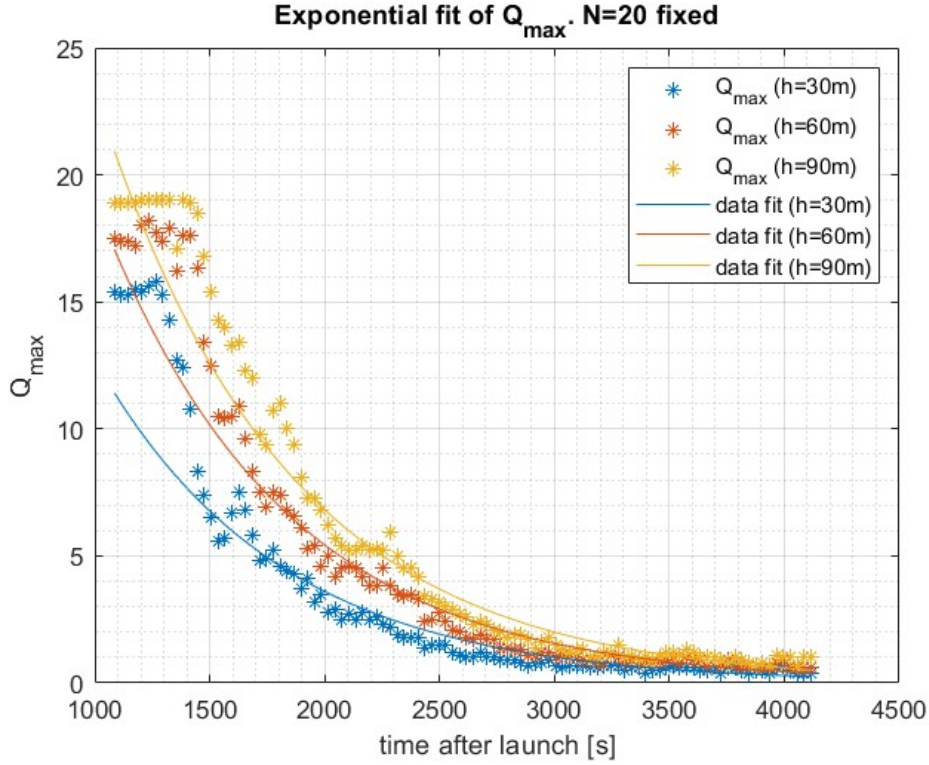


Figure 5.29: Q_{max} values over time for a fixed number of radiosondes

	A	α	equation
$h = 30 \text{ m}$	44.8290	-0.0013	$44.8290 + e^{-0.0013 t}$
$h = 60 \text{ m}$	66.3766	-0.0013	$66.3766 + e^{-0.0013 t}$
$h = 90 \text{ m}$	79.3250	-0.0012	$79.3250 + e^{-0.0012 t}$

Table 5.1: Fitted parameters and corresponding exponential models at different heights

As it was done in Subsection 4.4.6, starting from Richardson's theory [24], Q_{max} values over time were found for different fixed space intervals. The time interval in which a constant number of radiosondes was transmitting was considered, as shown in Figure 5.29. Values tend to decrease with an exponential behaviour, following the relationship $Q(t) = A + e^{-\alpha t}$, where the values of the constants A and α is reported in Table 5.1. It is possible to notice how, in this case, the values of α are nearly the half of those found for Vipiteno's cluster 4.4.6. It has to be highlighted that in this case a longer time interval was considered, so the dynamics tend to reach a plateau.

It would be interesting to analyze the behaviour for bigger space intervals.

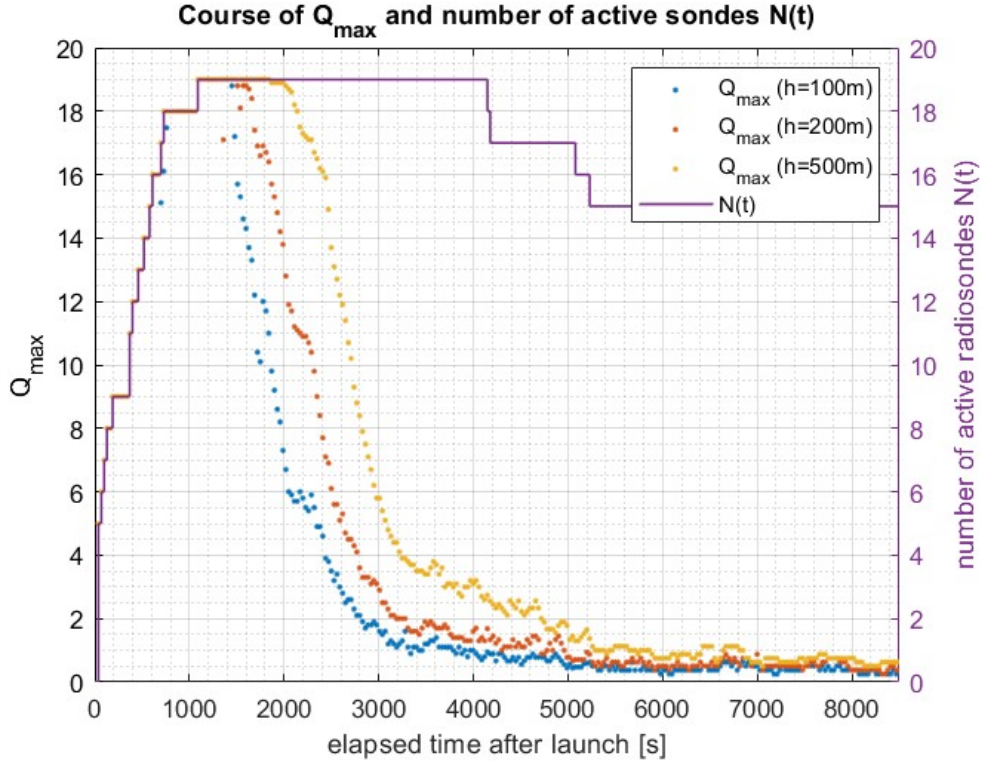


Figure 5.30: Q_{max} values over time for a variable number of radiosondes. The number of active radiosondes at that time is tracked with a purple solid line.

As it was done in Subsection 4.4.6, also in this case maximum values of Q_{max} were plotted considering the whole elapsed time in which the experiment took place. The number of active radiosondes for the considered time interval was tracked as well as shown in Figure 5.30.

Chapter 6

Radiosonde and ICON-2I: comparisons and assimilation dataset

6.1 Introduction

The study of the PBL is of fundamental importance not only from an observational point of view, as analysed so far, but also with regard to its representation within numerical weather prediction (NWP) models. The accurate representation of processes within the PBL in forecast models is of fundamental importance not only for forecasting high-impact events, but also, for example, for solar and wind power generation (Teixeira et al, 2025 [28]).

Its importance is not limited to large-scale models and medium-range forecasts (Beljaars A., 1992 [9]); it is also fundamental for regional models and short-range forecasts.

In the context of this thesis, in order to address the use of radiosondes in numerical modelling, it was possible to establish a collaboration with Agenzia ItaliaMeteo. Agenzia ItaliaMeteo, in collaboration with Arpa Emilia-Romagna, is responsible for the operational set-up and development of limited area model forecasts for Italy.

The topics addressed during this collaboration were the validation of observations and the use of observed datasets in data assimilation. Regarding the validation, a comparison has been made between data collected by the radiosondes along their trajectory with data provided by ICON-2I's analysis.

Of the various launches carried out, for the purposes of this thesis, we

chose to analyse the data collected from the cluster released during the experiment which took place in Vipiteno.

Understanding the differences between observations and model simulations is also relevant to the second, subsequent study, which, in the future, will involve the direct assimilation of Houseflies radiosondes' data into ICON-2I assimilation system.

6.2 ICON-2I

At present, ItaliaMeteo and Arpae are responsible for the joint management of the maintenance and development of national Numerical Weather Predictions (NWP) system. It is based on the ICOSahedral Nonhydrostatic (ICON) model which is developed by several institutions such as Max Planck Institute for Meteorology (MPI), Deutscher Wetterdienst (DWD), Karlsruhe Institute of Technology (KIT), German Climate Computing Center (DKRZ), Swiss National Supercomputing Centre (CSCS), Consortium for Small-scale Modeling (COSMO) and the Climate Limited-area Modelling (CLM) community. ICON is a non-hydrostatic model characterized by an approach for global and regional scales, based on an icosahedral unstructured grid, which eliminates the pole problem and ensures uniform resolution; it is also optimized for high-performance computing (HPC) and released as open-source software.

It is well known that the atmosphere has an intrinsically stochastic nature. In order to take this characteristic into account, an ensemble prediction system is used.

This approach made it possible, on one hand, to estimate the probability distribution of random analysis errors and uncertainties, and, on the other, to predict the probability distribution of forecast states.

Specifically, the forecasts ensemble is initialized from different initial conditions, and its evolution is computed using some schemes designed to represent model uncertainties.

This system serves three main purposes:

- 1) Improving the forecast: the ensemble average tends to naturally filter out the uncertain components while retaining those that show agreement among ensemble members.
- 2) Indicating the reliability of the forecast: when forecasts differ significantly among members, it is clear that the forecast uncertainty is high, conversely, strong agreement among members increase confidence in the results.

3) Provide a quantitative basis for probabilistic forecasting.

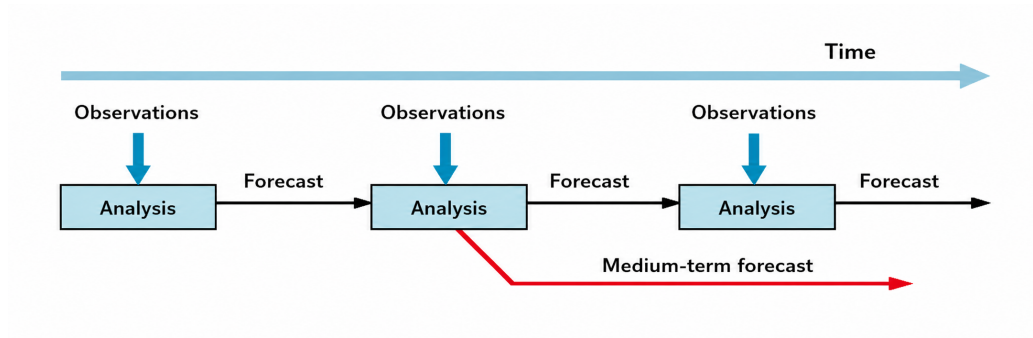


Figure 6.1: ICON-2I data assimilation system

Building on this concept, ICON-2I's data assimilation system is designed to continuously improve the representation of the atmospheric state by merging observations with model simulations. As already mentioned, atmospheric models are highly sensitive to the initial state, for this reason the model is not left free to evolve for an undefined amount of time, but is periodically initialized from the analysis field coming from the assimilation process.

The data assimilation system can be described as an iterative sequence: starting from previous forecasts, an estimate of the atmospheric state is obtained, referred to as the "background state". Observations from radars, satellites, radiosondes, planes, meteorological stations and other observing systems are collected and then combined with the model forecast in order to obtain the best possible estimate of the true state of the atmosphere at that moment. This analysis is used as a new starting condition for the next forecast cycle.

Into the ICON framework, the assimilation process is performed hourly, and is based on an ensemble of 40 simulations, each starting from slightly different initial conditions in order to represent the uncertainty of the system.

The assimilation method used is a Local Ensemble Transform Kalman Filter (LETKF). This filter exploits the ensemble spread to estimate the uncertainty of the forecast model.

The term "local" refers to the fact that observations are assimilated over limited spatial regions, which reduces the computational cost and allows for a better representation of local atmospheric phenomena.

The goal of this data assimilation system aims to find the best possible trade-off between model's forecasts and experimental observations. This

approach becomes particularly relevant when analyzing atmospheric boundary layers and mountainous regions, where turbulence, convection, strong vertical gradients and irregular orography combine to make atmospheric forecasting more challenging.

Data assimilation does not completely eliminate model errors, but it allows for periodic correction of simulations, limiting error propagation and improving forecast quality over short and medium ranges.

The system operationally assimilates data collected from radiosondes, planes, radars and ground stations providing information such as temperature, humidity, pressure and wind profiles. As explained in Gastaldo et Al. [16], most forecast uncertainty originates from inaccuracies in the initial conditions. Among the observations listed, radar data has a strong impact on the representation of convective systems and precipitation structures during the first forecast hours, which is particularly important under highly unstable atmospheric conditions.

Finally, it should be noted that, even with all those measures, uncertainties still remain due to observational errors and limitations of the numerical model. These limitations can be attributed to imperfect representations of microphysical and convective processes. The operational chain developed

and maintained by ItaliaMeteo and Arape Emilia-Romagna includes an ensemble-based data assimilation system, deterministic forecasts, and an ensemble forecast. The data assimilation system, which produces the analyses used to initialize all forecast runs, is a continuous system that assimilates observations on an hourly basis (Figure 6.4). Deterministic forecasts are issued twice a day, at 00 and 12 UTC, with a forecast horizon of 72 hours; their main application is forecasting, including the issuance of civil protection warnings. Also deterministic is the RUC (Rapid Update Cycle), which is issued every 3 hours and, with a forecast horizon of 24 hours, allows for frequent monitoring during high-impact events. Finally, the ensemble forecast is issued once a day at 00 UTC for the following two days, providing an estimate of forecast confidence through the determination of the uncertainty associated with the predicted scenarios.

ICON-2I's model configuration covers the geographical domain shown in Figure 6.2. It has a grid with an horizontal resolution of 2.2 km and the atmosphere is discretized into 65 vertical layers, as shown in Figure 6.3. Vertical levels follow the orography of the region and the distance between levels tend to increase with altitude.

Concerning the horizontal resolution of the model, it is located in the "grey-

6.2. ICON-2I

zone scale”: at this grid scales dimensions, atmospheric phenomena are just partially resolved and need a parametrization.

In particular, convective processes are neither totally resolved nor parametrized: deep convection (which is connected to large precipitating cloud systems) is explicitly resolved, while shallow convection (which involves small, non-precipitating cumulus clouds) is just parametrized.

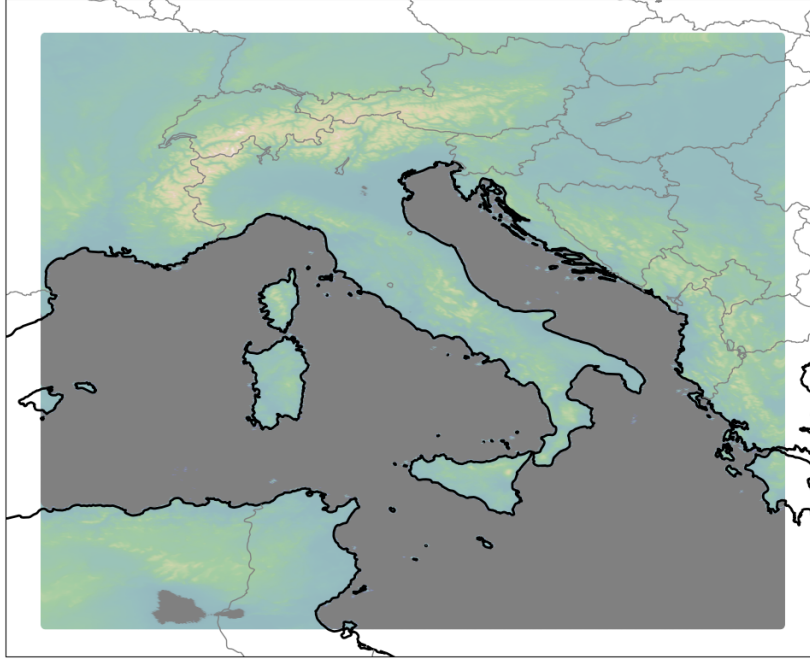


Figure 6.2: ICON-2I geographical domain

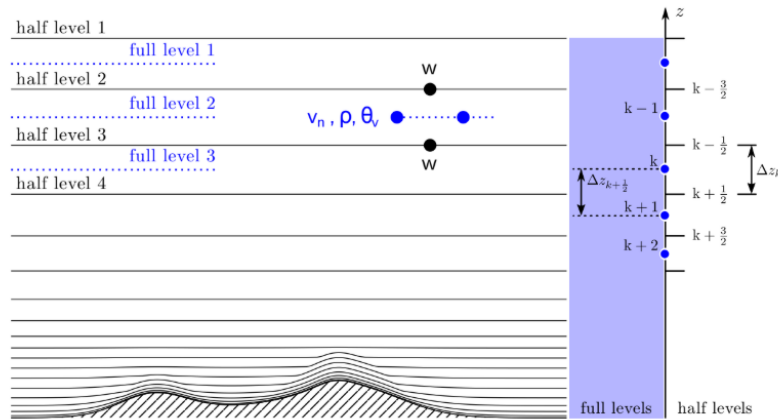


Figure 6.3: Illustration of ICON-2I's vertical levels

6.3 Comparisons between ICON-2I's and radiosonde's data

The mean trajectory and altitudes of the radiosonde cluster during the entire flight were computed, as shown in Figures 6.4 and 6.5.

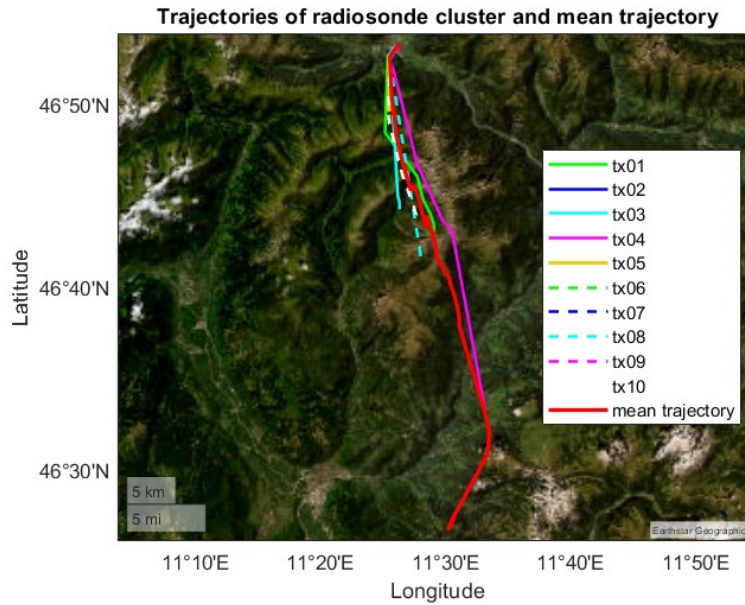


Figure 6.4: Sondes trajectories and the computed mean trajectory of the cluster (in red)

6.3. Comparisons between ICON-2I's and radiosonde's data

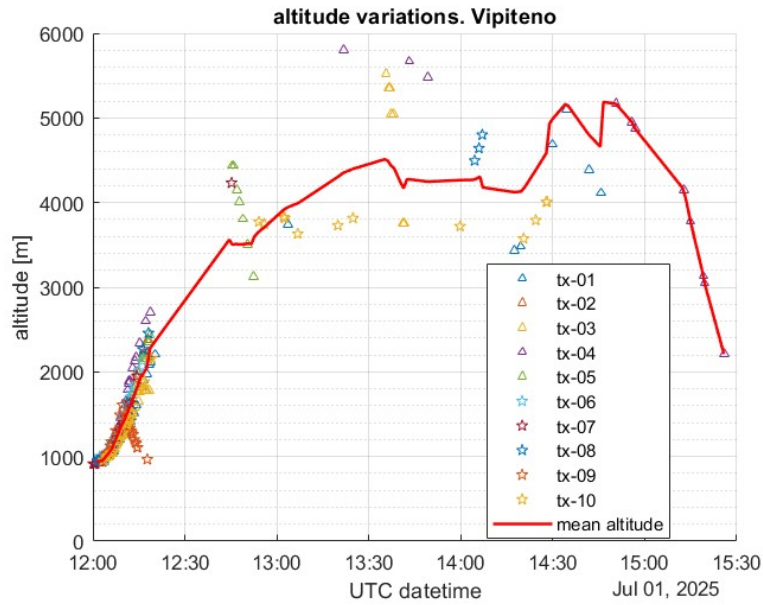


Figure 6.5: From the ICON-2I analyses, temperature, pressure and relative humidity values were extracted for the grid point with the latitude, longitude and altitude closest to those of the observations, in order to compare them with the data recorded by the radiosondes.

6.3. Comparisons between ICON-2I's and radiosonde's data

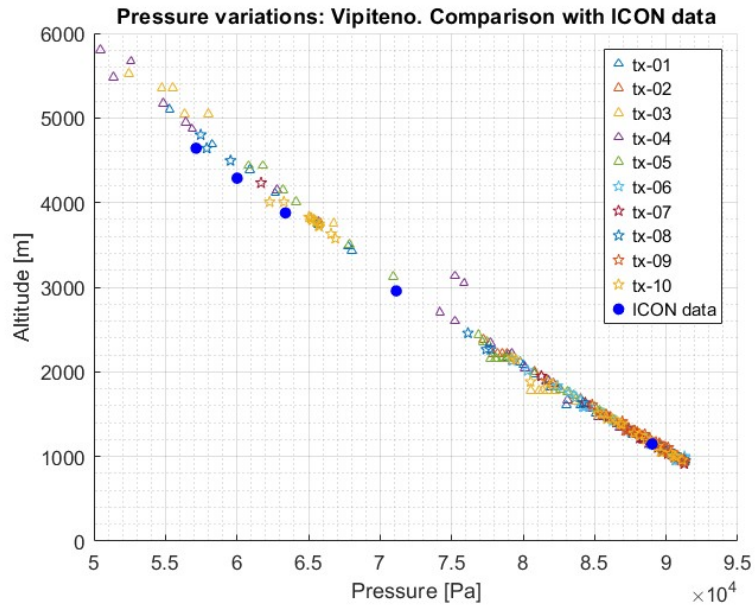


Figure 6.6: Comparison of the pressure values forecasted by ICON-2I (solid blue dot) and cluster's observations (empty symbols) as a function of the altitude (y-axis).

6.3. Comparisons between ICON-2I's and radiosonde's data

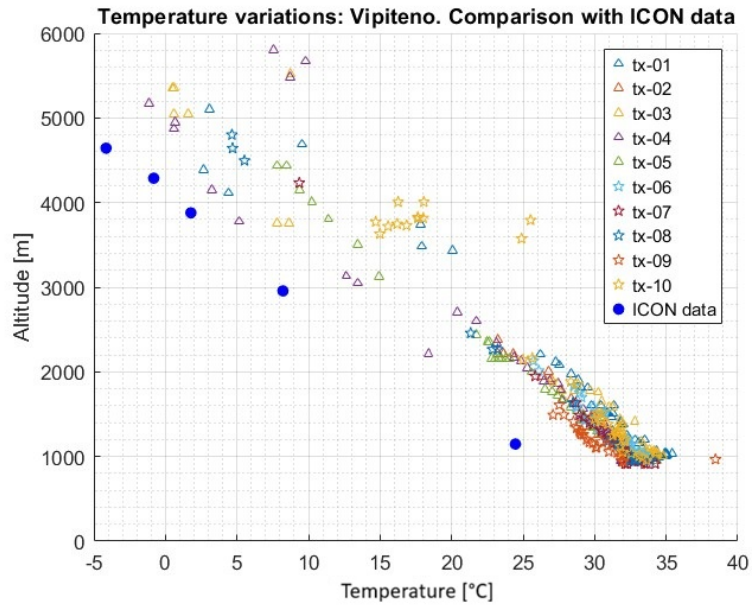


Figure 6.7: Comparison of the temperature values forecasted by ICON-2I (solid blue dot) and cluster's observations (empty symbols) as a function of the altitude (y-axis).

6.3. Comparisons between ICON-2I's and radiosonde's data

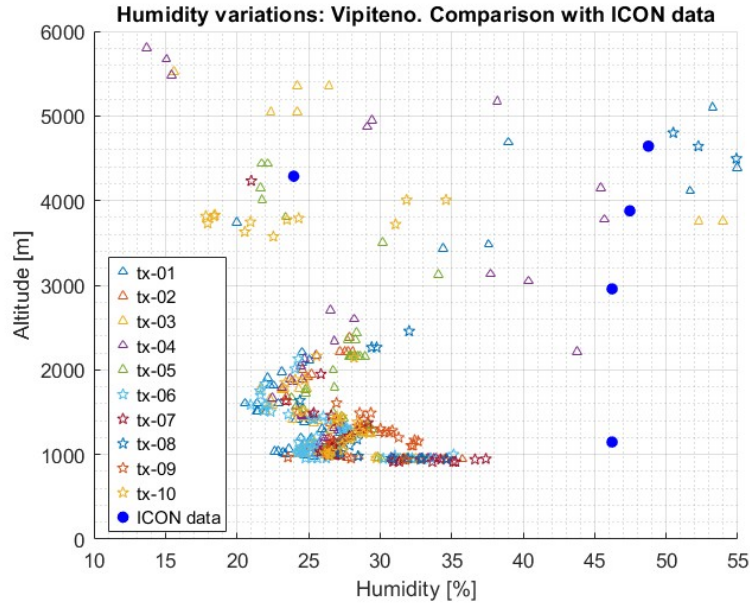


Figure 6.8: Comparison of the humidity values forecasted by ICON-2I (solid blue dot) and cluster's observations (empty symbols) as a function of the altitude (y-axis).

Observing the figures above, we can notice a behaviour similar to the one recorded during the dual sounding.

Figure 6.6 shows that pressure measurements are consistent with one another, as was also the case for the dual sounding. Temperature and humidity measurements (Figures 6.7 and 6.8), on the other hand, show clear differences.

As already noted, temperature measurements from the cluster tend to present an offset, which must be removed in order to obtain the correct profile behaviour. To estimate this offset, data recorded at 12:00 UTC from Vipiteno's ground station were used as reference 6.1, following the same approach adopted for dual the sounding test. The offset was computed as the difference between these reference values and the values recorded by the radiosondes during the first few seconds of the experiment; in particular, the first valid data from tx-04 were used.

Temperature	Humidity
27.73 °C	57.53 %

Table 6.1: Reference values, at 12:00 UTC, from Vipiteno's station, taken from [2]

6.3. Comparisons between ICON-2I's and radiosonde's data

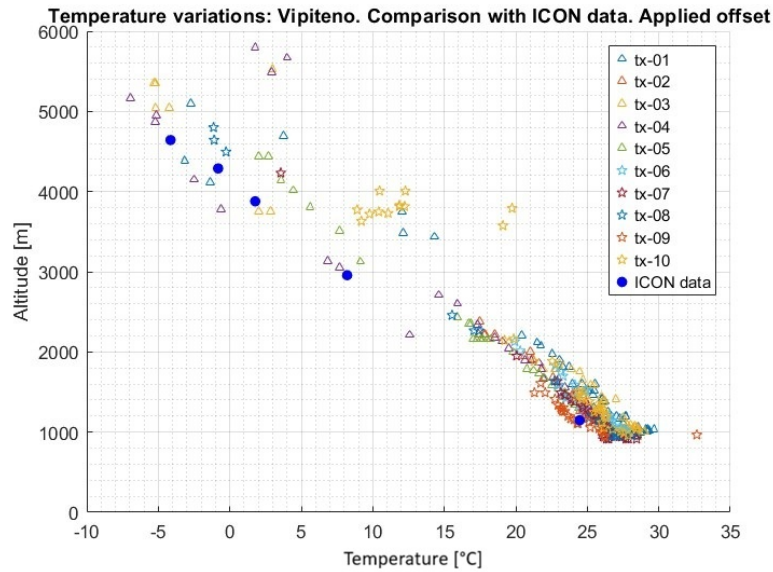


Figure 6.9: As Figure 6.7, but after the offset removal.

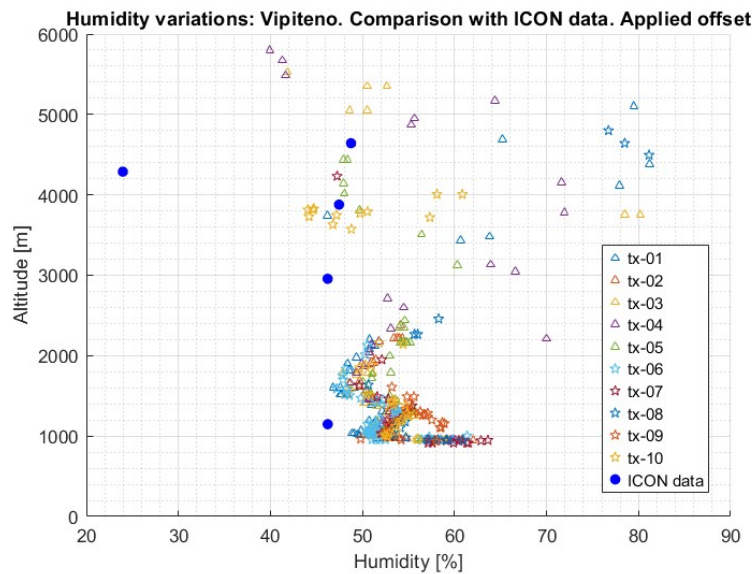


Figure 6.10: As Figure 6.8, but after the offset removal.

After offset removal, temperature values appear coherent with ICON-2I data, as shown in Figure 6.9, confirming the need for offset removal. Regarding relative humidity values, the data shown in Figure 6.10 seem to follow a more coherent pattern; however, in some cases, ICON-2I data still

appear to underestimate humidity values (this is particularly relevant considering that Houseflies' radiosondes already tend to underestimate real humidity profiles as well). Continuous profiles would be needed to achieve complete certainty, but further measurements are required to determine whether this is an isolated case or a recurrent behaviour; in the latter case, further investigations will be needed.

6.4 Future developments: assimilation of radiosondes data into ICON-2I

The ultimate aim of this project is to assimilate radiosonde data into ICON-2I. Before this can be done, however, a series of technical steps are required to prepare the data. To carry out this task, from 9 to 13 February 2026, we had the opportunity to collaborate with Dr. Virginia Poli at Agenzia ItaliaMeteo in Bologna, taking advantage of her knowledge of how the data assimilation system in ICON works.

The ICON-2I assimilation system acquires data NetCDF format, which is derived from the conversion of data in BUFR format.

In particular; the BUFR format is used to encode all observations at scattered points, i.e. those not defined on a regular grid. BUFR is a standard format defined by WMO (World Meteorological Organization) for exchanging atmospheric data and stands for "Binary Universal Form for the Representation of meteorological data".

The file must contain spatial information - latitude, longitude and altitude and the variables must be appropriately coded in accordance with the tables provided by the WMO.

data collected from the radiosondes is initially stored into JSON format and subsequently converted into CSV format using a python script, making it more accessible and user-friendly for post-processing and analysis.

The two different conversion methods were followed in parallel: one converts CSV files into BUFR format using a custom Python script, while the other uses the WMO `csv2bufr` function, which was the one that I followed. The main challenge was writing a JSON file that the system could use to perform conversion, containing required header information, data, meta-data and other relevant details.

During our visit to Agenzia ItaliaMeteo, we successfully converted files from CSV format into BUFR. The converted data was tested acquiring it into the archive used operationally for the assimilation, confirming that it had been correctly written into a valid format recognizable by the system. Considering this a satisfactory result, the next step will be to run some simulations using the radiosondes data in the assimilation system, in order to analyze the simulation results. This step will not be part of this dissertation and is still under development at the time of writing.

Conclusions and future developments

All the activities conducted during this thesis work were carried out in support of the Houseflies project, which started before the conclusion of this thesis and will continue for a long time.

Considering the wide range of activities covered in this work, it seems appropriate to organize this discussion according to the specific activity addressed.

Mater-Bi balloons

Even though this may seem the most trivial point of the work, producing a spherical and biodegradable balloon that also offers good resistance and performances is not an easy task and is crucial to the success of the work, since the aim is to study turbulence dynamics from a Lagrangian point of view. Only a perfectly spherical balloon can follow the flow as a particle, minimizing as much as possible the interference with the flow itself.

During this work, my role was to support the production of Mater-Bi balloons. Some support was given to Riccardo Villa [33] during his thesis work, and after the conclusion of his work I contributed to the welding activities using the welding machine he developed [33].

Welded Mater-Bi balloons were used to carry out retention tests, and the results showed that the weldings performed satisfactorily.

The new welding process considerably reduced the time necessary to produce a Mater-Bi welded balloon and also improved the overall quality of the product. However, the process is still too time-consuming for mass production. For this reason, industrial production of the balloons is among the future goals of the Houseflies project and it is already under development.

In-field experiments

In order to obtain data for analysis, in-field experiments involving the release of the radiosondes are necessary. During this work, two experimental campaigns were followed: one in Vipiteno and one in Carmagnola. Data were collected, cleaned and analyzed to study the general behaviour of tur-

bulence within the Atmospheric Boundary Layer.

These experiments featured a new communication technology for data collection that had not been used in previous campaigns: the LORAWAN wireless network. Implementing both peer-to-peer (p2p) and LORAWAN communication systems allowed us to collect data even when radiosondes travelled beyond the range covered by p2p. The longest distance recorded so far was during the Carmagnola campaign, where one of the radiosondes reached the Croatian coast.

A significant improvement has been achieved, but much work still remains: collected data does not arrive at constant time intervals, partly because some data packets arrive corrupted, and partly because large areas are not yet fully covered by the LORAWAN network.

This was particularly evident in Vipiteno experiment, where the LORAWAN coverage in the area was not really dense. As LORAWAN network density increases and a method to minimize packet loss is developed, data collection is expected to improve significantly.

Radiosonde

Radiosondes are the instruments through which atmospheric parameters can be measured. For this reason, a validation of collected data is crucial to assess their reliability.

During this work, comparisons were carried out between data collected by our radiosondes and data collected by a reference Vaisala's radiosonde.

Pressure profiles were aligned and consistent with one other. Temperature profiles showed the same overall trend but only became aligned after applying an offset to our radiosonde's data: considering the particularly high temperatures recorded on the days of the experiments, radiosondes probably overheated leading to higher temperature measurements. Regarding humidity profiles, the Houseflies radiosondes followed the general trend of the Vaisala profile, but with dampened measurements: this behaviour is connected to the fact that humidity measurements depend on temperature readings, overheating of the system and poor ventilation due to the small dimensions of the sensor and its low response time. This result can still be considered satisfactory given the low cost and small size of the sensor, although further improvements are required to obtain higher quality data. A future development involves equipping the radiosonde with an external relative humidity sensor, which would significantly decrease the dependence on microcontroller's heating, thereby improving quality data.

The new prototype version is already under development: it will be lighter and smaller and will also implement a CO/CO_2 sensor. Tests of this new prototype version are already scheduled.

Finally, it is worth to mention that Houseflies radiosonde is equipped with

a magnetometer. So far, magnetic field measurements were collected, but an adequate calibration of the sensor is still required to accurately track magnetic field fluctuations.

To address this issue, on 29 June I took part in dedicated calibration measurements performed at Istituto Nazionale di Ricerca Metrologica (INRiM) in collaboration with Dr. Gabriella Crotti. The collected datasets are currently being analyzed, with the aim of developing a proper calibration procedure for the onboard magnetic field sensor.

Comparison with ICON data During this thesis work, comparisons between data collected during Vipiteno experiment and analyses coming from ICON-2I numerical model were done, while comparisons with the Carmagnola dataset data were performed by Maria Palomba as part of her thesis work, which was still under development at the time of writing.

The results of these comparisons were consistent with those obtained when comparing our radiosonde with the Vaisala reference for pressure and temperature profiles: pressure profiles were consistent, while temperature profiles became consistent once an offset was applied to data collected by our radiosonde. Regarding humidity profiles, ICON-2I simulations tend to underestimate humidity values. Considering that only discrete data points along the trajectory of the radiosonde were compared, a continuous humidity profile would be needed to confirm this behaviour with greater confidence, further launches will therefore be essential to determine whether this underestimation is due from a systematic error or is merely coincidental. Should it prove to be a systematic error, introducing high quality data coming from radiosonde's Lagrangian trajectories into ICON-2I assimilation system could significantly benefit weather forecast accuracy.

Future developments of this project include the assimilation of Houseflies radiosondes cluster data into ICON-2I model. Our collaboration with Italia Meteo, discussed in the final part of this work and supervised by Dr. Virginia Poli, was focused on the realization of a workflow, as a data pre-processing, for converting data from CSV to BUFR format. This task was completed successfully and the converted data was recognised as valid by the archive used operationally by ICON-2I. The next step will be to run some simulations after introducing our data into the assimilation system.

All the aforementioned points merely summarize the current state of the project at the time of writing. Much has to be done, and a long list of future developments remains to be pursued.

On a personal note, being part of this project has been an extraordinary experience. It has given me countless opportunities to grow, both professionally and personally. The skills, knowledge, and experiences I have gained

throughout this journey are things I will carry with me forever, and I am deeply grateful to everyone who contributed to making this experience possible.

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