LAPPEENRANTA-LAHTI UNIVERSITY OF TECHNOLOGY LUT
School of Engineering Science
Degree Programme in Industrial Engineering and Management
Global Management of Innovation and Technology

*Jari Leinonen*

# AN ENVIRONMENTALLY FRIENDLY WEATHER BALLOON SYSTEM

Master's Thesis

Examiners: Professor Leonid Chechurin, Lappeenranta-Lahti University of Technology LUT
M.Sc. Timo Laine, Senior Planner, Observation Services, Finnish Meteorological Institute

# ABSTRACT

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**An Environmentally Friendly Weather Balloon System**

Master's thesis
2021
101 pages, 31 figures, 4 tables and 2 appendices
Examiners: Professor Leonid Chechurin, Lappeenranta-Lahti University of Technology LUT, and M.Sc. Timo Laine, Senior Planner, Observation Services, Finnish Meteorological Institute

This research investigates whether the weather balloon observation system can be made environmentally friendly. Through literature and patent search, combined with theory of inventive problem solving (TRIZ) methods, alternative materials and operations to the current system model are analyzed. Focusing on solutions applicable to the target environment, goal and budget, changes to the current policies are proposed. Furthermore, the findings are tested through two field experiments, with the objective of providing empirical data to the study as well as demonstrating proof-of-concept systems, as alternatives to the current one.

By focusing on key features, this research seeks to gain a holistic view of the current and future operating models, consequently enabling the management level of relevant organizations to consider the proposed changes with all the necessary information at hand. These changes include (but not limited to) improving the current tracking method to allow easier retrieval of launched radiosondes, a biodegradable shell structure, color changes, a network receiver system based on existing field equipment, an open access database, and landing coordinate prediction and reporting model for the public.

This research contributes not only to the available literature but also to the operational models, by suggesting more environmentally friendly ways of conducting high-altitude weather observations through radiosonde technology.

Keywords: Weather, balloon, radiosonde, biodegradable, tracking, remote sensing, retrieval

# TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT
School of Engineering Science
Tuotantotalouden koulutusohjelma

Jari Leinonen

**Ympäristöystävällinen Säähavaintopallojärjestelmä**

Diplomityö
2021
101 sivua, 31 kuvaa, 4 taulukkoa ja 2 liitettä
Tarkastajat: Professori Leonid Chechurin, Lappeenranta-Lahti teknillinen yliopisto LUT, ja FM Timo Laine, vanhempi suunnittelija, Havaintopalvelut, Ilmatieteenlaitos

Tämä tutkimus pyrkii selvittämään, voidaanko säähavaintopallojärjestelmä tehdä ympäristöystävälliseksi. Kirjallisuuden ja patenttihaun avulla, yhdistettynä keksinnöllisten ongelmanratkaisumenetelmien (TRIZ) teoriaan, analysoidaan vaihtoehtoisia materiaaleja ja toimintoja nykyiselle järjestelmämallille. Kohdeympäristöön, tavoitteeseen ja budjettiin keskittyvien ratkaisujen kautta voidaan nykyisiin käytäntöihin ehdottaa muutoksia. Lisäksi löydöksiä testataan kahdella kenttäkokeella, joiden tavoitteena on tuottaa tutkimukseen empiiristä tietoa sekä esitellä konseptit vaihtoehtoina nykyiselle järjestelmälle.

Keskittymällä järjestelmien keskeisimpiin piirteisiin tämä tutkimus pyrkii luomaan kokonaisvaltaisen kuvan nykyisistä ja tulevista toimintamalleista, jolloin asianosaisten organisaatioiden johto saa kaiken tarvittavan tiedon ehdotettuja muutoksia käsitellessään. Näihin muutoksiin lukeutuvat muun muassa nykyisen seurantamenetelmän parantaminen lähetettyjen radiosondien jäljittämisen ja palauttamisen helpottamiseksi, biohajoava kuorirakenne, värimuutokset, olemassa oleviin kenttälaitteisiin perustuva vastaanotinverkko, avoimen pääsyn tietokanta sekä julkinen laskeutumiskoordinaattien ennustus- ja raportointimalli.

Tämä tutkimus tukee aihealueesta saatavilla olevaa kirjallisuutta sekä myös toimintamalleja ehdottamalla ympäristöystävällisempiä tapoja suorittaa ilmakehän radiosonditekniikkaan perustuvia säähavaintoja.

Avainsanat: Sää, havaintopallo, radiosondi, biohajoava, seuranta, kaukokartoitus, jäljitys

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30.12.2021
*Jari Leinonen*

# TABLE OF CONTENTS

# 1 INTRODUCTION

The science of predicting weather relies on accurate observations of current weather conditions around the globe, from ground level up to the stratosphere. Since the 1930s, these observations have been mainly taken with radiosonde devices attached to large balloons, with the device signaling the sensory data, such as temperature, humidity and atmospheric pressure back to the sending station. With approximately 900 – 1300 upper air stations around the world, out of which two thirds send two balloons daily and the rest up to four, the amount of weather balloons in the sky globally equals to roughly 900 000 to 1 250 000 units a year (WeatherSTEM, 2017; WMO, 2021).

A weather balloon system typically includes a latex weather balloon, a plastic rigging, in many countries a plastic parachute, and a radiosonde device. The radiosonde device consists of mainly a small PCB board, with microcontrollers and a GPS unit, and several AA lithium batteries enclosed in a polystyrene box, with a metal whip radio antenna and a measurements boom protruding from the unit. The GPS coordinates are used to calculate wind direction and speed at the communicated height. The device sends the measurements and the GPS coordinates back to the upper air observation station by radio while traveling from ground level up to roughly 30 kilometers high, where the lack of air pressure causes the helium or hydrogen inside the latex balloon to expand and cause a balloon burst. At this height, the lack of air pressure can cause 8 G forces to the components, and the temperature of the air can be as low as -90 °C, creating extreme demands for the durability of the system (NOAA, 2016; Weather Online, 2021).

As the device descends, in some cases it continues to transmit data back to the sending station as well as any other station within the reach. Due to the curvature of the planet, once the radiosonde descents beyond the horizon, the sending station loses contact with the sonde at roughly one kilometer above the ground and the sounding ends. The entire process takes 1,5 to 2 hours and the balloon system travels approximately 50-200 kilometers from the sending station, depending on weather conditions, occasionally even further. Because contact is lost while the radiosonde is still up in the air, the winds on ground level can still carry the sonde, especially if assisted with a parachute, several hundred meters if not kilometers away from the last known position of the device. As such, these devices are considered consumables as the final landing site cannot be reliably identified and the cost of retrieving the radiosonde can easily exceed the value of the unit, with the sounding costing approximately 100-300 euros per launch, depending on the country (T. Laine, FMI, private correspondence, November 4, 2021).

Most meteorological organizations lack the funding to launch wide-scale radiosonde retrieval operations, as the very limited budget is generally better spent on sending as many radiosondes as possible and therefore providing accurate weather predictions, which in turn can save the global economy millions of euros or dollars in damages if adverse weather conditions are predicted well in advance. Therefore, the finding and retrieval of radiosondes is largely left to the public, such as hobbyist and clean-up organizations. In the USA, approximately twenty percent of radiosondes are returned and refurbished (NOAA, 2010), but in most other countries the return rate is closer to a percent or two (Vaisala, Private correspondence, June 11, 2021). This means that approximately one million radiosondes are lost every year to nature, with all of its wires, batteries, electric components and the polystyrene encasing.

As weather conditions largely depend on what the conditions are in the atmosphere, ground-based solutions cannot match the accuracy of radiosondes in the air. While other weather observation methods have so far been used, such as tens of thousands of surface stations, buoys, radars, ships, commercial aircrafts as well as satellite systems around the globe (WMO, 2021), none of has proven to be as reliable and accurate as the weather balloon system. No other device can travel inside a storm and report back the exact direction and strength of the cloud mass, at such a relatively low-cost range. Moreover, cloud surfaces tend to reflect back signals or beams, causing inaccuracies in remote sensing data, which can lead to false predictions. Therefore, global weather forecasting will continue to rely on the use of radiosonde soundings for the foreseeable future.

The current weather balloon system has been built to withstand extreme conditions. The rigging of the system is mainly composed of a 25–55-meter plastic string, which can withstand forces equaling approximately hundred times the weight of a standard radiosonde (L. Hirvonen, Piippo Oy, private communication, June 23, 2021; NOAA, 2016), therefore being very strong but as a tradeoff not biodegradable. This can cause problems with smaller wildlife, as sea and forest creatures can become entangled in the wires and do not have the strength to break them. Similarly, the polystyrene box used to protect the microcontrollers and batteries from the extreme weather conditions is known to decompose very slowly, having a lifespan of at least five hundred years, up to a million years (Davis, 2019; Dilthey, 2018; Kimukai *et al.*, 2020).

Lithium batteries and the electric components will similarly take hundreds of years to decompose (IBC-M, 2019).

Due to the very long decomposition rate of the weather balloon system components and the amount of radiosondes lost every year, the environmental impact of these weather observations is notable. This research explores options for reducing this impact through various methods, including the possibility to replace some of the materials used in the atmospheric sounding or increasing the amount of radiosondes returned to the manufacturer by investing in better tracking systems.

Since biodegradable materials generally are not as durable as existing solutions, as they are specifically built to naturally degrade, the focus of this research will be set on using the right materials at the right application scenario as well as producing a low-cost tracking system that would enable better accuracy in pinpointing the landing coordinates of the radiosonde for retrieval purposes. Emphasis is also placed on the budget restrictions of these organizations, without compromising the accuracy of the weather observations. Because the current system has been built with the goal of producing maximum value at the lowest possible cost, any changes to the composition of the system or investments in infrastructure unfortunately also mean increase in the overall cost of weather observations, or alternatively fewer balloon launches per year and therefore less accurate weather predictions. However, with the global environment increasingly suffering from the effects of man-made processes, these added costs are inevitable and necessary in order to protect the environment from all causes of pollution, even as small and scientifically unique as a hundred-gram radiosonde.

# 2 GOAL AND METHODOLOGY

The goal of this research was to find answers to the following question:

**Primary research question:** *In what ways is it possible to reduce the environmental impact of weather balloon operations?*

In order to cover all the possible perspectives for answering the primary question and to take any limitations into account, several sub-questions needed to be considered:

1. *Can biodegradable materials be reliably used in scientific research or weather observations in Earth's atmosphere?*
2. *Which technologies and materials would reduce the environmental impact of atmospheric sounding, considering the limited budgets of meteorological institutes?*
3. *What investments in infrastructure could prevent atmospheric sounding from harming the environment?*

As the subject of this research was relatively wide, the methods used to assess applicable solutions varied greatly. However, in order to produce comparable and applicable results, the scope of the research was not narrowed down intentionally, as the high-altitude ballooning in itself is a very niche science. Because of the comprehensiveness and cross-scientific nature of the research, the focus in this study has been to draw out the key elements and figures from each section, rather than burrow too deep into the details unless beneficial to the overall understanding of the issue.

Preliminary inquiries into the subject revealed that there would not be a universally acceptable solution which would apply to every possible scenario and requirement of the field. By considering a range of opportunities and solutions, it would be possible to provide enough information to the decision makers to select the best methods for their target application, rather than propose a single solution, which may not be best suited for all the particular tasks. Therefore, the research was split to multiple concurrent sub-studies each of which focused on a particular aspect of the weather observation system.

## 2.1 Definitions

This research considers the environmental impact being the toxicity of the material as well as its biodegradation cycle when discarded in nature. Because not all components of the weather balloon train can be expected to fully biodegrade, a wide selection of currently available alternatives is considered. Moreover, there are very few definitions and standards regarding biodegradability, as each material has its own requirements in terms of natural degradation, and the environment into which the material is discarded can vary greatly. Some materials might start their degradation cycle at 0 °C and disappear completely within a week, other materials might require higher temperatures and take weeks or months to disintegrate, and some materials could disintegrate in warm climate within a week and take months in a cooler one. All of these could hypothetically be considered biodegradable. It is therefore not possible to draw clear limits for biodegradability, as in essence every material degrades, although some do so within days and some might take hundred years to do so. One of the most useful standards is the European standard NE 13432 for biodegradable plastics, which defines the criteria a plastic needs to fulfill. The standard uses the term "biodegradable" and "compostable" interchangeably, because composting is the only process that can be controlled, measured and quantified. The criteria for biodegradability are: 1) disintegration, referring to fragmentation and loss of visibility, 2) biodegradability, where at least 90 percent of the product must have been converted to $CO_2$ by microorganisms in less than 6 months, 3) no negative effects to the composting process, and 4) heavy metal content must be below maximum values and no ecotoxicological effects towards plants (European Bioplastics, 2015; Ciriminna & Pagliaro, 2020). Notable here is that these thresholds must be achieved through laboratory tests. In reality, the amount of microbiological agents in nature is much less, therefore leading to slower degradation process.

This research considers biodegradable materials as following NE 13432 standard but also being able to begin the degradation process without the need of industrial or artificially cultivated microbiological agents in any natural environment where the average temperatures are above zero Celsius, thus not freezing. This definition excludes materials that are not capable of biodegrading without the inclusion of additional agents or surroundings not usually found in sea or the wilderness. For example, a product made of wood treated with natural compounds may or may not reasonably degrade when discarded in nature, depending on the substance used, but could still reach the NE 13432 standard’s limits when processed through industrial composts. Moreover, while some materials may not be able to fulfill all of these criteria, they can still be considered, if they bring benefits to the current design of weather balloon components in terms of environmental impact.

With the terms “weather balloon observation” and “weather balloon system”, this research refers to the entire train of components, including the actual balloon, rigging, optional parachute or radar target, and the payload *id est* radiosonde. While this research uses the Vaisala RS41 as reference, the analyses and findings apply to every radiosonde currently in operation, including most commonly used variations of the entire weather balloon system. Finally, all cost estimates mentioned in this research are based on examples at the time of the research or prices from actual invoices. Therefore, they are given to indicate an approximation and range of cost, rather than absolute figures, and may be subject to change over time.

## 2.2 Research methods

### 2.2.1 Literature research

High-altitude ballooning has primarily been a very niche market, with very little academic focus. This is evident in the amount of literature available on the subject, with online web pages of meteorological organizations as well as professional and amateur ballooning communities overwhelmingly exceeding the available information from academia. This is evident in the peer-reviewed literature research conducted on the subject. Using the Web of Science as well as Scopus online libraries through Lappeenranta-Lahti University of Technology’s (LUT) Primo library services produced a wide range of results (Clarivate, 2021; Elsevier, 2021). The keywords used included “Weather AND balloon*”, "High-altitude AND balloon", “Biodegr* AND parachut*” and “Compostable Fabric” and several different variations of them.

The first set of keywords, “Weather AND balloon*” produced 714 articles from two databases, including all fields. However, filtering to the past five years and to categories of Meteorology Atmospheric Sciences, Environmental Sciences, Astronomy Astrophysics, Engineering Aerospace and Geosciences Multidisciplinary narrowed the results to 180 articles. Very few of these had any actual relation to the subject matter of this research and even less described any features of the general composition or use of weather balloons in their standard sounding purposes.

The second keyword set “High-altitude AND balloon” produced 831 results, which with the abovementioned filters were reduced to 126 articles. While providing more applicable research papers, the subject matter focused primarily on specific applications of high-altitude balloons, such as infrared imagery, altitude control systems, polar exploration as well as mathematical models for ascent performance calculations. None detailed a standard weather balloon system, nor any sustainable or environmentally friendly operations of these systems.

The rest of the keywords produced either zero or less than a dozen results. Therefore, it was evident that any academic solution for making a standard weather balloon environmentally friendlier would likely be cross-functional, deriving from research done on other fields which could potentially be applied to high-altitude balloons. Simultaneously, alternative sources would need to be considered, such as online material produced by the amateurs, hobbyist, scientists and professionals working in the fields of high-altitude ballooning, meteorology, aeronautics and astronautics. Scientific articles as well as online guidebooks, community forums as well as news articles would form the primary source of information. With the use of modern search engines, these sources proved to be relatively abundant. Being in some instances less credible sources, these online materials were assessed as second-hand information and framed against interviews conducted with subject-matter experts from the partnering meteorological organizations, in order to lend credibility to the information provided.

Moreover, as the science behind weather balloons is almost a hundred years old (NOAA, 2016), most scientific literature pertaining the subject would be far older than the past decade with possibly outdated information. Radiosonde technology as well as weather sounding has been developed professionally by a handful of organizations, such as Vaisala, with their internal Research and Development departments, furthermore explaining the lack of academic material on the subject. This lack of recent publications on the matter with any environmental focus is also the gap which this research seeks to fulfill.

### 2.2.2 Patent search

The patent search was conducted on Espacenet patent search portal and the World Intellectual Property Organization WIPO Patentscope portal (EPO, 2021; WIPO, 2021). Both were used to identify solutions which would apply to the target application. Therefore, the key words used for the search included “weather balloon”, “high-altitude balloon”, biodegradable plastic”, “biodegradable PCB” and “biodegradable parachute”. Other key words were also used on ad hoc basis and therefore not recorded, only to check if an applicable solution or derivation of an existing idea had already been patented. Unlike literature research, which focused on accumulated knowledge on the subject area, the patent search concentrated on finding specific solutions to specific issues. As only applicable patents were selected, recording the total number of patents found through these services was not considered relevant for the overall subject.

### 2.2.3 Theory of Inventive Problem Solving (TRIZ)

TRIZ methods were used to gather and assess the second sub-question, focusing on methods and materials to be used in weather observations. The Theory of Inventive Problem Solving is a method of systematic creativity or ideation (Altshuller & Shapiro, 1956). The problem of “disappearing radiosondes” were presented to a group of TRIZ course students at the LUT University, tasked with using research tools for identifying and assessing all the applicable solutions. At this stage, the researcher had already conducted a preliminary literature analysis as well as conducted several preliminary interviews; however, an unbiased and unprejudiced group of students would lend validity to the analysis as well as provide additional solutions that could have been previously overlooked.

A brainstorming session was conducted to gather initial ideas as well as to introduce the subject to the team. The scope was not limited to the subject of weather balloons; instead, possible solutions from different fields were gathered in addition to existing solutions. After the session, the identified solutions were split into specific fields and each field generalized by function definition analysis, such as communication methods, guidance methods, tracking methods and retrieval methods. These fields were then structured into work packages, each of which included function-oriented search, *id est* literature analysis from academic, scientific and online sources. Finally, the identified solutions from each field were assessed and their applicability to a wider use among the meteorological organizations analyzed.

The TRIZ method proved to be successful in narrowing down the scope to few selected solutions, while properly assessing any other far-reaching ideas, which proved to be either too costly or inapplicable.

### 2.2.4 Field expert interviews

The most productive method for acquiring information on the subject of weather balloon systems and their environmental impact was email interviewing of field experts. As weather balloon observations are conducted globally, the current research into the environmental solutions was primarily conducted by agents in various parts of the world. Moreover, each solution was different and each expert focused on a different aspect of the weather balloon system, and in many cases on a completely different field of industry, which prevented any structured interviews from being conducted. Therefore, semi-structured email interviews allowed the participants to gather their responses at their own pace and own time zone. Such interviews were conducted primarily with professionals in Australia, Finland, the United Kingdom and the United States of America.

Moreover, email interviews allowed several subject-matter experts to provide answers to a group interview, such as correspondence between the researcher and the professionals from the Finnish Meteorological Institute (FMI) in Helsinki, Finland, the European Centre for Medium-Range Weather Forecasts (ECMWF) in Redding, UK, as well as the Met Office in Exeter, UK. As the subject matter was rather wide, any time-limited interview with the relevant parties might not have been as productive than allowing past experiences and creative discussion over long period of time to guide the interview.

In addition to email interviews, the methods included unstructured phone interviews with manufacturing companies, meteorological offices and government offices as well as one face-to-face meeting with Vaisala, a leading supplier of meteorological technology around the world. As the research was conducted in 2021, the global COVID-19 pandemic prevented any face-to-face meetings, except a single COVID-controlled meeting at Vaisala headquarters with subject-matter experts.

Finally, further information was provided during the field experiments at the Finnish Meteorological Institute's observatory in Jokioinen. As the focus was on conducting the experiments, the information retrieved during that time was unstructured and *ad hoc* in nature.

### 2.2.5 Field experiments

Having identified applicable solutions, field experiments were conducted in order to assess them and to provide proof-of-concept evidence to the relevant parties. With the focus on both the materials used in the construction of the sounding equipment as well as improving the tracking capabilities of these flights, several components were built for two experiments launched consecutively. The modules were built based on previous flights made by amateur balloonists around the globe as well as modules specifically built and programmed for this particular research. The electronic equipment, including transmitters and receivers as well as databases and online content, was produced solely by the researcher. Prior to the flight, the payloads were exhaustively tested in a Vötsch VC 4018 climate test chamber at the LUT Voima facility of the Lappeenranta-Lahti University of Technology, capable of producing a -40 °C environment in a laboratory setting. Because of the pandemic, the research was paused several times, as the global situation lengthened logistics times and prevented field experiments from being conducted within the intended time frame. These delays did not have any impact on the research itself.

The field experiment consisted of a minimum viable product (MVP), with the radiosonde itself providing GPS data from one kilometer up and an addition component providing landing coordinates after the sounding has ended. The add-on module was composed of a microcontroller sending GPS signals via text messages using 2G network. This method proved to be the most cost-efficient and globally applicable solution, although it does have specific limitations in terms of height as well as network coverage. The construct and the limitations are detailed in later chapters of this paper. The add-on module was enclosed in a box made out of fully biodegradable wood pulp, which proved to be as efficient as polystyrene in terms of insulating the equipment, covered in biodegradable waterproof paper to prevent moisture and water bodies from damaging the equipment inside. The add-on module was attached to a standard Vaisala RS41 radiosonde, roughly doubling the weight of the sounding equipment to 205 grams, carried with the standard 350-gram latex balloon.

Following the MVP launch, another payload was launched, consisting of several modules for tracking the balloon as well as providing imagery of the flight. The balloon used was a larger 1200-gram balloon capable of lifting several kilos of equipment. The modules included in the flight was a GSM-based transmitter, similarly connected to a 2G network, as well as a LoRa transmitter for assessing the viability of LoRa tracking on ground level as well as up in the air. As securing a fully biodegradable box capable of holding over a kilogram of electronic equipment was not viable, a traditional polystyrene cooling box was used. Since the focus of this research was to provide solutions for daily weather balloon operations, using biodegradable solutions larger than used in the MVP launch would have been excessive and prohibitive, as well as requiring industrial manufacturing processes to obtain. While the MVP launch focused on the biodegradability of the used materials combined with the most cost-effective tracking solution, the larger launch allowed several tracking methods to be assessed in a single launch. By using consecutive launches within the same day, the data provided by both were comparable and reliable. GSM and LoRa receivers installed on the ground picked up the signals and transmitted them to a database used for map visualization purposes during and after the flight. Moreover, the on-board modules were programmed to save the logs on their microSD cards for post-flight analysis.

Both launches were furthermore tracked on the ground using the Automatic Packet Reporting System (APRS) network as well as three purpose-built tracking stations. The tracking stations were installed at two different private properties on opposite sides of the launch site and the expected flight area, as well as one on the vehicle used for retrieving the payloads. These trackers, combined with the existing APRS amateur network, were used to assess the viability of ground-based infrastructure, wherein the tracking stations would pick up the standard radio signals emitted by the radiosonde and therefore circumventing the problem of a lost signal below the horizon. A fourth hand-held device with a range of approximately two kilometers allowed pinpointing on the radio signal once it had landed, as the radiosonde generally continues to broadcast several hours after it has landed. The small device was primarily used as a backup solution, had any other method failed.

# 3 HIGH-ALTITUDE BALLOON OBSERVATIONS

In order to assess the methods through which the environmental impact of weather balloon observations can be reduced, it is imperative to understand the equipment and processes related to these missions. As the core system is composed of different elements, each component needs to be analyzed both as a part of the system and as an individual entity. This will lead into identifying the most suitable alternatives for each.

## 3.1 The weather balloon

The general composition of a weather balloon system has remained relatively unchanged for the hundred years they have been used (NOAA, 2016). A balloon train is typically comprised of five elements; a sealed latex or chloroprene balloon, filled with hydrogen or helium gas, a parachute and a payload containing the equipment such as radiosondes and other sensor systems, all rigged to each other with cords (Gemignani, 2019; Basic Air Data, 2011). A simplified version is available in Figure 1. The sensors of the radiosonde typically measure the surrounding temperature, humidity and pressure, as well as wind speed and direction via GPS signals, throughout the ascend to stratosphere as well as descent after the balloon has burst. Using radio signals, the data is transmitted every two seconds back to the upper air observation station that released the balloon. The data contain crucial information of the surrounding weather conditions for scientists to predict future weather events (Vaisala, 2020). This payload can vary from mere hundred grams to several kilos, depending on their size and application (Price, 2019). A typical modern radiosonde carried for weather observations (Figure 2) weights around 100 grams, while an ozone sensing equipment can weight several hundred grams (Dubois *et al.*, 2002). They are usually packed in lightweight polystyrene or cardboard boxes (Hopper, 2011).

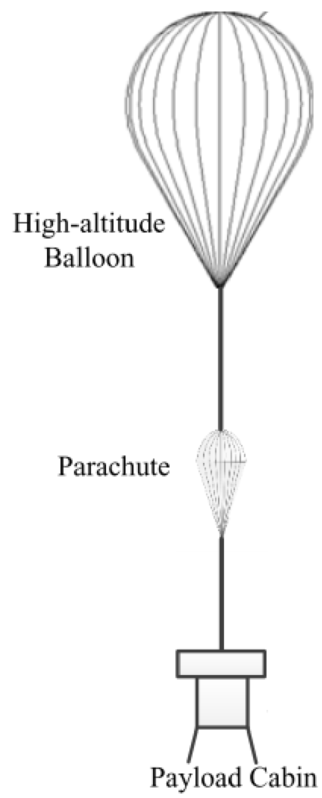


**Figure 1**: Weather balloon composition (Modified from source: Wang *et al.*, 2020, p.40)

While most weather balloons rise only to roughly 25-35 kilometers during their two-hour flight, the more advanced balloons can stay afloat for days, even months, at higher altitudes. Regardless of their time afloat, all of these unmanned vehicles are subject to harsh conditions, which is why their composition must be robust. As described in Wang *et al.* (2020, p.43), "the temperature in the near-space can be very low from -50 °C to -70 °C". Above the Arctic or Antarctic, it can go as low as -100 °C.

Although many electronic components, such as batteries, normally cease to work below -20 °C, battling the temperatures is not the only challenge facing the flight. The whole flight might be spent in a torrent of rain and thunder, even inside tropical storms. Turbulent winds can jolt the payload; however, on a calm day the winds generally cease at an altitude of five kilometers, leading to a relatively smooth ascent, wet or dry depending on weather conditions (Eniscuola Energy and Environment, 2011). At an altitude of 9-10 kilometers, the air pressure starts to drop quite rapidly, which is why toy balloons usually burst at this height. Professional weather balloons are made of thick latex or neoprene rubber, which can expand five times its launch diameter of 1,5 meters (National Weather Service, 2020), thus withstanding the drop in outside air pressure. However, as the balloon floats higher, the helium or hydrogen contents of the balloon continue to expand against the less than 1% of atmosphere surrounding it, eventually causing the balloon to burst at an altitude of 25-35 kilometers. This sudden change in structure dynamics causes as high as 8G forces on the payload and the attached cords, as there is very little surrounding air to counter the sudden change in trajectory (GSBChallenge, 2020). For the rigging carrying a 100–200-gram payload, this means a force equaling the weight of one kilogram, and for an ozone sounding equipment of nearly a kilogram in weight, the g-forces equal a weight of 10 kilograms (L. Hirvonen, Piippo Oy, private communication, June 23, 2021). Gravity starts to pull the payload back to Earth, eventually ceasing to a slow descend by the accompanied parachute, where used (GSBChallenge, 2020). In Finland, parachutes are not currently used for the daily weather balloon launches, as the radiosondes are generally lost in forests or seas with very low density of people and the use of parachutes would therefore be considered an added cost without tangible benefits (T. Laine, FMI, private communication, March 25, 2021).

**Figure 2**: Vaisala RS41 radiosonde with the cord unwinder (Vaisala, 2021a)

Most high-altitude balloon experiments carry GPS locators, which are used to track balloon movement and therefore wind direction and force (AIAA, 2020). Typically, the radiosondes communicate with the launching ground station using radio waves throughout the flight. As the balloon flight generally takes 1,5 to 2 hours, the winds and Earth's westerly movement can carry the balloon in any direction, ranging from mere tens of kilometers to several hundred kilometers away from the original upper air observation station. These stations are equipped with antennas which can sit as low as just a few meters off the ground (Vaisala, 2021b; Wei, n.d.). This means that once the balloon bursts and the radiosonde starts to descend, the signal is lost approximately one kilometer above the ground. This is mainly due to the curvature of the planet as well as any surrounding hills or mountains blocking the signals. While radio signals would travel well over water bodies, most launch stations around the world are located further in the country, for the radiosonde to capture as much of the local weather as possible rather than the one above the surrounding sea (T. Laine, FMI, private correspondence, November 4, 2021). In Finland, for example, most balloons launched from Jokioinen end up in the forests and lakes of Central and Southern Finland, the Gulf of Finland, or even Estonia, carried by the primarily southwestern wind and the rotation of the planet (T. Laine, FMI, private correspondence, November 4, 2021; Hellinen *et al*., 2019).

It is common practice for many weather institutions not to actively track their balloons due to the high cost related to equipment retrieval. For example, the Canadian weather service releases 62 weather balloons every day without any intention on retrieving the equipment, other than mailing instructions for those who happen to come across the package (Beeby, 2018). Similarly, 184 balloons are released every day from the 92 weather stations in the US, approximately 67160 balloons a year, with only 20% being returned for refurbishment and relaunch. Similar reports are found from across the world in Australia and the surrounding Indian and Pacific oceans (Bamford, 2019). As the balloons are generally sold as consumables, many manufacturers do not refurbish their radiosondes. With refurbishment, any unidentified microscopic damages to the electronic components could cause failures, which carries the risk that the entire weather balloon along with the radiosonde was launched a second time for no benefit but rather added cost to the sender as well as natural resources. Some manufacturers are willing to carry that risk, other do not (Vaisala, private correspondence, June 11, 2021).

While the latex of the balloon itself will eventually decompose, it can take months, even years to do so, while the parachute, rigging and equipment remain discarded in nature for hundreds of years (Beeby, 2018). This is known to cause issues especially in marine environments, where the plastic waste poses significant threat to both the wildlife but also the coral reefs and plants (Bamford, 2019). Weather balloons per se are not listed as top pollutants of the oceans, with cigarette filters holding the top place, but they still contribute to the accumulation of plastic and rope debris holding the second and tenth places, respectively, in the top marine debris item list (Marine Litter Solutions, 2011). However, the accumulation of polystyrene has become a major concern, due to the very low decomposition time as well as the molecular structure of the plastic, generating very small plastic particles, which could be easily eaten by the wildlife (Sharp, 2020; Saido *et al*., 2020). So far, the only way to retrieve any of the debris is to manually collect it from beaches and forests. Usually this responsibility falls on individual hobbyists or nature conservation organizations. For example, Tangaroa Blue organizes a cleanup operation over a 3 km of beach line in Australia every three months and each event has produced 300 – 3000 pieces of weather balloon targets (Tangaroa Blue, 2018a).

## 3.2 Component analysis

### 3.2.1 The latex balloon

There are very few studies conducted on the biodegradability of the components included in the weather balloon train. While the balloon manufacturing industry claims the balloon to be fully biodegradable, as latex is essentially made of natural rubber, the studies into the subject are conflicting. The most cited one in the industry is a study conducted in 1989 by D.K. Burchette, which claims that the balloon fragments show significant degradation after six weeks of exposure to the nature, decomposing at the same rate as oak tree leaves (Burchette, 1989). However, in their natural environment, an oak tree foliage takes several years to decompose (Straigyte *et al*., 2009).

The most recent study conducted by the Institute of Marine & Antarctic Studies at the University of Tasmania reveals that latex balloons generally do not biodegrade at any significant rate. The study investigated the degradation rate of latex balloons in freshwater, seawater and industrial compost and after 16 weeks they had lost as little as 1-2% of their mass (Gilmour, 2020). Another independent study by an amateur organization in California, United States, indicates that the latex balloon decomposes much slower than officially claimed. The privately conducted experiment has witnessed a degradation time of over seven years and counting (Balloons Blow, 2021). While the composition of weather balloons is different from toy balloons, the amount of rubber used in weather balloons is paramount in comparison, as the weather balloon must expand much larger than any standard balloon. Conversely, a weather balloon would generally have different chemical treatments than those performed on toy balloons, which could have metals infused in them or special coating applied, thus affecting the biodegradation rate. Nevertheless, the weather balloons are generally protected against degradation by the use of additives, in order to improve shelf life but also to protect the balloon against the harsh environment it is sent to (O'Shea *et al*., 2014). Although fragments of latex balloons have been proven to degrade as fast as 87 days when exposed to seawater, the polymer nanoparticles formed by the degradation process still pose a serious risk especially to juvenile animals (Lambert *et al*., 2013). As the degradation speed depends on the size of the fragment as well as the environment it lands in, in terms of UV radiation, oxygen levels, temperature and moisture, there are no single truths about the time it takes for a weather balloon to degrade. The studies conducted so far would indicate it takes anything between three months to several years for a weather balloon to degrade, possibly even a decade depending on conditions.

Regardless of the biodegradability rate of weather balloons, once the balloons reach their maximum altitude, they burst into very small strips of latex, spreading over a wide area of land or sea (Figure 3). These balloon fragments can be mistaken for prey, such as jellyfish, by birds and larger sea mammals such as sharks and tortoises (Whiting (1998), in O'Shea *et al*., 2014). As they degrade very slowly, they typically cause blockages in the digestive systems of these animals (O'Shea *et al*., 2014; Balloons Blow, 2021). Eventually, these animals starve to death, as their stomachs cannot withhold any food, being filled by an insoluble mass of rubber. There are over 170 species that have evidently been affected by the balloon fragments. Moreover, the location of the balloon launch station as well as sea currents quite often cause the balloon trains and the latex fragments to conglomerate into specific areas, causing further havoc at these sites, as evident in a recent study at the Great Barrier Reef. Over the course of 21 months, the teams collected approximately 2500 weather balloon fragments from the shores of Australia, with the most collected close to the reef. In Australia, an estimated 65-70% of balloons released by the Bureau of Meteorology (BoM) end up in the ocean, creating a major risk to the marine environment (O'Shea *et al*., 2014). However, unlike in Europe, the BoM has not yet enabled descent data communications during weather sounding, which prevents the bureau from tracking the balloons to their final landing site, to confirm or disprove these estimations (J. Shelley, Bureau of Meteorology, private correspondence, March 10, 2021).

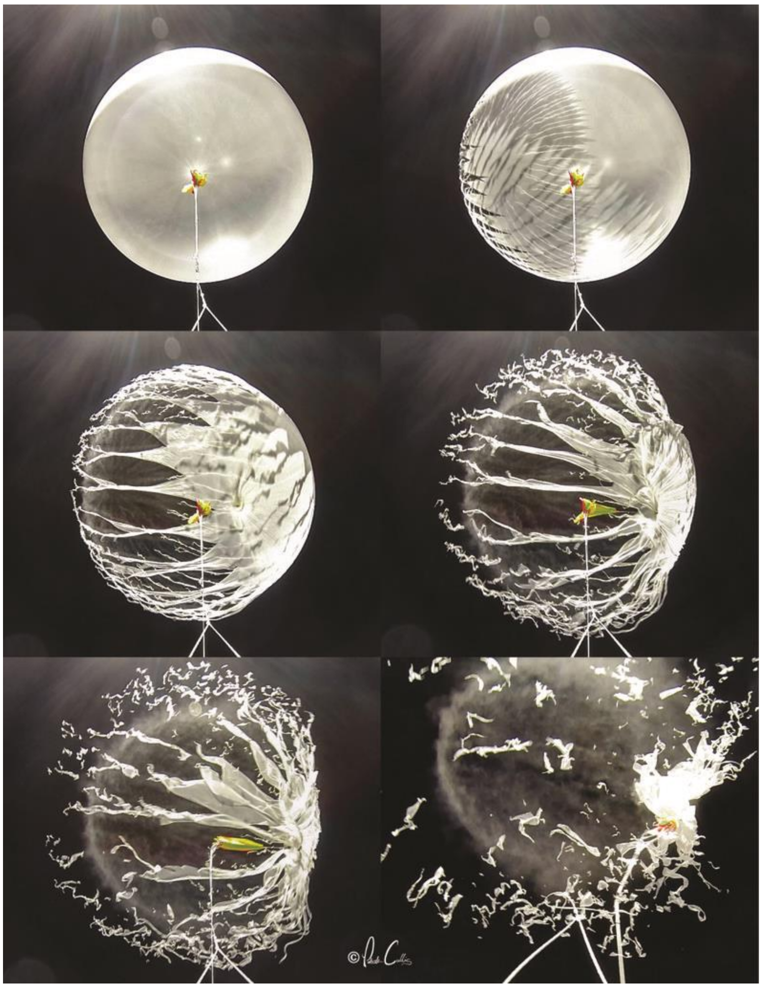

**Figure 3**: Weather balloon burst (Cullis *et al*., 2017)

Although the 1989 study claims the biodegradation rate to be fast enough for latex balloons not to be considered an environmental hazard, combined with the amount of balloons lost every year as well as the amount of fragments these balloons tend to break into, the amount of rubber discarded in nature is considerable, counted by the tens if not hundreds of millions of individual pieces per year. Manufacturers have therefore begun investigating the environmental impacts of weather balloons as well as the possibilities to replace latex with another more biodegradable solution. At the time of writing this research, the findings of those investigations cannot be disclosed in public (TOTEX Corporation, private correspondence, March 4, 2021). Considering the environment these balloons are being used in and the weather conditions they are exposed to, even with its shortcomings the latex balloon seems to be the best possible choice, until further inventions pave way to a more environmentally friendly solution (Vaisala, private correspondence, June 11, 2021).

While the use of latex seems to be quite unavoidable at this stage, there are methods that can prevent these fragments from being consumed by the wildlife. A study from 2006, focusing on the visual capabilities of turtles and fishes, indicates that most sea creatures can detect color, especially ranging from wavelengths 400nm to 550nm, *id est* purple, blue, green and yellow (Fritsches & Warrant, 2006). Moreover, some leading marine conservation researchers in Australia have provided evidence that the standard white or beige color of the widely used balloon is the worst in terms of ingestion by birds and turtles, as it is most likely mistaken for a jellyfish. As most animals can see the color blue, the hypothesis stands that changing to blue color would prevent the balloons from being misidentified. The Bureau of Meteorology in Australia has recently changed their 1200-gram ozone balloons, which are among the largest latex balloons commonly used, to blue (J. Shelley, Bureau of Meteorology, private correspondence, March 9, 2021). At the time of writing this research, the change of balloon color to blue bears no or very little added costs (TOTEX Corporation, private correspondence, March 10, 2021). Therefore, while there is currently no evidence that this method has any tangible results, it is still a no-cost improvement to the current design and use.

One research from the Montana State University has proposed the latex balloons to be reused instead of allowing them to burst. A paper by Basta *et al.* (2015) depicts an altitude control system, which would effectively turn a weather balloon into a zero-pressure balloon. The latter is a larger, more durable and heavier type of atmospheric balloon used for days or months in higher altitudes to conduct scientific research related to radiation, space sciences, biology and other atmospheric studies requiring near-space altitudes without the need to launch a rocket. The pressure inside the balloon can be regulated in order to both prevent the balloon from bursting but also to control the balloon's movement by using wind layers at different altitudes to guide the experiment to the required direction. Zero pressure balloons are therefore more expensive (NASA, 2017). As defined by Basta *et al.* (2015), with a simple valve and a low-cost microcontroller, a latex balloon can effectively be converted to a regulated balloon. The raw cost of the valve technology is quoted as $98 which, though careful selection of components and mass manufacturing, can be decreased. Once the mission is over, the valve can release the gas inside the balloon, allowing it to be retrieved with the payload and reused (Basta *et al.,* 2015, p.14, 80-81). Unfortunately, natural latex may not operate as efficiently after repeated use; it would be worthwhile to investigate which materials could be suitable for this application as well as the applicability of a regulated weather balloon system on a global scale.

Transforming the current fleet of daily balloon sounding operations into a long-term system of floating weather balloons would mean global coordination and global investments. As the rotation of the planet tend to move any balloon eastward, a floating balloon system would gradually move along the planet's movement, eventually requiring a replacement. A fleet of balloons sent from, for example, Australia or Japan would eventually end up over the Pacific Ocean with no coverage of the target land, requiring a replacement from west, therefore requiring the entire globe to be covered in a network of balloons through a major global operation. Moreover, as regulated balloons require winds of different altitudes to travel to the desired direction, this may leave gaps in the target measurement altitudes whenever a specific balloon deliberately changes its height and position (Kayhan, 2017). Additionally, any network of floating balloons would need to take into consideration the prevailing winds of the planet, which could effectively conglomerate the balloons into specific pathways, eventually leaving gaps in the surrounding areas (NWS, n.d.a). Further research on such a network would be required to fully assess its applicability on a global scale, potentially using NASA's Columbia Scientific Balloon Facility's current and previous experiments with long-term balloon operations as a base line (NASA, 2021).

Finally, helium is generated only by the slow beta decay of radioactive thorium and uranium deep within Earth's crust. There are no other sources for helium, rendering it a finite source, in terms of a human life duration. While the current reserves are still able to supply helium, the unregulated spend can lead into shortage of helium, especially for future generations where technologies such as fusion power, magnetic resonance imaging (MRI) or nuclear magnetic resonance (NMR) spectroscopy depend on helium supply (Zogopoulos, 2020; PEAK Scientific, 2019). This calls for a more rational use of the limited resources.

As such, many weather organizations around the world continue to use hydrogen, which is not only cheaper but also readily available as a molecular element in almost every other compound on Earth. Hydrogen can be produced from natural gases, fossil fuels, biomass, water electrolysis, ethanol and many other sources (AFDC, 2016). This makes it currently four times cheaper than helium. Some organizations, such as the Swedish Meteorological and Hydrological Institute, have opted to use the more limited but less volatile helium, while the neighboring Finnish Meteorological Institute use helium only for manual observations, utilizing hydrogen in the automated daily operations (T. Laine, FMI, private correspondence, August 26, 2021). One potential reason for this is that hydrogen gas is highly flammable, making it a fire hazard if the balloon does not burst as well as requiring more strict storage control measures (BoM, 2018). With hydrogen being the more traditional gas used in weather balloons, considering the cost and resource limitations of helium, it would be more environmentally friendly to use hydrogen whenever possible.

### 3.2.2 The rigging

The requirements for the wires used for carrying the payload are relatively high. One should not allow the payload to detach from the balloon, after all, regardless of the surrounding weather conditions, as it would render the rest of the sounding a failure. As the balloon burst in near-zero pressure causes extreme acceleration forces to the payload, the parachute and the balloon fragments, the cord must withstand forces of at minimum ten times the weight of the payload. For a standard radiosonde weighing approximately 100-200 gram, the current tensile strength of 10-15 kilograms means almost a hundred-fold tolerance (L. Hirvonen, Piippo Oy, private communication, June 23, 2021). Moreover, the rigging must be as lightweight as possible, to minimize the amount of helium gas used. Therefore, the current solution is to use very thin cord made of polyester or polypropylene (PP), hence non-biodegradable. Polyester and PP fabrics generally take anywhere from 20 to several hundred years to decompose (Stanes & Gibson, 2017; BioSphere Plastic, 2021).

While many of the manufacturers have made research into replacing the plastic cord with a biodegradable or at least compostable alternative, those investigations have so far been futile. The minimum requirement for the wire is tensile strength of approximately three kilograms as well as general integrity, *id est* if braided the wire must not open up even under stress. However, all biodegradable strings, such as jute, hemp or flax, have been too heavy and too thick. The length of the rigging used in the weather balloon train is approximately 25-55 meters, which prevents the heat of the ascending balloon from affecting the readings as well as keeps the radiosonde still. A shorter cord can cause a pendulum motion, which would need to be filtered out of the measurements, as any heat trace left by the balloon would be visible whenever the radiosonde passes through the balloon's wake (Kizu *et al.*, 2018). Therefore, a cord this long made of any currently available biodegradable material is evidently not suitable for the radiosonde reel (L. Hirvonen, Piippo Oy, private communication, June 23, 2021). At the same time, the length of the wire can become a hazard to wildlife, with the animals becoming entangled and not having the required strength to break it (Trapani *et al.*, 2018).

However, biodegradable plastics are emerging. While not having the strength of a PP wire, with the right production techniques these materials could potentially be processed to achieve at least the minimum requirements for the wires. For example, by producing a large sheet of biodegradable plastics, it could be cut into a thin flat cord (L. Hirvonen, Piippo Oy, private communication, June 23, 2021). Research would need to be conducted if such cords would be able to fulfil the requirements of a weather sounding as well as the biodegradability rate of such products.

Moreover, companies such as Spinnova in Finland are exploring ways to generate environmentally friendly clothing material from wood pulp without the use of chemical processing and 99% less water. The yarn made of white continuous filaments currently have a strength of cotton, which is not enough to match the requirements for a weather balloon flight (Spinnova, private correspondence, July 30, 2021), but the potential for future research into improving the tensile strength of this material could be a worthwhile investment.

Nevertheless, considering the high tensile strength of the polypropylene and polyester wires, it would be worthwhile to investigate if radiosondes could survive with a lower-grade plastic wire, considering that the equipment weights only a hundred grams. With the current wire withstanding over a hundred times more weight in mild temperatures, it would be worth to investigate if any other material could survive the extreme weathers and still be able to withstand approximately 10-20 times the weight, to account for the dynamic forces affecting the wire. Naturally, such wires would not be suitable for any heavier equipment, but if targeted and marketed exclusively for standard radiosondes, they would be much more environmentally friendly than the current solution.

### 3.2.3 The parachute

The parachute used in weather soundings are generally made of nylon, which inherently has a biodegradation time of 30-40 years (United States National Park Service, 2009), or polypropylene which lasts for dozens if not hundreds of years (Stanes & Gibson, 2017; BioSphere Plastic, 2021). Many meteorological organizations have therefore discontinued to use parachutes in their sounding operations, to reduce the environmental impact but naturally to decrease the overall cost of the operations. However, this is not possible in heavily congested areas, invoking further research into biodegradable fabrics. Vaisala has begun its own investigation into environmentally friendly weather balloon operations, which also covers biodegradable parachutes and strings (Bamford, 2019). There are currently several programs investigating the possibility to replace standard nylon parachutes with alternatives less harmful to the environment.

One such program was launched in 2012 by the United States Department of Defense's Environmental Security Technology Certification Program (ESTCP), which focused on "biodegradable sonobuoy decelerators", *id est* parachutes for "non-personnel cargo". Their line of investigation revolved around replacing the nylon fabric with a "polyvinyl alcohol (PVOH) based film". While not identical to nylon, the film had proven to be an adequate replacement while using "a non-toxic, water soluble synthetic polymer" as its baseline. The cost of the parachute had been found to be "similar" to the traditional nylon parachute (ESTCP, 2012). However, a major concern in this type of a parachute were the effects of rain and high humidity to the strength and pliability of the material. Moreover, humidity at storage conditions had not been fully tested, which could decrease the designed 5-year shelf life. Finally, the tests were conducted at a low altitude of 335 meters. The effects of -50 °C could potentially cause molecular damage to the PVOH structure (Ingram *et al.*, 2015).

The first effective parachutes in history were made of cotton canvas, later replaced with lighter silk or heavier viscose for durability. Viscose production generates pollution such as carbon disulfide as a by-product, therefore requiring rigorous controls at the manufacturing process (Bionity, 2021). Silk, on the other hand, is very laborious to produce (CFDA, 2021). At the beginning of the 20th century the supply of silk was reduced, thus calling for more readily-available alternatives, paving way to synthetic polymer *id est* nylon parachutes which were durable, light and cheap, and has thus prevailed to present days (Kaur, 2013). However, as the payload is essentially inanimate objects weighting less than a kilo, the requirements for durability are lower than with parachutes designed for humans, which should open up the window for wide range of alternatives. Naturally, the parachute will be subject to the same conditions as the balloon itself during ascend and descend. Therefore, it will need to be robust enough to carry the payload even when wet or when exposed to extreme conditions and movements. Otherwise, the payload will turn into a potentially deadly debris falling from the sky especially with heavier ozone measurement payloads.

One such line of investigation would be to replace the nylon parachute with a non-woven biodegradable alternative. A study by Wortman *et al.* in 2015 explored the use of biodegradable plastic films and spunbond non-woven biofabrics as mulches for crops, specifically tomato and bell pepper fields. While bioplastics started deteriorating after only 3-5 weeks, the performance from non-woven textiles proved to be suitable for the task, without showing any degradation throughout the season. As such, they could prove to be able to withstand the stress of high-altitude flight, although their use in parachute application would be limited. However, the Wortman *et al.* research paper concluded that non-woven biofabrics are generally 7 to 10 times heavier and even 400 times thicker than bioplastics, rendering them unsuitable for weather sounding operations. Moreover, once discarded in nature, it could take them months to start the biodegradation cycle (p.217).

The thermodynamics and kinetics of ecologically friendly plastics were recently analyzed by a research group in Germany. The research conducted by Patnaik *et al.* (2020) focused on "viz. non-woven plastic and corn starch-based biodegradable plastics" (p.14991) with temperatures ranging from -100 °C to 300 °C. The differential scanning calorimeter (DSC) plot demonstrated surprisingly linear performance between -60 °C to 35 °C range, projecting the use of these plastics even in atmospheric research (p.14995). While these plant-based plastics may be too rigid for use in parachutes and cords, they could be viable options in payload and especially radiosonde structures.

Research on the performance of three other types of biodegradable plastics was conducted at the University of Cambridge in February 2020, in which Pantaloni *et al.* (2020) investigated the mechanical performance of “fully green composites” against industrial-grade non-woven flax (p.109). These were based on polyhydroxyalkanoate (PHA), polybutylene-succinate (PBS) and polylactide (PLA) matrices. Their attributes related to temperature exposure, tensile strength and stiffness were observed to be equal or better than those of synthetic, non-degradable fibers (namely polypropylene (PP)). These measures also indicated that their use in harsh environments such as high-altitude balloon flights would be a feasible option. The degradation rate varied with the material, with 37% of the initial strength of PLA being lost after just six days in a garden compost, yet being extended to 190 days for 50% degradation of PHA (Pantaloni, 2020, p.119). Naturally, this time would be increased when exposed to the wilderness where a lower concentration of bacteria will slow down the process, exhibiting the notable difference between compostable and biodegradable materials. Nevertheless, these were relatively promising results.

The same Polylactic Acid (PLA) was scrutinized two years earlier by Maqsood and Seide in the Netherlands (2018a; 2018b). Their research focused on using PLA for apparel production, namely socks and gloves. These 100% PLA fabrics proved to be durable enough for daily use and have relatively good thermal resistance. While the research was lacking comparison with non-biodegradable alternatives but focused more on comparing different knitting techniques, the costs for producing PLA fabric for apparel use was determined to be the same as socks and gloves produced from synthetic polymers (Maqsood & Seide, 2018a, p.172). However, the drawback of standard PLA is that it loses all strength at temperatures above +50 °C and is naturally brittle (Markforged, 2021). Therefore, further research into improving the durability of this material would be required if it would be considered an option for parachute applications.

Polyhydroxyalkanoates (PHA) had been previously analyzed in another study. Bugnicourt *et al.* (2014) investigated the current and future applications of PHA plastics in packaging, coating, fabrics and additives. By nature, PHA is a biopolymer or organic plastic grown out of pure microbial cultures, thus proving to be a viable sustainable alternative to oil-based plastics (p.791). It was concluded that PHA has a better mechanical strength compared to PLA, but has a similar inherent feature of being brittle (p.803). This might exclude PHA from being used in high-altitude environments, where low temperatures may degrade the PHA performance to an unstable level (Bugnicourt *et al.*, 2014)

Furthermore, the United Nations Environmental Programme (UNEP) released a report in

2015 in which they highlight the issue of biodegradable plastics left into the wilderness (Kershaw, 2015). In order to start the degradation process, PLA typically requires higher temperatures and existence of micro-organisms which may be absent in, for example, oceans. As stated in the report, “despite the biological origins degradation under natural environmental conditions is very slow and it requires industrial composting for complete biodegradation” (Kershaw, 2015, p.22).

Nevertheless, out of the three biodegradable plastics mentioned above, polybutylene-succinate (PBS) bioplastic has proven to be a successful candidate for producing a biodegradable parachute. While the exact biodegradability capabilities are subject to further research, the Bureau of Meteorology in Australia has been able to obtain and test parachutes made of bio-based polybutylene-succinate. These parachutes were locally engineered and produced by a company in Australia, who at the time of writing has requested to remain anonymous due to cooperation with global meteorological technology companies and the parachute being in trial stages. The new material has proven to be capable and even outperforming the polypropylene. This change in material composition equals a biodegradability rate reduction from hundreds of years to mere months (Shaiju *et al*., 2020). Moreover, the parachutes have been dyed blue in order to reduce the likelihood of being ingested by wildlife during the degradation process (J. Shelley, Bureau of Meteorology, private correspondence, March 9, 2021).

While there are multiple different types of biodegradable parachutes available, for example those used by the AirDropBox system to deliver Humanitarian aid to emergency locations (AirDropBox, 2019), or other small supply delivery packages dropped by the US Navy, it is evident that relatively few can withstand the extreme weather elements in stratosphere due to the biodegradability nature of the products. Therefore, a lot of emphasis has been laid on trials such as those currently being conducted in Australia, as well as currently available solutions being developed towards this target application. There are relatively suitable biodegradable parachutes already in production, for example by Specialised Canvas Services Ltd. in the United Kingdom and by Totex in Japan. Unfortunately, as the parachutes are under corporate contracts, the companies were unable to disclose any information to a public document such as a Master’s Thesis, other than mentioning the production costs to be different only by material costs (Specialised Canvas Services Ltd., private correspondence, February 25, 2021; TOTEX Corporation, private correspondence, March 5, 2021).

### 3.2.4 The radar target

Radiosondes were originally tracked by radar, due to the lack of on-board GPS. For this purpose, all balloon operations would use a radar target, generally composed of aluminum foil over a polystyrene structure. With radiosondes being equipped with GPS and the location being transmitted via radio, the radar targets have become obsolete. Despite this, many countries still use the targets as a direct (and cheaper) replacement for parachutes, since they generate drag similar to a drogue, slowing down the descent (J. Shelley, Bureau of Meteorology, private correspondence, March 9, 2021).

In 2014, as a response to public pressure to reduce the amount of plastics discarded in nature, the Bureau of Meteorology in Australia replaced the plastic radar targets with cardboard alternatives (Tangaroa Blue, 2018b; J. Shelley, Bureau of Meteorology, private correspondence, March 9, 2021). These targets have been designed and produced by a company The Total Package located in Melbourne, Australia. Made of recycled paper corrugated cardboard with a 12-micron silver-infused film on both sides, these radar targets perform better than the original polystyrene radar targets, with the weight of the target remaining relatively the same (K. Keating, The Total Package, private correspondence, March 4, 2021).

Despite this overall improvement in design, the film lining has received criticism for not being fully biodegradable (H. Tait, Tangaroa Blue, private correspondence, April 5, 2021). Biodegradable or at least compostable laminates already exist in the market, for example those produced from polylactic acid (PLA) by Lam'on (Lam'on, 2020), from cellulose diacetate by Celloglas (Pinkney, 2016) or from polypropylene-based plastic by Grafenia (Handley, 2018). Moreover, biodegradable reflective materials have also been invented, such as the retroreflective element made of PLA or polyglycolic acid (PGA) (Parmanen & Ruotsinsalo, 2015). The previously mentioned brittleness of PLA would likely not be a major concern when used as a surface element beneath a laminate and thus not being subjected to kinetic forces. However, the need to replace the reflective silver with biodegradable alternatives is only minor, as silver it its solid form is non-toxic and biologically inert (Dartmouth College, 2021).

Therefore, it would be possible to produce a fully biodegradable radar target, using recycled paper cardboard lined with, for example, silver-infused PBS laminate. However, the weight of the radar target may become an element of concern, as any added weight means more gas to be used or a slower ascent. The Total Package has been able to overcome this problem by redesigning the target while maintaining its reflective properties (K. Keating, The Total Package, private correspondence, March 4, 2021). Moreover, as radar targets are currently used either for flights where the on-board instruments do not have GPS capabilities or to slow down the ascent (Tangaroa Blue, 2018b), it would be reasonable to redesign the targets as purpose-built drogues rather than radar reflectors. The current radar targets with the more traditional designs could still be used where needed, but the tailored drogue could have worldwide applications as a replacement for parachutes, without needing to add silver to the composition and thus reducing the overall cost further.

### 3.2.5 The payload box

The encasing of the radiosonde is typically made of polystyrene, either in the form of a bare styrofoam box or a hard plastic box (CHMI, n.d.; NWS, n.d.). The main purpose of the encasing is to protect the electronics inside from freezing temperatures, rain, moisture, wind, dynamic forces and any other element of nature that could affect the instruments. While a hard casing has been most commonly used, manufacturers have been turning to styrofoam encasing to reduce the overall weight of the radiosonde while maintaining or even improving the insulation and floatation qualities of the payload box (Brewer & Dover, 2018). Compared to the previous generation radiosondes, the recent ones have been notably smaller in size, effectively halving the amount of plastics used to produce the radiosonde and reducing the energy requirements to minimum. Moreover, the total greenhouse gas emissions of these products are relatively low, equaling a car drive of 30 kilometers per unit (Vaisala, 2017a). However, this does not include the environmental impact of the product after it has been used.

While styrofoam is evidently the most effective material to be used in radiosonde applications, including cost-effectiveness (Vaisala, private correspondence, June 11, 2021), it has been noted to decompose extremely slowly. As previously mentioned, the lifespan of polystyrene ranges from five hundred years up to a million years, (Davis, 2019; Dilthey, 2018; Kimukai *et al.*, 2020) making it one of the longest lasting components of the entire radiosonde composition. Moreover, styrofoam has a tendency to break into smaller particles, including nanoparticles, which can permeate organisms. These particles have been increasingly present in the air, soil and waters around the world, accumulating along human and animal food chains, as the nanoparticles do not break down further at any significant rate (Kik, 2020). This calls for measures to prevent further release of polystyrene particles into the nature.

Replacing styrofoam with a biodegradable alternative will inevitably weaken the general composition of the radiosonde. It will either make it heavier, therefore requiring more lifting gas (and thus lower maximum altitudes) or longer flight times, or it could insulate poorly, thus causing failures in sounding operations and becoming litter with very little scientific benefits. These contrasting features of insulating well yet being lightweight, as well as extremely cheap, makes styrofoam very difficult to replace. Nevertheless, there are alternatives being produced worldwide, which come close to being competitive and environmentally friendly. While such drawbacks as added weight are unavoidable when using biodegradable alternatives, considering the trade-off between longer flight times and reducing the amount of polystyrene particles in nature, the disadvantages caused by biodegradability may become marginal in the larger picture, especially if supported by alternative data gathering methods, which are discussed later in this research.

One possible, yet heavy, alternative to styrofoam could be a newly developed Myco Foam, made of mycelium, a vegetative part of a mushroom. The producer, Ecovative Design, developed the material in 2007 to replace the current polystyrene packaging with a 100% biodegradable alternative. In the production process, straw, cornhusks, lentil pods and other local agricultural waste is fed to mycelium within a mold and left to grow for five days. The mushroom fibers fill the space within the mold, thus producing the desired frame. After this "incubation period" the mold is removed and the mycelium dried to prevent further growth. The resulting solid structure can be used as a direct replacement for any packaging material, thermal or acoustic insulation panel, grown out of waste (Living Circular, 2016). As such, it has potential to be used at least as a packaging material for radiosondes but possibly as the outer shell as well.

However, Myco Foam weights approximately 43 $kg/m^3$, which is twice as much as the density of 18 $kg/m^3$ of the expanded polystyrene (EPS) used in radiosondes (Bonnefin, 2017; AVCalc, 2021). An RS41 radiosonde weights approximately 80 grams, out of which 25 grams is in the shell, causing a Myco Foam alternative to increase the overall weight of the radiosonde by approximately 40%. Considering a recent development of the Vaisala RS41 radiosonde, which replaced the solid plastic casing with a soft EPS shell and thus reducing the weight of the sonde equipment from 100 grams to 80 grams, using Myco Foam would mean returning slightly above the previous weight levels (Brewer & Dover, 2018).

While Myco Foam can be easily used as packaging material for any sensitive material, such as computers (Living Circular, 2016), it is only water-resistant and not waterproof (Fisher, 2010). Therefore, the use of Myco Foam as an alternative for radiosondes might require further processing especially if being used for sounding during thunderstorms or heavy rain. This processing could increase the weight of the product further. Nevertheless, this does not necessarily prevent Myco Foam from being used in this application, especially if coupled with effective biodegradable waterproof coating.

In terms of insulation, there are also more traditional alternatives which are fully biodegradable, for example cellulose made of wood pulp. Paper and wood have long been used as insulators and are reappearing as environmentally friendly alternatives to current polystyrene-based products. While mainly considered for use in building insulation, the material has potential for other applications as well. The drawback associated with cellulose fiber is the inherent property of wood to attract moisture, which in building applications has the potential to cause mold if not properly installed or maintained (Hurtado *et al*., 2015).

The drawback of mold accumulation would not be much of a concern for small-scale products such as radiosondes, which are already stored in dry containers and are in essence used once for a period of few hours. Moreover, cellulose fiber in its loose form weights approximately 17 $kg/m^3$ (Aclara Technologies, 2021), equaling the density of styrofoam, although requiring a binding agent to be applicable as a casing rather than an insulator, which would certainly add weight to the structure.

With proper manufacturing processes, wood pulp and cellulose can be used to generate very lightweight yet durable products. Such methods can also make wood pulp water-repellent. For example, Empa, the Swiss Federal Laboratories for Materials Science and Technology, has developed nanocellulose foams, which are being used to combat oil spills in oceans. The chemically-treated nanofibrillated cellulose (NFC) have been mixed with reactive alkoxysilane molecules, to prevent it from absorbing water, and ice-templating is used to produce an ultra-porous structure. This makes the sponge capable of absorbing only oil-based liquids (Zhang *et al*, 2014; Empa, 2014). However, the ultra-porous structure is very lightweight, at around one kilogram per cubic meter (Antonini *et al*., 2019). This causes structural instability, which would make the current product too fragile to be used as radiosonde shell material. Moreover, the foam is not 100% hydrophobic, and due to the open-pored structure the lambda values in terms of thermal insulation are relatively poorer, compared to EPS foam. However, with further research, the structural stability and water-resistance could be improved. Therefore, in theory it would be possible to develop and produce a cellulose-based foam, which would match the needs of a sounding equipment while being fully biodegradable. At the moment, a mechanically stable NFC foam made from a 2 wt% NFC-suspension has a density of 29 $kg/m^3$, therefore exceeding the qualities of EPS until developed further, but still less than Myco Foam. Hypothetically, using Empa’s NFC solution as a baseline for further products could effectively transform lost radiosondes into oil and waste-absorbing cleaning units, thus effectively nullifying or at least diminishing the environmental waste they produce. The costs of such research and development would need to be assessed, in the light of limited funding by the weather organizations. The foams are not yet commercially available, but in the pipeline of the company Weidmann Fiber Technology (T. Geiger, Empa, private correspondence, June 24 – November 3, 2021)

In contrast, another research by Wang *et al*. (2021) has evaluated the manufacturing processes of wood sponges, with focus more on sewage absorbent applications. With chemical treatment affecting the pH values, NaOH and $NaClO_2$ concentrations as well as porosity, balsa wood sponges could be optimized for resilience and absorption capacity. While the water and waste absorption properties of wood-based foams can certainly be improved with proper treatment, with dedicated research the opposite functionalities can be achieved as well, as evident by the abovementioned development conducted by Empa. Unfortunately, such developments are rare, due to the traditional purposes of wood sponges. Nevertheless, the all-encompassing benefits of using wood has been determined to be low cost, low density, porosity and sustainability, all of which would make wood sponges viable to be used as insulation and shell material for radiosondes as well (Wang *et al*., 2021). The inherent property of attracting and absorbing moisture can be combated with either chemical treatments or biodegradable outer-shell solutions, such as physical covers or waterproof coating.

Such a coating is already in the market. In 2014, researchers from Queensland University of Technology in Australia developed a fully biodegradable coating made of lignin, a natural water repellent extracted from bagasse, a byproduct of the sugar cane industry. As such, the coating is cost-effective while providing waterproofing as well as strengthening properties comparable or even above traditional wax coatings (Edye & Tietz, 2015). A very thin layer of such coating could provide the necessary outer layer to any biodegradable container. For wood pulp, the coating might not be ideal for very porous structures, but the porosity of different layers of wood pulp or sponges could be altered with proper manufacturing processes. Lignin as a biopolymer is not subject to dramatic changes even in freezing conditions, making it a viable option for atmospheric applications as well (Bogler & Borduas, 2020). However, further research on lignin-based coating in freezing conditions would be required to fully assess its applicability.

Another option is to use a solid shell on top of the insulator. A natural, biodegradable and inherently insulative option would be to use paper, which can also be coated to become water resistant while allowing air pressure changes to occur through the surface. The company Rite in the Rain has developed such a product, with their paper products capable of being submerged in water for long periods of time without performance degradation. As such, the paper decomposes slower than standard paper, but it will do so nevertheless. The paper is made with environmentally responsible processes, composed of 100% cellulose fiber with wet strength additive, using acrylic coating for water resistance. The coating is water-based, comprising of styrenic acrylic copolymer, a wax and fillers, therefore fully biodegradable (J. Mattingly, Rite in the Rain, private correspondence, July 7, 2021; Silver *et al.*, 2005). When stored dry, the paper retains its properties for hundreds of years, thus not having any storage degradation issues (Rite in the Rain, 2021). The most resilient layer of the product is the acrylic coating, which has a natural biodegradation rate of 28-32 days when exposed to microbial systems (Gaytán *et al.*, 2021). Designed to withstand any type of weather conditions, oils and other various substances for extended periods of time (Rite in the Rain, 2021), it should also be able to withstand the toils of a weather sounding operation in extreme conditions for the duration of the flight without any impact on its performance, yet being capable of naturally degrading when exposed to seawater or soil.

Finally, one option for the shell would be to produce the whole cover from an entirely new organic, biodegradable and extremely hydrophobic material, developed by a multinational team of scientists led by Dr. Milionis of ETH Zurich University in Switzerland. The material uses a surface structure made of cellulose micropillars, enabling it to be self-cleaning and waterproof. Moreover, water drop, jet impact and folding tests confirm the material to be durable enough to be used in bioengineering applications, while being able to fully biodegrade in three months (Milionis *et al.*, 2018). Unfortunately, the material is not yet commercially available, but has potential to be used in radiosonde operations as well, depending on further tests.

### 3.2.6 The radiosonde

For the electronics inside the radiosonde package, there is very little room for improvement, in terms of sustainability. At the time of conducting this research, there are no biodegradable electronics available. Nevertheless, there are few considerations to make when selecting the materials used to support the electronic components.

Biodegradable plastics can offer a more sustainable approach to various electrical components, wherein the materials used to produce the products could be derived from natural resources. While the use of PLA, PHA or any other similar bioplastic does not offer definite solutions to the problem of the devices being completely discarded in nature, they could offer some degree of biodegradability to the overall composition. In other words, while traditional plastics do not biodegrade at all, bioplastics would at least eventually degrade. Such products could be used for printed circuit boards (PCB) and battery compartments, thus reducing the overall impact the electronics have on environment.

Research by Guna *et al.* (2016) demonstrated the use of natural resources to produce fully biodegradable PCBs. The boards were made of banana fibers and wheat gluten, which proved to be as effective and as resilient as their plastic counterparts. The raw materials are essentially byproducts of agricultural industry and therefore relatively cheap. While the prototypes produced during the study were hand-made, it would be possible to apply mechanical manufacturing processes to mass-produce such boards on larger scale. The finished products demonstrated similar mechanical properties (such as tensile strength), dielectric properties as well as heat dissipation properties as current plastic PCBs. No chemicals were used in the process, making the finished prototypes completely environmentally friendly. As the biodegraded PCBs were only tested in high humidity and high heat, the tests did not consider freezing conditions, which would need to be investigated further (Guna *et al.*, 2016). Unfortunately, this type of biodegradable PCBs are not yet commercially available.

However, there are other options, such as the wooden Soluboard produced by Jiva Materials (2020). The board is made of flax and thus completely soluble in water. Performing similarly to any standard PCB, the Soluboard prototypes is currently being evaluated by potential customers, with the approval process still ongoing due to the intense requirements by the industry standards (Jiva Materials, 2020). Flax being lightweight, the Soluboard could become a viable replacement for the PCB boards used in radiosondes, although this would similarly require additional testing in freezing conditions.

Recent research on biodegradable battery technologies shows promising results. With the lithium batteries used in radiosondes typically take hundreds of years to decompose (IBC-M, 2019), replacing them with biodegradable alternatives would be ideal. However, it is evident that the biodegradable alternatives cannot yet compete with industrial pure lithium batteries in terms of performance and cost. The biodegradable battery technology is still at its early phase, and it would likely take years before they become available, not to mention comparable in performance to the batteries used in radiosondes (Lee *et al*., 221; Delaporte *et al*., 2020).

Such systems have already been proposed to some degree, such as the high-performance fully biodegradable primary battery system designed by Huang *et al*. (2018), but the applications for those are ultra-low-power devices such as implants. Further research would be required to produce a battery in the scale of an AA battery standard, with similar output through the usage scale as a pure lithium battery (Energizer, n.d.).

While biodegradable electronics are still largely in development, there are emerging products which can assist in reducing the overall environmental impact of the radiosonde system. Biodegradable plastics can offer some degree of improvement over the current design, reducing the biodegradation cycle from hundreds of years to just few years or even few months. While further research is being conducted on producing more environmentally friendly products, switching to currently available solutions as early as possible would lead the way to further improvements and cut the amount of non-biodegradable plastic discarded in nature on a yearly basis.

The same applies to any component of the weather sounding system, including the outer shell and the parachute, which evidently could be replaced with biodegradable alternatives relatively soon. While rigorous testing is needed (and currently being made) to ensure the applicability of these solutions in the target environment, it could be argued that a marginal decrease in performance might be outweighed by the environmental benefits gained from switching to alternative materials. If a failure in the sounding equipment leads to waste with very little scientific gain, the barrier needs to be established where single failures are acceptable compared to the continued use of current plastic components. If governing agents such as the World Meteorological Organization are unable to dictate a threshold, manufacturers still have the potential to offer more sustainable alternatives and communicate the estimated failure rates (or success rates) of these products in relation to other products in their catalogues. This would enable those interested in using "biodegradable" radiosondes to conduct field-testing on prototypes and to develop the product further.

Annex III to the Protocol on Environmental Protection of the Antarctic Treaty (Madrid Protocol) requires any waste producer or disposed in Antarctic to be reduced as far as practically possible. This also means collecting the waste material, unless the removal process would generate a greater environmental impact than discarding the waste. In 2013, the Bureau of Meteorology in Australia conducted a balloon recovery mission in Antarctica, which demonstrated that recovering balloons in such adverse environment could be dangerous, if not impossible, in addition to generating pollution from the vehicles used for the recovery effort as well as possibly inflicting damage to the delicate landscapes and ecological communities (Australian Antarctic Program, 2013; J. Shelley, BoM, private correspondence, March 10, 2021). As such, a biodegradable solution would be ideal where safe recovery of the equipment is not possible.

Naturally, this change to biodegradable alternatives will eventually translate into further costs, which would need to be transmitted to the funding elements of the governing organizations rather than left to the shoulders of local meteorological organizations, as their budgets are restricted by the governments. For the local units, any added cost means less weather soundings per year, meaning less accurate weather forecasts. If the governments of the world wish to invest in sustainable solutions, this means increased funding for the organizations using those solutions. The global change from the current economic model, where cost is one of the main drivers of commerce, into a sustainable, environmentally responsible model inevitably means added costs for everyone, but any delay in switching to sustainable alternatives would evidently be more expensive in the long run (Ekins & Zenghelis, 2021).

# 4 ALTERNATIVE SOLUTIONS

Ideologically, the most environmentally friendly radiosonde would be the complete absence of a radiosonde. Hypothetically, this would mean either providing exactly the same data remotely or being capable of 100% retrieval rate. For the first option, remote sensing can either be conducted from ground level or alternatively from space above. For reaching a maximum retrieval rate, the radiosonde would either need to be a semi-permanent solution which is easily retrieved from the sky or the consumable-type sondes need to be easily tracked and retrieved after their mission ends.

## 4.1 Tethered sensing

The first weather observations from atmosphere in the $19^{th}$ century were conducted via tethered balloons and kites, accompanied by thermometers and barometers. However, by 1920 it had become clear that the length of the tether, as well as the capabilities of the equipment, were inadequate for providing accurate forecasts, thus paving way for the radiosonde (Maloney, 2017). The latest attempt to use a tethered solution as a permanent weather observatory was in France in the 1980s, using Kevlar cables for reinforcement. However, the experiment was a failure due to wind conditions as well as challenges with air-safety (Pommereau, 2015). One kilometer of a relatively light Kevlar cable weights 967 kilograms, requiring a massive balloon to keep in the air (DeMerchant, 2021). If the cable would break, it would generate a hazard to everyone within one-kilometer radius on the ground. Moreover, the balloon would be heavily influenced by winds and storms, causing added tensile strain on the cable.

While the weather events observed by humans usually occur in the troposphere, ranging from ground level up to 15 kilometers, they are influenced by changes in stratosphere (NASA, 2019). Moreover, the ozone layer sits at an altitude of 15 to 30 kilometers, occasionally even higher (EPA, 2021). Therefore, any weather observation would need to be able to reach the altitudes beyond 15 kilometers, making a tethered solution not viable as a replacement for radiosondes.

Nevertheless, tethered balloon systems are currently being used in mountain ranges, for example in Alaska, to complement the data obtained from radiosondes (Dexheimer, 2018). Their reach in terms of ground elevation is still limited.

## 4.2 Permanent platforms

One theory born from the brainstorming sessions with TRIZ students was the use of a semi-permanent balloon network, constantly floating throughout the atmosphere. The idea was based on Patent US2014015694A1 Incentivized Recovery of Balloon Materials, where a balloon would form a node in a network of several balloons. The network would constantly observe each other and if any of the balloons would cease to function properly, the landing location of the balloon would be determined by the other balloons in the network. This landing location would then be transmitted to the public as a recovery-assistance signal, indicating an incentive for recovering the balloon (Teller *et al*., 2012). For prolonged use of such a network, any fallen balloon would need to be replenished from balloon launch locations around the globe.

If the balloon network is composed of large zero-pressure balloons, which can operate days or even months in the atmosphere, it might be theoretically possible to navigate the balloons using prevalent wind conditions at specific altitudes for moving the balloon around. This can be achieved by controlling the pressure of the balloon, with an on-board gas reserve and gas valves within the balloon (Pommereau, 2015). This navigation could hypothetically also be used by the falling balloon to reach a predetermined designated location (Teller *et al*., 2012). However, if a balloon has already started falling, it would not be able to use any wind conditions or rotation of the Earth to its advantage in altitudes above the balloon. Moreover, the prevailing winds caused by the Coriolis effect would effectively conglomerate the balloons in the network along specific tracks, which would be hard to combat even with constant replenishment of fresh balloons (National Geographic, 2021).

Nevertheless, Loon LLC, a subsidiary of Alphabet Inc., had been able to produce such a network at an altitude of 18km to 25km, to generate an aerial wireless network to be used to access internet in remote locations. The company was able to build a full-sized network over Kenya, comprising of 35 balloons covering an area of 50 000 square kilometers (Peters, 2021). The balloons relied on wind data produced by the National Oceanic and Atmospheric Administration (NOAA) in the United States, but also contributed to the same data model (Parker, 2013). The project was finally shut down early 2021, as being too expensive to operate (Peters, 2021). However, the balloon network would not be able to provide the same data as radiosondes, simply because in order to stay in designated course the balloons cannot drop to lower airstreams or raise to higher ones to take measurements, which would cause them to drift out of position. If allowed to do so, the balloon network would need to be fully synchronized, where each balloon would find an optimal airstream to cover the area left by another balloon. This would require knowing the prevailing wind conditions before the measurements are taken, which means that to navigate the balloons would need the information they are being sent to investigate. In theory, it might be possible to use static electric profilers on the ground to predict wind conditions at certain heights and thus assist the network from spinning out of control, but as evident in the chapter below, these profilers and the remote sensors are not yet capable of reaching the required altitudes above 15 kilometers.

Moreover, the balloon network would not be able to be self-sufficient, requiring other weather observation methods such as the abovementioned remote sensors, thus generating a mass of cost. A study by James Burr in Australian National University College estimated the total cost of a Loon network over five years of operations approximately 40318 AUD / 25822 EUR per balloon (Burr, 2015). With a total surface area of 510 million square kilometers, to cover the entire Earth with a balloon network similar to the Loon network would require approximately 357 000 balloons. The total cost of such a network alone would therefore be approximately 9,2 billion euros over five years of operations, not including the remote sensors and launch facilities on the ground. In comparison, with one million radiosondes being launched every year globally, with an approximate cost of 100-300 euros per launch (T. Laine, FMI, private correspondence, November 4, 2021), the total worldwide cost of the current solution over five years is approximately one billion euros. Even if the costs per network balloon could be reduced to half of the costs associated with Loon, the overall cost of the total network would exceed five times the costs of the current radiosonde solution, with questionable benefits to the accuracy of the weather data. Moreover, being large zero-pressure balloons, added costs would need to be allocated to the retrieval of any fallen node. The main benefit would be the almost complete lack of environmental waste, if properly maintained.

## 4.3 Remote sensing

### 4.3.1 Electric profilers

The National Oceanic and Atmospheric Organization (NOAA) have been using atmospheric profilers to measure wind speeds and directions in the atmosphere among 35 field stations around the United States (O'Shea *et al*., 2014). These profilers are essentially Doppler radars utilizing different frequency bands to cover different layers of the atmosphere. The most expensive equipment has been able to cover heights up to 16 kilometers, therefore barely reaching the lower boundary between troposphere and stratosphere, while the most commonly used profilers can take measurements up to 8 kilometers (NOAA PSL, n.d.). While these profilers definitely cover the most crucial part of the atmosphere in terms of weather events, they cannot compete with radiosondes in providing in-air, in-location data from ground level up to mid-stratosphere.

Wind profilers can also give virtual temperature measurements, which are not capable of detecting temperature and humidity structures in detail (Brown, 2017; Stankov *et al*., 2003). Therefore, for remote temperature sensing another type of sensor is needed. While remote temperature sensing can be achieved from any surface, the measurements from the thin air of the stratosphere are easily affected by the air mass of the troposphere, when using ground-based solutions. To complement the ground sensors, ESA and NASA together with the meteorological organizations have launched satellites, which have other limitations, as discussed in the following chapter.

Any remote sensing is based on assumptions rather than precise measurements, which can cause limitations towards accurate weather predictions. The same limitations apply to remote humidity and remote air pressure, where ground-based remote sensing is not accurate enough in the range of 15 to 30 kilometers to provide reliable data for weather forecasting (Seman, 2020; National Research Council, 1997). Therefore, while remote sensors and profilers on the ground can provide relatively accurate data from ground to the upper limit of the troposphere, they are not adequate enough to cover the entire region affecting the weather conditions, limiting their use as a direct replacement to radiosondes.

### 4.3.2 Satellites

Over the past couple of decades, satellites have been utilized to cover the gaps left by the ground-based sensors. There are currently over nine hundred Earth observation satellites in orbit, taking different remote measurements of the ground or the surrounding atmosphere (Mohanta, 2021). The satellites cover almost the entire globe, with geostationary satellites covering longitudinal and the satellites in polar orbit covering latitudinal slices of the Earth.

For example, the Aeolus mission was launched in 2018 to measure wind profiles around the globe. The entire satellite carries just one instrument, a Doppler wind lidar, observing the wind conditions in the atmosphere. The mission had a 3-year lifespan, with a total cost of 451 million euros. Comparing to the global radiosonde operations, Aeolus was 30% cheaper, however covering only 20% of the entire data set. Moreover, the mission requirements documentation indicates that Aeolus was designed to “provide accurate wind observation profiles in clear atmosphere, within and below optically thin clouds, and at the top of optically thick clouds” (ESA, 2016, p.22). While being usable in relatively clear-sky conditions, the applicability of Aeolus to replace radiosondes in rain conditions was limited.

The Global Navigation Satellite System Receiver for Atmospheric Sounding, or GRAS, was an instrument for measuring atmospheric temperature and humidity, launched along the three Meteorological Operational (MetOp) satellites in 2006. The instrument follows a constellation of 24 GPS satellites, using Doppler shift of the received signal to determine the atmospheric conditions through which the signal has passed, during occultation. With these measurements, the GRAS instrument is able to produce approximately 500 profiles of atmospheric temperature, humidity and pressure every day, even above sea level (ESA, 2006). GRAS is one of the most successful instruments launched to space, with 80% of its data being used for weather prediction models by the Met Office in the United Kingdom. However, this is not the case with most satellites, as only on average 20% of satellite data is assimilated to be used for weather forecasts. Many of the satellites have issues with cloud penetration, horizontal error correlations between measurements, and difficulties in using the data over land or sea-ice. Therefore, most measurements from these satellites come from the upper atmosphere, as emitted by the elements below (Met Office, 2016).

Other satellite systems and meteorological organizations have experienced similar difficulties in utilizing satellite data. A study in collaboration between universities in China and Greece has proposed a temperature and humidity profile retrieval system utilizing the Chinese Fengyun-3D Hyperspectral Infrared Radiation Atmospheric Sounding (HIRAS) satellite. The system has been designed to be used only during clear-sky conditions, with cloud coverage posing limitations to data and prediction accuracy (Zhu *et al.*, 2020).

While satellites can offer complements to the ground-based remote sensors and profilers, these two methods of measuring the atmosphere from two opposite directions still cannot compete with the sheer accuracy of having the sensors directly within the target environment, logging real-time data, rather than making estimations based on data around the target environment with gaps in between. This is also evident in the Met Office's Fact sheet 18, indicating over 95% assimilation of radiosonde data for weather prediction modeling (Met Office, 2016).

Furthermore, the economic gains from accurate weather predictions have been measured by Hautala and Leviäkangas (2007) to exceed five times the cost of current weather data collection operations. Businesses and governments rely on this data to produce services for traffic, logistics, construction, property management, energy production and agriculture, in addition to preparing early for natural catastrophes. Without accurate weather predictions, the economic impact would be enormous (Hautala & Leviäkangas, 2007). This, together with the abovementioned limitations of any other kind of weather data collection method, makes the radiosonde an irreplaceable element in the whole weather data system.

## 4.4 Retrieval

If a radiosonde cannot at the moment be completely replaced by other remote sensing technologies, the environmental impact of the equipment can only be minimized either through complete biodegradability of the entire product, which as concluded before is not possible, or a full retrieval model, where every sonde sent to the sky is returned to the sender.

For the latter proposal, this would mean either a way to ensure the radiosonde is returned to the launch station after landing, or for the radiosonde itself to fly back to the launch station, in which case a self-navigating glider could be used. Such gliders have already been used for few experimental flights in Sodankylä, Finland. The payload was attached to a winged glider developed by Meteolabor. The aircraft uses GPS coordinates at launch and at the point of balloon burst to calculate a trajectory towards the launch site. Because of weaker wind conditions within stratosphere, the return would need to take place while above 10-15 kilometers, which has a limited air pressure to generate lift for the glider. Closer to the ground, the winds which carried the balloon away from the launch site would affect the glider as well, generating problems in reaching the site, while the glider spirals down. The study found that sometimes the glider would land a few kilometers away from the launch site, thus requiring a separate pickup attempt, somewhat nullifying its usability (Kräuchi & Philipona, 2016). This can be overcome by preconfiguring several possible landing sites and using on-board robotics to maneuver the glider to any of them, depending on weather conditions (Win *et al.*, 2021). This would naturally require additional logistics for returning the gliders daily to the launch site. Moreover, the cost of the glider would be several thousand euros per unit, with additional costs involved in pre-configuration for each flight, maintenance and occasional recovery from wilderness. The glider itself weights 1,9 kilograms, thus requiring larger balloons and more gas to be used, rendering itself unviable to be used with a 75-gram radiosonde.

The most useful option, therefore, would be to return the radiosonde to the sender after it has landed. In order to do so, a tracking and retrieval method would need to be applied to the daily sounding operations. While radiosondes can be re-used, which is common practice in the USA and was historically in Switzerland, the Vaisala products utilized by meteorological organizations worldwide are not currently refurbished. Future models in current development by radiosonde manufacturers may have replaceable sensors and recalibration capabilities, although there are concerns for the economic viability of such activities as well as the durability and performance of the sensors after being replaced or refurbished (D. Edwards, Met Office, private correspondence, February 24, 2021). Nevertheless, the need to reduce the environmental impact of the radiosondes calls for retrieval of the sondes, and refurbishment if possible to reduce the emissions caused by continuous manufacturing of complete products.

### 4.4.1 Tracking

In order to retrieve radiosondes on a larger scale than being accomplished today, the tracking capabilities of the radiosonde would need to be improved. The use of descend data has been enabled quite recently by the manufacturers, with many of the countries worldwide still only receiving the signal on the way up and thus completely missing the second half of the sounding, including final coordinates (D. Edwards, Met Office, private correspondence, February 24, 2021). Many European countries have enabled this, through both public pressure from the amateur community as well as a request from the scientific community to gather more data (Vaisala, private correspondence, June 11, 2021).

The radiosonde systems use radio frequencies 1680 MHz or 403 MHz, which are reliable and can easily cover the required distances (Overlook Horizon, 2020a). Amateur radio frequencies cover the bands of 144,39 MHz in the North America, 433,8 and 432,5 MHz in Europe and 145,175 MHz in Australia (Singam, 2019, p.2). However, because of the curvature of the Earth, the launch stations typically lose communications with the radiosonde at an altitude of 500-1000 meters (T. Laine, FMI, private correspondence, November 4, 2021). The winds at ground level, as well as the trajectory of the landing, can drift the falling radiosonde several hundred meters away from the last known position, thus rendering a retrieval effort ineffectual when relying on the current descend data alone. In order to enable a successful retrieval, added tracking capabilities are needed.

There are, in essence, two ways to locate any object; external tracking, which in the case of a radiosonde means a network of ground receivers tracking the radio signal emitted by the sonde, or internal tracking, meaning the equipment itself successfully communicates its own position using alternative communication methods. For external tracking, added costs would be inflicted on the existing infrastructure in the form of added receivers, and for internal tracking the operational cost of the radiosonde would be increased due to additional components. As stated by David Edwards from the Met Office in United Kingdom; “Radiosonde programmes are expensive to run, with much of the cost coming from consumables. The cost of an additional transmitter might be relatively small, but even 20 € may cost as much as the balloon and lifting gas used, so it is not trivial if thousands are being launched annually. It would be key to be able to balance any additional cost with measurable benefits, in order to secure additional funding, otherwise the increased costs may necessitate fewer launches.” (D. Edwards, Met Office, private correspondence, February 24, 2021)

External tracking

For successfully tracking a radiosonde’s built-in signal to the ground level, a network of radio receivers would need to be established around the globe. The receivers would each provide coverage similar to a mobile phone network, although their function would be to only listen for the incoming radio transmissions. Officially this has not been attempted yet, although METEO FRANCE and Meteomodem have implemented a second receiver on the other side of a mountain at one site, to enable coverage in an area where line of sight would otherwise be blocked (D. Edwards, Met Office, private correspondence, February 18, 2021).

An amateur network of such receivers, the Automatic Packet Reporting System (APRS) have already been established in 2006 to enable tracking of any radio signal, including radiosondes (APRS, 2021). Moreover, the United Kingdom High Altitude Society (UKHAS) released the SondeHub Tracker website in 2021 to track radiosondes specifically (UKHAS, 2021a), as an extension to their existing HabHub tracker, which visualizes the location of any system suitable for their protocol. Finally yet importantly, Radiosondy.info (Lewiński, 2021) displays the same data as the previous two, but also feeds information into the APRS network. All these networks rely on receivers set up by radio amateurs around the world, with ground coverage dictated by the volunteers building and running the receivers. Often these receivers are based on single-board computers accompanied by simple radio equipment or USB modems, with software analyzing the signal and transmitting the data over internet to these service websites (UKHAS, 2016; Akerman, 2018). Radiosondy, established by Michał Lewiński in 2017, specializes in teaching its user base on how to build ground receivers and it has successfully gamified the hunt for lost radiosondes. By November 2021, almost 40 000 sondes have been retrieved and reported found since the launch of the website (Lewiński, 2021).

While APRS, HabHub and Radiosondy have been successful in tracking the radiosondes, they are still based on a community of individual users on their spare time, limited by their availability and the performance of their equipment. Moreover, the receivers can vary from large radio towers to small models sitting on windowsills, therefore generating gaps in coverage. For professional use, these amateur networks would need to be replaced with an official one.

Naturally, creating such a network would generate costs in relation to determining ideal network node locations, capital investments in equipment as well as ongoing maintenance. In terms of node locations, the current ground weather stations or mobile network towers could offer ideal sites. The ground-level automated observatories generally have good coverage of the country, as evident in Figure 4. However, these are limited by the fact that the stations and their equipment are relatively close to ground, which can have issues with planet curvature and line of sight being blocked by terrain. However, compared to the current model where the launch station is the sole receiver of the radiosonde signal, any added receiver would bring benefits to the model. These network receivers would not need to be as large or sensitive as the current equipment, considering that a low-cost network of receivers would be more than enough for the task. By being closer to the payload, the nodes could handle the transmission processing with small single-board computers.


**Figure 4**: FMI ground weather stations in southwest Finland (private photograph at FMI Jokioinen Observatory, November 4, 2021)

With an approximate distance between the ground stations being 50 kilometers, receivers installed in every ground station would enable tracking of the radiosonde to approximately 50-

100 meters in elevation above the ground, depending on terrain conditions (More, 2019). Forests generally do not block radio signals, but can affect its quality (Kingsley, 2002).

The network tracking can be improved by installing the receivers higher from the ground, for example in mobile network towers. These towers have much higher density than the FMI weather stations and are approximately 50-150 meters high in rural areas (CellMapper, 2021; DNA, private correspondence, May 27, 2021). If a receiver would be installed on grid towers at 50 kilometers distance from each other, at an average height of 50 meters, they would be able to track the radio signal all the way to the final landing position. Reducing the height to 40 meters would require a maximum of 45 kilometers between the receivers, less to account for terrain elevation differences (More, 2019). In most cases the top of the tower is already occupied by the telecommunications equipment, but there is space available below these. The price for renting space from these towers is dependent on height, available space in the equipment compartment as well as power requirements of the receivers. Moreover, the installation and maintenance services would need to be purchased separately (DNA, private correspondence, May 27, 2021). Due to the public nature of this research, the actual prices were not provided. However, if the production costs of a cellular tower are approximately 150 000 euros (Liebman, 2018) and comparing this to the rental prices of industrial or commercial space in Finland, the cost of tower rental, especially in the lower parts of the tower, could be estimated approximately 400 euros per tower per month, including maintenance. If towers with 50-kilometer separation were used, covering the entire Finland would require 42 towers in total. With each installation costing, as a ballpark estimate, 300 euros, plus the cost of the equipment being, let us say, 300 euros for a decent single-board computer-based solution, peripherals included (Raspberry Pi Foundation, n.d.), the once-off costs per unit would be approximately 600 euros, up to 1000 with added labor costs, testing and other costs included. Every unit would have at least a 3-year lifecycle before being replaced by a new one. With the above hypothesis regarding the monthly costs of the towers as well as the once-off costs, the total cost of receivers covering the whole Finland would equal approximately 640 000 euros for the period of three years. If installed on weather stations alone, the costs would be much less, up to 186 000 euros for the three-year period, with 100 euros per unit per month allocated to maintenance. However, with the latter option the accuracy of the final landing position would suffer slightly, from few meters up to a hundred meters depending on wind conditions, possibly even more.

While the specific costs of radiosonde launches in Finland were not publicly available, using the 100-300 euro bracket as a base line, with 2190 launches per year, the cost of additional ground receivers would equal approximately 10-20% increase in annual budgets (T. Laine, private correspondence, November 4, 2021). While it might seem excessive to cover the entire country with receivers, in order to have a globally applicable solution, as radiosondes from neighboring countries often drift across the borders, an internationally comprehensive network would be required. For pilot projects, though, a regional network should be sufficient, with 4-8 receivers covering a range of approximately 100 kilometers around the launch site. Any addition to the current single-tower receiver infrastructure would bring benefits. Additionally, if receivers would be added to every new ground station, the allocated installation and maintenance costs would be reduced.

Finally, satellite tracking could provide highly accurate location services, wherein satellites would track and communicate the location of the radiosonde to the launch station. However, the current cost of these systems is out of reach of daily operations, with Iridium satellite network requiring, for example, a RockBLOCK 9603 SatComm module costing over 200 euros (Nootropic Design, 2021), and the Globalstar STX3 Simplex transmitter costing over 100 euros per unit (OSAT, 2021a), plus a subscription model for each transmitter costing 10 euros a month (OSAT, 2021b). Some weather balloon flights, especially among the amateur community, use a SPOT satellite tracking (Overlook Horizon, 2020b), which is also relatively expensive, costing over 100 euros per unit but does not require a subscription (SPOT, 2021). These satellite messaging solutions require a clear view of the sky and do not operate if landing upside down, therefore requiring additional gimbals to keep them upright. Therefore, their use would effectively double or triple the current cost of the radiosonde operations.

### Internal tracking

Satellites could in theory provide assistance for transmitting the signal from the radiosonde onwards. As the radiosonde has a built-in GPS module to determine its location, it would only need to communicate this data, for example via communication satellites. The majority of communication satellites are located in geostationary orbits at an altitude of 35 000 kilometers, in order to provide a permanent relay point in the sky in relation to the ground level (Union of

Concerned Scientists, 2021). This requires larger directional antennas with sufficient transmission power, thus not applicable for radiosondes.

The closest possible satellites suitable for communication relay are currently being deployed to a minimum altitude of 160 kilometers, revolving around Earth once every 90 minutes (IADC, 2007; Ainoa, 2018). Depending on the model, the radiosonde transmission power is approximately 300 milliwatts (NOAA, 2016), which is just at the edge of range for reaching these satellites, although with the use of RB31 directional antenna the range can be extended to 350 kilometers (M. Lehmuskero, Vaisala, private correspondence, March 11, 2021). The RB31 has been designed to be used with receivers rather than transmitters, due to its size (Vaisala, 2017b). Moreover, because of their fast rotation, the lowest satellites constantly leave gaps in their coverage, and with the whip antenna of a radiosonde providing wide horizontal coverage but poor vertical one, a small directional antenna would be needed onboard the sonde, pointed up to the satellites while still leaving momentary gaps in the coverage (Ainoa, 2018; Zufferey, 2013). As the Low Earth Orbit (LEO) communication satellite network is still in its development phase, for the most effective communication, two different antennas would be required, with the standard omnidirectional whip antenna of the radiosonde providing horizontal coverage and the directional antenna vertical. This would require directing communications to both of these antennas as well as doubling the power reserves of the radiosonde. The added weight from the extra batteries as well as the directional antenna would inflict currently unknown added costs.

The LEO satellite network could still be a viable option in the future when the network expands and becomes economically feasible. If the communication network becomes dense enough, it has the potential to replace the current radiosonde communication method, wherein a directional antenna pointed up would be the only antenna required for transmitting the data. As such, it would function even at ground level, as long as the directional antenna is pointed to the correct direction. Upon reaching the ground, the final transmitted coordinates would be from ground level up to several meters before landing, depending on conditions.

The antenna design could be improved further by replacing the omnidirectional whip antenna or any parabolic directional antennas with a new design derived from the Pagoda-2 antennas recently developed for drones. The Pagoda has a similar donut-shaped radiation pattern as the omnidirectional one, but covers better the vertical axis, resulting in a pattern of almost a complete sphere. The antenna was originally designed to be used with frequency 5,8

GHz, as a circular polarized antenna, which left no gaps in coverage in any direction. This enabled drone pilots to receive video signal from the drones without interruption, thus making it possible to use first person view (FPV) to fly the drone. The directional antennas used in communication satellites should be able to pick up the signal regardless of polarization, if the Pagoda antenna would be redesigned for lower frequencies and longer ranges (Sam, 2017; HobbyKing, 2018). This would effectively allow a single type of an antenna to be used for both satellite as well as ground-level communications. The only issues might arise from the current range and weight of these antennas, which would need to be investigated and developed further.

For heavier manual operations such as ozone sounding or radiation field research the meteorological organizations use Mode S Out transponders, such as uAvionix ping200Sr, which effectively allow the balloons to be tracked by radar and air traffic control systems (R. Kivi, FMI, private correspondence, November 26, 2021). These transponders broadcast their IDs, GPS data and velocity at predefined intervals to the ADS-B receivers onboard aircrafts and airports. This enables both collision avoidance with aircrafts but also effective tracking of the balloons once in the air. However, in essence these transponders act similarly to radiosondes, with the same issues with radio signal coverage at ground level. Moreover, the cost of a single transponder is approximately 4000 euros, making them 20-30 times more expensive than radiosondes (uAvionix, 2021). Therefore, they are only deployed to more expensive flights, where public radar tracking and retrieval of the equipment is crucial.

Bird tracking uses an affordable internal tracking method to resolve flight patterns of birds. The University of Amsterdam has been able to build an effective tracking system with miniature GPS trackers attached to birds (Bouten, 2009). However, the data relay takes place only when the birds fly back to their nests or the local colony, with a maximum VHF transmission distance of one kilometer (W. Bouten, Universiteit van Amsterdam, private correspondence, May 22, 2021; Kauth *et al*., 2020). However, another bird tracking method uses Argos Platform Transmitter Terminals, which transmit data to the Argos satellites devoted to environmental studies. The terminals emit a standard signal, which is picked up by the Argos satellites, and using Doppler effect calculations the ground stations can calculate the location of the terminal. Unfortunately, this method is accurate only up to 600 meters (Atkinson, n.d.).

One possible solution could be the ICARUS Initiative, or International Cooperation for Animal Research Using Space, where the International Space Station (ISS) will act as a relay for tags coming from transmitters attached to birds. The data will be hosted by Movebank, which is a free online bird-tracking database. Unfortunately, the Icarus project is not yet in operation and with the decline of the ISS, the project might have to soon find other alternative relay stations (Max-Planck-Gesellschaft, 2021).

Finally, GPS coordinates are occasionally transmitted via mobile phone networks, which are accurate down to a meter or less, but require a network coverage to operate. With constantly-moving birds, this can be achieved at relative ease, but it may pose challenges for radiosondes.

If the focus is on retrieving the radiosonde, it would be logical to assume that any location that is relatively accessible would also have mobile network coverage. Of course, this may not be the case in all regions and scenarios, for example if the radiosondes tend to drift to sea, but for populated areas which are also focus points for weather forecast data collection, a mobile network can be considered a standard part of the local infrastructure. According to statistics, in 2020 as much as 83 percent of the global human population had access to 4G network, with 94% being covered by any mobile standard (O'Dea, 2021; TheGlobalEconomy, 2021). 71% of the world is covered in water (American River Water Education Center, 2020), therefore demanding biodegradable solutions for the balloons drifting to sea, but with most upper-air observatories based on land and the expected travel distance being 50-200 kilometers, the landing location of the radiosondes would also be either on land or in water areas still somewhat reachable by mobile networks. Naturally, this assumption excludes observations conducted in remote locations such as Antarctica or Greenland. Mobile phone towers generally have an unobstructed range up to 70 kilometers (Kanchwala, 2021), thus making the technology a viable option to be used also over water bodies, relatively close to land. Any radiosonde drifting beyond that range can be considered unrecoverable in any case, unless carried to shore by tide or ocean currents, at which point any power reserve available for communication would have been exhausted.

GSM tracking solutions have been successfully deployed for all kinds of ground-based systems. It can be used to track baggage through airports (Rathore, 2015), track vehicle movements (LiveViewGPS, 2021) as well as for bird tracking, as described above. Previously, the major limitation in using the mobile network for tracking weather balloons has been the scarcity of network coverage (Overlook Horizon, 2020b), which as evident above has increasingly been resolved by the service providers around the globe. Moreover, the laws and regulations have historically prevented airborne use of mobile phone technology, which is no longer entirely the case in most countries. The Federal Communications Commission (FCC) in the US still prohibits the use of cellular telephones while airborne (FCC, 2010). Similar laws exist in other countries; for example, in Finland Traficom rule 15 limits the use of airborne mobile transmissions to governmental administrative duties only or for providing emergency services. An additional permission is required if the frequencies used fall within the ranges of 2300-2320 MHz, 24,250-25,100 GHz and 25,100-27,500 GHz (Traficom, 2021). However, 2G uses 1800MHz, 1900MHz, 850MHz and 900MHz, 3G uses 800 MHz, 850 MHz, 900 MHz, 1700 MHz, 1900 MHz and 2100 MHz bands (GSMA, 2017) and 4G uses a variety of bands ranging from 450 MHz up to 5,9 GHz (Halberd Bastion, 2021), therefore generally falling outside of these limitations. 5G technology is generally short-ranged, approximately 500 meters, compared to the older-generation technologies, thus ill-suited for tracking radiosondes in the wild (Jones, 2017).

In the USA, the FCC regulation is often circumvented through additional licenses acquired by government and emergency services as well as airlines, and can in fact be considered a relic of a time when the effects of airborne mobile communications were not well known. The primary fear was that the use of mobile phones would interfere with the navigational systems of airplanes, especially causing instrument failures as well as causing additional work for pilots in crisis situations when communications or navigation would be disrupted. Furthermore, there were concerns that the unobstructed airborne phone signal would reach several towers and therefore cause unnecessary overloading of the tower network. However, with modern technologies, these concerns have been proven marginal, with no effect on the aircraft nor the network. An investigation by the Electronic Communications Committee in 2020 analyzed the impact of aerial user equipment utilizing mobile communications networks and concluded that LTE (4G) networks can easily handle few aerial devices (ECC, 2020). Older technology may still experience occasional disruptions, but by upgrading the airplane fleets and tower networks, these issues are resolved (Menza, 2019; McMahon, 2008). The European Union Aviation Safety Agency (EASA) lifted the ban on mobile phones on board aircrafts in 2014 (EASA, 2014), with the FCC still considering to follow suit (FCC, 2015). Nevertheless, FCC has approved the 450 and 800 MHz frequency bands to be used for air-ground radiotelephone services (FCC, 2017), to be used by commercial airlines, and as mentioned above it is possible to get a waiver from FCC if needed, as well as from any local communication agency around the world, especially for official purposes.

While radiosondes would not generally fly anywhere near airplanes, therefore avoiding any issues with any navigational systems of those planes, the same rules and regulations regarding air safety apply to them. Even though the main reason for prohibiting airborne mobile technology use was to protect the instruments on board airplanes, which a radiosonde does not have, the comprehensive ban of this technology along all forms of airborne vehicles, manned or not, generates issues with using GSM tracking with radiosondes. For wider use especially in the USA, a separate license would need to be applied for or the regulation otherwise circumvented by technological solutions.

The easiest technical way around the problem would be to disable the GSM tracking system while off the ground, which in turn saves battery. However, this generates further complications. How would the radiosonde know it is not on the ground? The on-board GPS tracker can only measure its altitude in relation to sea level but it cannot tell if the device is elevated from the ground. While most mobile phones can do this, they rely on elevation data fetched through internet, to calculate the distance to the ground. Radiosondes do not have this option, requiring a standalone solution. One possible option would be to have the elevation data stored onboard the radiosonde, downloaded from, for example, USGS (USGS, n.d.) which gives arc-second resolution of 30 meters. These files are generally compressed and large, containing terabytes of data, and are usually made of images collected by the Japanese Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) system onboard satellites, combined with data from the National Aeronautics and Space Administration (NASA). According to NASA, this requires data processing beforehand in order to package the data in a user-friendly format, to be usable as a reference table for microcontrollers. At the moment, very few organizations store the elevation data in table values (Earthdata, NASA, private correspondence, Match 9, 2021; Cole & Buis, 2011). Such organizations include, for example, Google and Wolfram, both of which require investments in purchasing these data sets (Google Maps Platform, 2021; Wolfram Research Europe, private correspondence, June 11, 2021). Outdated versions of elevation maps can be obtained from the Virtual Terrain Project (2013) or ViewFinderPanoramas (2014) but have the same limitations as mentioned above. With these solutions requiring large permanent storage capabilities onboard the radiosondes, they are not feasible for everyday operations (Earthdata, NASA, private correspondence, Match 9, 2021).

Other possible methods for detecting the ground would be to use radar technology, such as ultrasound or motion sensors. Moreover, accelerometers could be used to detect when the radiosonde stands still, therefore presumably on ground level, allowing GSM transmissions to occur. However, these sensors add complexity to the system, with radars requiring specific directional sensors that may be of no use if the payload would fall upside down. Any added complexity to the tracking system generates a point of failure, considering the extreme conditions in stratosphere, which has a considerable potential to prevent reliable operations.

Therefore, the most applicable solution would be to apply for the abovementioned waiver, if being obstructed by legislation, and enabling the GSM trackers' telecommunications modules only below specific thresholds, thus relieving the potential stress to tower networks. Naturally, such thresholds would have limited usability in mountainous regions, but such artificial limitations in software can easily be reprogrammed to match the launch station. For example, in Finland, the GSM module can be programmed to activate and search for towers only below the altitude of 2000 meters. This is common practice with amateur GSM trackers being used with high-altitude balloons in the USA. 2000 meters can be considered a safe distance, with no interference to any other airborne device as well as no noticeable disruption to the networks below (Walker et al., 2016; Akerman, 2017). Therefore, as an addition to the current GPS-radio tracking system, a GPS-GSM tracker could offer a cost-effective yet highly accurate data communication method from ground level up to the altitude where the standard radio transmission gets obstructed, thus complementing the system well. These systems have already been successfully used in Finland, with TK102 GPS-GSM trackers being attached to larger payloads (R. Kivi, FMI, private correspondence, February 18, 2021). Such trackers are relatively costly, approximately 70 euros per unit, although reusable (TeknikProffset, 2021).

Consequently, an economically feasible GSM tracker would need to be developed, suitable for daily radiosonde operations, where the loss of a tracker could be included in the annual operational budget, although being reusable once found. Moreover, the tracker would need to be designed to have minimal impact on the environment, as any added component to the current radiosonde model increases the overall impact of the whole system, unless those components significantly increase the retrieval rate. Finally, these trackers do not need to be rated for atmospheric sounding, in terms of their capability to withstand the extreme conditions in the air. There are no cellular networks in high altitudes, and most low-cost GPS modules typically lose contact at 18 000 meters (Seidle, 2010). Neither of these are needed, as the module would only need to be able to transmit the last few hundred meters of the journey down. Therefore, by programming the tracker to reboot in case of systems errors via a watchdog service, or in case of a power failure to boot up as soon as power is restored, and automatically start the service, the tracker would be perfectly able to perform its intended task. Such a module would enable an effective GSM tracking solution, as a complementary system to the current radiosonde tracking method.

Lately, the emergence of power-efficient communications technologies, such as Low-Power Wide-Area Network (LPWAN), have enabled economically feasible Internet of Things (IoT) communications and tracking systems. One common use of the LPWAN technology is LoRa (*id est* Long Range) (Bor, 2016), with modules becoming available for the wider audience at relatively low cost, although being patented. These modules consume very little energy, requiring only very simple type of microcontrollers to operate and very light battery reserves. With a LoRa module costing merely 5 euros, they are ideal components of any IoT project (Raj, 2019; Benavides, 2019). They have relatively good reach, being capable of 7-kilometer ranges while indoors and 10-20 kilometers in line-of-sight (Murata, 2021). Utilizing the LoRaWAN communications protocol, some LoRa modules have been able to reach even 766 kilometers. However, this required specialized equipment and antenna solutions aboard weather balloons (TTN, 2019). In terms of radiosonde tracking, however, they possess the same challenge with the curvature of the earth. The technology is still based on radio signals reaching a receiver, similarly to the current radiosonde signal being transmitted to the launch site. Once being blocked by terrain the communication is lost. Therefore, as an alternative to current radiosonde technology, they could only be potentially used as a replacement and therefore a low-power version of the current radio technology, with no added benefits to the communication of the final landing location. Moreover, LoRa technology is relatively new, with wide areas of no coverage in terms of amateur receivers (TTN, 2021). It would therefore be easier to invest in the networks of the current radio technology, rather than replace both the receivers and the transmitters to LoRa with very little added benefit.

Finally, outside of any external or internal tracking methods, a prediction model can be used to estimate the final landing position, based on available weather forecast and location data. Such a prediction engine exists, run by UKHAS (UKHAS, 2021b). The model downloads weather forecast data from NOAA Global Forecast System, covering the different altitudes, and using coordinate, ascend rate, descend rate and burst altitude inputs from the user calculates a prediction on where the payload will approximately land based on the available data. The University of Wyoming and University of Southampton have also launched similar services, but with HabHub dominating the market, these sites have been taken out of service (UKHAS, 2020). Notable with the prediction models is that while they can give precise estimates on where the balloon will land, the actual behavior of the payload while ascending and descending depends on momentary weather conditions, balloon gas fill, payload mass and other variables not currently covered by such software. Therefore, their estimates are simply approximations and cannot be used to accurately pinpoint any payload. Instead, their use relates to picking the optimal launch windows, during which the payload could be expected to fly to the desired direction and land within the target region.

A more accurate prediction could in theory be calculated from the final trajectory of the radiosonde. By using actual flight data, the descent trajectory combined with the aforementioned information from NASA/ASTER regarding ground elevation could be used to pinpoint the actual landing site. An external network of receivers could be used to improve the accuracy of the prediction model by incorporating signals from the crucial final few hundred meters. However, because the landing sites could be dotted with tall trees, buildings, power lines or any other unpredictable obstacle, to which the radiosonde might or might not bump on its way down, it could be challenging to generate a model accurate enough to be used for indicating the final landing position. Therefore, a prediction model could be expected to be accurate down to an area ranging from a couple of meters to few dozen meters in diameter. Whether or not this is accurate enough for retrieval depends largely on the environment around the coordinates. With dense tracking networks as well as high-quality ground elevation and prediction modeling, these challenges would be mitigated.

### 4.4.2 Reporting and collection

The current amateur tracking networks, namely APRS, HabHub and Radiosondy, all host a map service, to allow balloon operators to easily track their flights and eventually find the landing location. From the map objects, they can get useful information regarding the tracked vehicle, such as coordinates, direction, altitude and time of communication. Naturally, these visualizations are helpful in aiding the operator to the final coordinates, but any service capable of showing specific landing coordinates on a map would be enough to determine the location of the payload, such as Google Maps (Google, n.d.).

In 2013, the Finnish Meteorological Institute begun hosting their data openly, free to be used by the public. The Open Data Download Services, utilizing Open Geospatial Consortium (OGC) Web Feature Service (WFS), can be used to access the database in machine-readable Geography Markup Language (GML) format. In practical terms, any device can generate a query to the interface to pull the specific data from the database. A typical query for the data would look like this:

http://opendata.fmi.fi/wfs?service=WFS&request=GetFeature&storedquery_id=fmi::observations::weather::sounding::multipointcoverage&starttime=2021-05-10T00:00:00Z&endtime=2021-05-11T00:00:00Z

This query will fetch all the radiosonde weather sounding data for May 10, 2021. For example, position data may look like this: 60.81397 23.49825 104.6 1620604800. Notable is that the dataset uses epoch timestamp format, which can be converted to human-readable format once the data has been downloaded. In the above example, the epoch timestamp 1620604800 equals May 10, 2021 12:00:00 AM GMT. Naturally, the database is not visualized but intended for query-type executions as well as data processing (FMI, 2013).

As a public organization, the data gathered by the organization should also be public, available to those who need it, which is why FMI originally published the data. Being funded by the public, the core duty of FMI is seen to serve the public and therefore be transparent in its operations as far as reasonably possible. By 2017, the portal had over 10 000 users, pulling 9,6 queries every second, indicating a demand for such data (Vallinheimo, 2017). New innovative commercial services has been built around the data (Gispo, 2021), with universities using it for educational purposes as well (Kähkönen, 2018). Therefore, the benefits generated by publishing it free vastly outweigh any disadvantages such as added costs.

If all meteorological organizations around the world would publish their data for free, just as FMI has done, the sheer innovative force of the public can be harnessed to assist and solve challenges which these organizations face every day, in many cases being restricted by their limited budgets. This also includes the retrieval of lost radiosondes. As stated by David Edwards of Met Office in the United Kingdom, "Met Services are unlikely to have the resources or infrastructure to be able to retrieve the instruments themselves, but perhaps if the landing locations were made public, then more might be collected and returned. There are collect and return schemes running for several ozone sonde systems in Europe, as these are more expensive instruments, which can be re-used." (D. Edwards, Met Office, private correspondence, February 24, 2021) While radiosondes are not always recycled, a public retrieval scheme, where final location data would be openly published, would bring major benefits to the conservation of wildlife and the natural habitat. In such a scheme, the final coordinates of the radiosonde would bring validity to the programme, although a simple outreach to the public could also generate innovative ideas on how to pinpoint and retrieve the radiosondes most effectively. Such open innovation practices are becoming commonplace with globally leading companies, for example Samsung, Lego, Mozilla, Facebook, General Electric, Philips and many others (Morikawa, 2016). Through open innovation, professionals and amateurs from different layers of society can bring old and new ideas together, in unforeseen combinations, utilizing technologies and processes which the companies' Research & Development organizations could not have envisioned, unless spending massive amount of time and effort on pursuing every possible lead (Chesbrough, 2003).

As mentioned before, in addition to allowing new innovations to emerge, the prevalence of humans all around the planet could be utilized in retrieving, returning or recycling the radiosondes. There is an increased public interest in trekking the outdoors but also on gamifying the activities, as evident by the geocaching hobby. Geocaching refers to a type of a treasure hunt, where people hide objects into the wild for others to find. These objects are broadcasted on geocaching websites (Edmiston, 2017). For example, in Finland, there are over 2000 geocaches in total, which the active members of the geocaching community has been able to find over 112 000 times by over 42 000 hobbyist, out of which 7000 are active (between September 2006 and September 2021) (GeoCache, 2021).

Globally, there are over three million geocaches logged in 191 different countries, on seven continents (including Antarctica). These geocaches have been found 642 million times since year 2000, being maintained by 361 000 geocache owners (GeoCaching, 2021).

Finding parcels in the wilderness and logging them is a growing hobby. If coupled with the potential to return the found cache and as a reward clean up the nature around us, there is potential to utilize this interest to clean up lost radiosondes as well. There are options to also gamify the public retrieval of radiosondes, by offering incentives or rewards for those who manage to gather and return the most.

There is also a growing interest on cleaning up the nature. There are at least a dozen globally active organizations primarily focused on marine cleanup projects (Eisenhauer, 2020). There are also hundreds of environmental organizations as well as nature clean up groups, both amateur and professional (Clean Up the World, 2021; Natural Restorations; 2021, Lessler, 2021; Shoreline Cleanup, 2021; WWF, 2021) including the globally recognized Earth Day (EarthDay, 2021). With climate change around the corner, focus is increasingly set on preserving the nature, as evident by the ban on single-use plastics in Europe (European Commission, 2021).

While radiosondes do not fall into this category, being coupled with devices to perform another type of activity than any single-use plastic, they are nevertheless human-made objects discarded in nature after their mission is accomplished. The growing concern over the natural state of our environment extends to the scientific community as well as the public. With such a large force, the retrieval of radiosondes could be achieved, if equipped with enough information and tools to do so.

In this chapter, several systems have been proposed, many of which could be utilized to greatly reduce the environmental impact of radiosondes. While it is evident that semi-permanent installations as well as remote sensing can only offer limited solutions until developed further, the key to an environmentally friendly weather balloon system at this stage lies within an increased tracking functionality, coupled with the component alternatives identified earlier. As the most cost-effective solution requires further analysis of available options, a field test is required to evaluate the most prominent ones.

# 5 FIELD TEST

In order to assess viable options for environmentally friendly radiosonde systems in real life, two field experiments were conceived. One of them would focus primarily on the feasibility of different tracking systems and the other one would take the budget restrictions of meteorological organizations into account while demonstrating the most applicable solution, as defined by the previous chapters. This latter test would feature a prototype tracking device in a prototype shell, as a proof-of-concept for a minimum viable product for achieving environmental friendliness.

For the tracking system comparison payload, the accuracy of both external and internal tracking methods would be assessed. This would require tracking devices to be installed in strategic points around the launch area as well as different communications systems from within the payload. Naturally, both payloads would be tracked using the external networks, in order to quantify the results. For the prototype payload, the goal would be to produce an accurate tracking device at a cost of less than 10 euros, enclosed in a biodegradable shell. This would mean that if the device would be attached to every radiosonde, it would increase the overall operational costs by approximately 5% at maximum (T. Laine, FMI, private correspondence, November 4, 2021).

## 5.1 Module design

For external tracking, the focus is on tracking the current radio signal of the radiosonde. Therefore, data would be collected from both the current system used by the Finnish Meteorological Institute as well as from the APRS network. The network would be fortified by devices installed on two sides of the expected trajectory, as well as on board the car used to retrieve the payloads.

For internal tracking, both field experiments would be using GPS-locators linked to the cellular network in order to transmit GPS coordinates through civilian networks. The chosen network method was 2G, which is no longer available in all parts of the world, but which has the longest range of currently available mobile networks and has excellent coverage in Europe, being continuously used for IoT operations. Nevertheless, it is going to be phased out in 2025, paving way to 5G. 4G will continue to be available, and with decent range it can be used as a low-cost future alternative to the 2G modules presented in this research (Schreiner, 2021). Furthermore, a simple 4G-based tracking system would be relatively easy to construct, identical in overall design as the produced 2G trackers.

The coordinates would be received and stored by a gateway system which would also upload the data to a cloud-based solution. Moreover, the coordinates would also be sent to a backup mobile phone. The trackers themselves would also record the data on a microSD card. Such precautions ensured that the data would be available for post-flight analysis even in case of battery or component failures in any of the equipment.

Most of the designs were derived from existing products developed and used by amateur high-altitude balloon communities or tracking system developers. This enabled cost-efficiency while enabling the collection of research data using proven methods. Moreover, these solutions were well documented, allowing the researcher to produce the required components within a reasonable period, within reasonable budget and allowing modifications to be made with relative ease by the researcher. Some of the modules required custom programming as well as soldering of electrical components by the researcher as well. Moreover, databases and some online content was produced by the researcher to be used for this study.

Each section below contains the total retail price of the produced module, at VAT 24%. The prices are fetched from the invoices at the moment of purchase and may have changed since then. As a private individual, the researcher did not have access to corporate sales functions and therefore the prices include any import fees incurred by the purchasing of these goods. These costs will allow budget restrictions to be considered for each solution.

In addition to the below components, several camera modules were obtained or produced, to be loaded among the payload of the tracking system test. These cameras had the primary function of providing the university, the researcher and relevant parties with images from the stratosphere, to be used in future research or teaching material.

### 5.1.1 Radio signal trackers

Three radio receivers were built using Raspberry Pi 3 Model B and an RTL2832 Software Defined Radio (RTL-SDR) USB dongle. Raspberry Pi 3 Model B is a small, credit-card-sized single-board computer developed by the Raspberry Pi foundation in the United Kingdom, typically running a Linux operating system (Opensource, n.d.). For this project, the computers were running the kxyTrack 1.5.4 radiosonde tracking software on a modified Linux platform (Lewiński, 2021). The RTL-SDR modules were originally built for receiving digital video signals but have been reconfigured by appropriate software (such as the above kxyTrack) to listen and decode specific radio frequencies (Gilani, 2021). The frequencies in this experiment were set to a range from 402.0 to 404.0, with 403.0 being the default used in the FMI sounding operations. RTL-SDR has also been used by meteorological organizations, with NOAA using SkySonde software to decode and plot radiosonde data (RTS-SDR, 2017).

While all three receivers featured the same core computer type, three different RTL-SDR dongles were used; one with a FC0012 tuner chip, one with R820T2 and one with R828D. Moreover, three different antenna setups were utilized. The FC0012 dongle was installed on board the car used for retrieving the radiosondes, featuring a bullhorn antenna tuned for 400-433 MHz frequency band as well as Lithium-Ion power bank as power source. The R820T2 dongle was installed on private property in Vähikkälä, 60 kilometers east of Jokioinen, featuring a dual-antenna setup with both antennas tuned to 403 MHz. One of the antennas was an extendable one, the other one was custom-built ground plane antenna. The property featured a high hill towards east, which would block any radio signals in that direction, but would receive well from the direction of Jokioinen. The partial coverage was mitigated by the availability of radio amateur towers in Hämeenlinna in the APRS network. Finally, the R828D dongle featured a single UT-106 car antenna, built for frequency bands 136-174MHz and 400-520MHz. This setup was installed on private property in Lempäälä, 70 kilometers north of Jokioinen, with good reception south towards Jokioinen but being blocked by the roof of the building towards north. Radio amateur towers in Tampere would mitigate the blind spot, should the radiosondes fly over the area. The call signs of these radio receivers were YARIL2-15, YARIL2-12 and YARIL2-10, respectively.

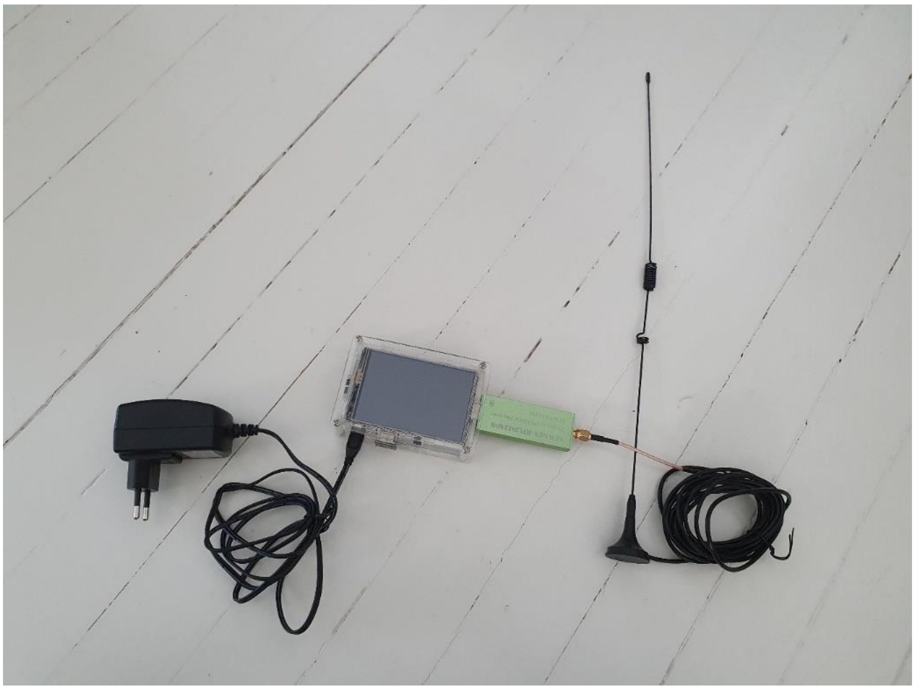

**Figure 5**: Preliminary setup of radio signal receiver call sign YARIL2-10. The green R820T2 dongle was later changed to R828D type.

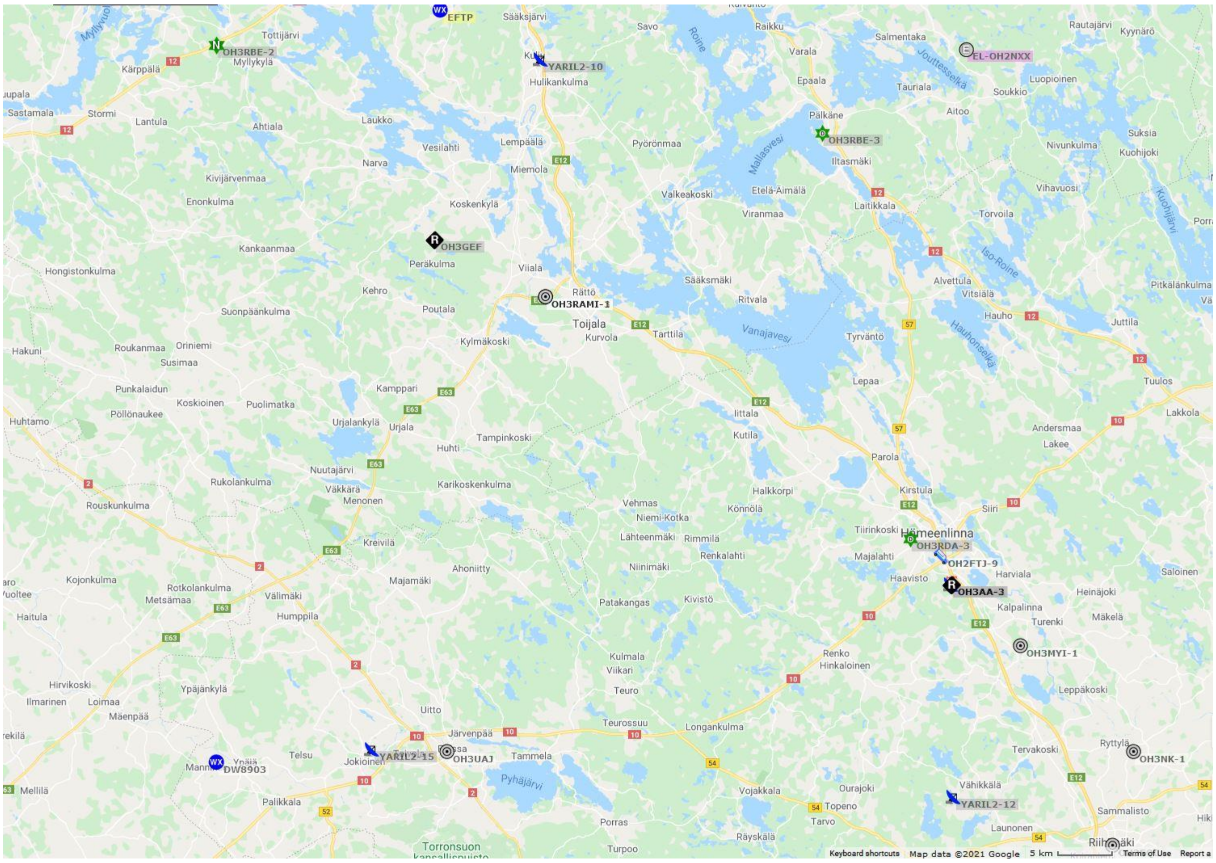


**Figure 6**: Location of radio receivers (marked as blue parabolic antennas) in the area of operations, with YARIL2-15 at launch site in Jokioinen (APRS, 2021)

The goal of these radio signal receivers was to receive the radio signal emitted by the RS41 radiosonde and decode the data. They would then upload the coordinates and other data to the APRS.fi website, therefore allowing a visual plotting of the flight trajectory. These trackers, along with the other APRS radio receivers in the area, would demonstrate the feasibility of using a network of receivers, installed for example in FMI-operated weather stations around the country. All data packets received by the APRS network were available for analysis in the Radiosondy.info website, therefore providing this research enough data to measure the accuracy of this network.

All three receivers had the Raspberry Pi’s native watchdog hardware service enabled. This service monitors the system and if it detects a freeze of any kind, it would automatically reboot the device. With automatic loading of the kxyTrack system, any failed system would be able to recover independently.

The average cost of a radio signal tracker was:
Raspberry Pi 3 Model B: 44,90 €
MicroSD card: 4,90 €
RTL-SDR dongle: 13,25 €
UT-106 antenna: 4,10 €
TOTAL: 67,15 €

### 5.1.2 Handheld radio signal tracker

A small handheld Lilygo TTGO LoRa32 433 MHz unit was obtained to be used close to the landing site of the payloads. This module has been reconfigured and tuned to the radiosonde frequency and can be configured to any specific frequency near the band. As the batteries of an RS41 radiosonde will power the unit for approximately five hours (Vaisala, private correspondence, June 11, 2021), the sonde continues to broadcast the data after it has landed. As the radio signal travels through trees, the handheld unit is able to receive the data, decode it and then transmit the location data over Bluetooth to a phone running MySondy GO application (MySondy GO, n.d.; Mahidharia, 2020). This was used as a backup method for locating the payload if any other tracking method had failed.

Cost:

LILYGO TTGO LoRa32 433MHz: 15,82 €

200mAh Lithium-Polymer battery: reused from existing reserve, any power bank would have worked as well.

### 5.1.3 Primary GSM tracker

An internal tracker for transmitting coordinates via SMS messages was built on Raspberry Pi Zero W with a Waveshare GSM/GPRS/GNSS HAT. The Raspberry Pi Zero W is a smaller version of the Model B single-board computer, with a less powerful processor but still featuring WiFi and Bluetooth connectivity and a full 40-pin Input/Output header (Raspberry Pi Foundation, 2017). The Rasperry Pi is a popular choice for amateur high-altitude balloon communities, due to its weight and processing capability (Akerman, 2013). The Waveshare module has been specifically built as an add-on for the Raspberry Pi, featuring 2G GSM and GPRS connectivity, support for GPS (via external antenna), COMPASS, Glonass and LBS base station positioning (Waveshare, n.d.). The module uses standard SIM cards, which for this experiment were selected as prepaid cards. This enabled flexible remote configuring of the prepaid subscription. The Raspberry Pi Zero W had the Raspberry Pi OS Lite operating system installed on a Kingston Industrial microSD card. All of the components were rated to operate in -40 °C. A dual-port 10 000-mAh Lithium-Ion power bank was selected as a power source, with a USB-powered electric heater providing heat to both the power bank and the payload. The effect of cold temperature on electronics is mainly a concern for the power source, as coldness typically lowers the output of available charge. This is somewhat mitigated by the waste heat generated by the electronics and power banks within the payload cabinet. In some cases, amateurs use hand warmers containing iron powder, being activated by air, but these can have issues in stratosphere where the lack of air can reduce the effectiveness of these warmers (Chin *et al.*, 2016). Therefore, an electric heater was selected as the most useful option. The power bank was intentionally oversized for this project, as smaller versions would have worked as well, but with the electric heater sharing the power source, together with the effects of cold temperatures (Williams, 2019), the power-to-weight ratio was determined to be the best with the selected bank, from a range of power banks available to the researcher. Moreover, a power bank outputs a standard 5 volts. Pure Lithium AA batteries are ideal for radiosonde operations as they work well in freezing temperatures, in terms of power output and power-to-weight ratio (Energizer, n.d.). Alkaline, Lithium-Ion and Lithium-Polymer batteries, on the other hand, do not fare as well, but have their limited use (Williams, 2019). However, as a single AA-battery outputs approximately 1,2 to 1,8 volts, the use of any AA battery setup would have required a step-down module to align the output of several batteries to 5 volts, therefore adding unnecessary complexity to the current setup as overall weight was of little importance for data collection in this flight.

The Raspberry Pi was scripted with Python to read the GPS data from the Waveshare module and if available, the current altitude of the module was assessed. This clause made it possible to activate the network connection to the nearest tower only when below 2000 meters high. Once at the correct altitude, a pre-scripted message was relayed to the Waveshare module's GSM function and further transmitted to the available network. Two different message types were predefined, one for a gateway module, which would store the data internally and also upload the data to HabHub tracking service, and one for the phone used by the researcher, to track the module by coordinates on Google Maps service. The gateway message was programmed to be sent out once every five minutes and the phone message once every twenty minutes. This was determined to be both power-efficient and sufficient in determining the final landing coordinates of the payload (Onehitwonder, 2020; Akerman, 2018).

Finally, the Raspberry Pi's native watchdog hardware service was enabled. The Python scripts had been configured to run on every boot automatically. This enabled the system to recover from any failure state and continue functioning as programmed.

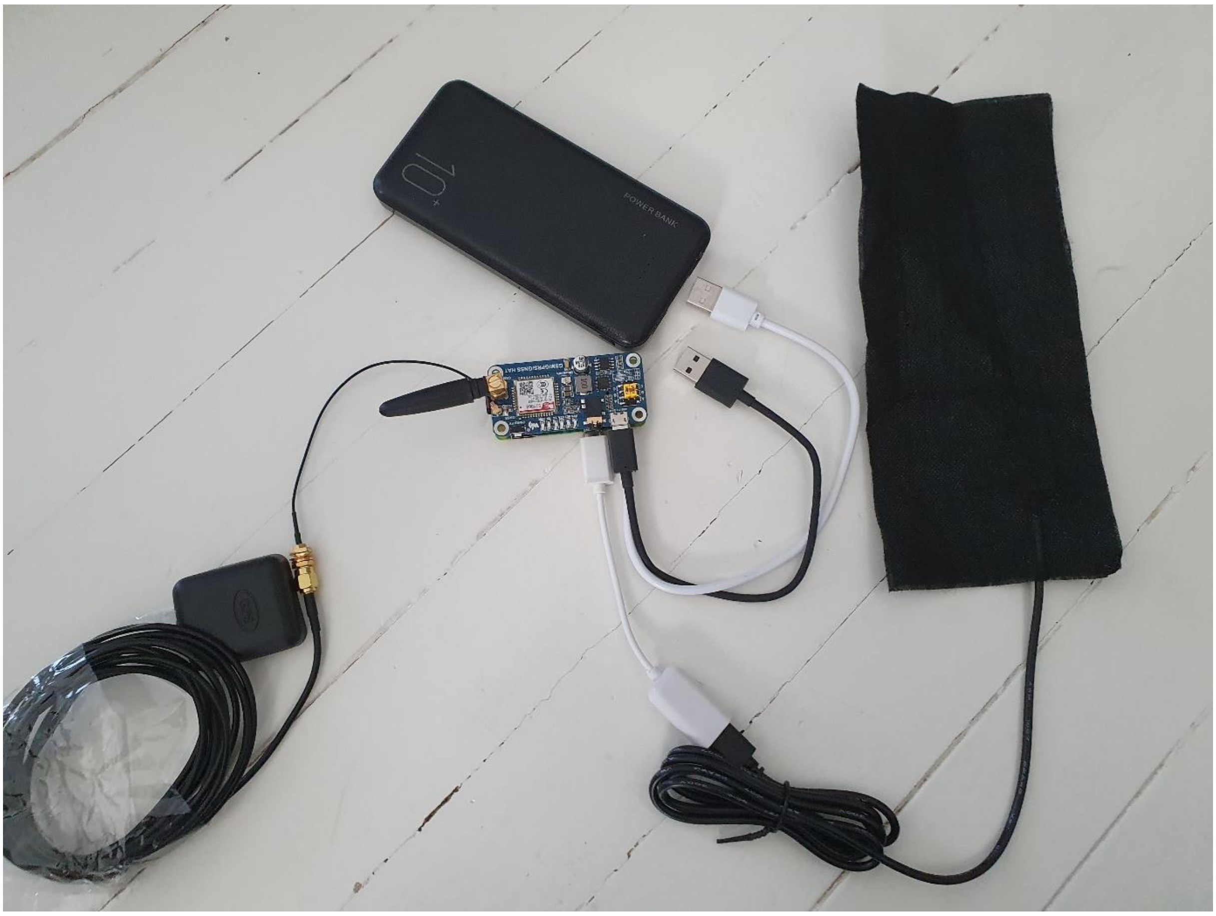


**Figure 7**: The Primary GSM tracker with power bank, external GPS antenna and an electric heater blanket.

In addition to the Primary GSM tracker, an alternative backup tracker was produced based on Lilygo TTGO T-Call v1.4 and modified to work within the same limits as the primary tracker but providing the coordinate data to a Blynk cloud app installed on the researcher’s phone (CircuitSchools, 2020). However, due to weight constraints, the backup tracker was abandoned.

The total cost of the primary GSM tracker was:
Raspberry Pi Zero W: 9,05 €
Kingston Industrial 8Gb microSD: 12,90 €
Waveshare GSM/GSM/GPRS/GNSS HAT: 27,95 €
FLOVEME 10 000mAh Power Bank: 8,66 €
Standard GPS antenna: 2,68 €
USB electric heater: 1,81 €

Prepaid subscription: 1 € / day, 5 € minimum

TOTAL: 68,05 €

### 5.1.4 SMS gateway

A Raspberry Pi 3 Model B+ was selected for running the SMS gateway service, coupled with a Huawei E1552 HSDPA USB stick. The Huawei stick provided the Raspberry Pi computer 3G connectivity, for receiving the text messages from the GSM trackers. The Lite OS was used for running Python scripts with necessary libraries loaded to support the Huawei stick. The scripts would read any text message sent to the phone number associated with the SIM card within the stick and then forward it to the HabHub cloud tracking system for online map service. The gateway also stored the messages and other relevant data to a log file on the microSD card hosting the operating system. The subscription of the SIM card was a DNA device internet, which is typically used in trail cameras (DNA, 2021). With a static subscription model, the only requirements were to have the service always available and capable of receiving text messages. The gateway was also configured with the watchdog service (Borisov, 2021).

Costs associated with the gateway:

Raspberry Pi 3 Model B+: 49,90 €

Huawei E1552 HSDPA USB stick: Reused

Mobile subscription: 1,90 € / month

TOTAL: 51,80 €

### 5.1.5 LoRa tracker

A LoRa GPS tracker was also built, utilizing an Arduino Nano microcontroller, a Neo-6M GPS module, a SX1278 433MHz LoRa module, a 433MHz antenna and a 9V Lithium battery as the power source. The goal with the LoRa tracker was to evaluate the feasibility of using LoRa as an alternative communication method with the budget constraints in mind. Therefore, the components selected for the test were ordered separately and the units and their wires soldered or clipped together to form the final product. Because the Arduino Nano does not natively have a microSD card slot, the microcontroller was not capable of maintaining a permanent log file. The program for the tracker was written by the researcher in C++ and uploaded through Arduino IDE software, utilizing pre-existing libraries.

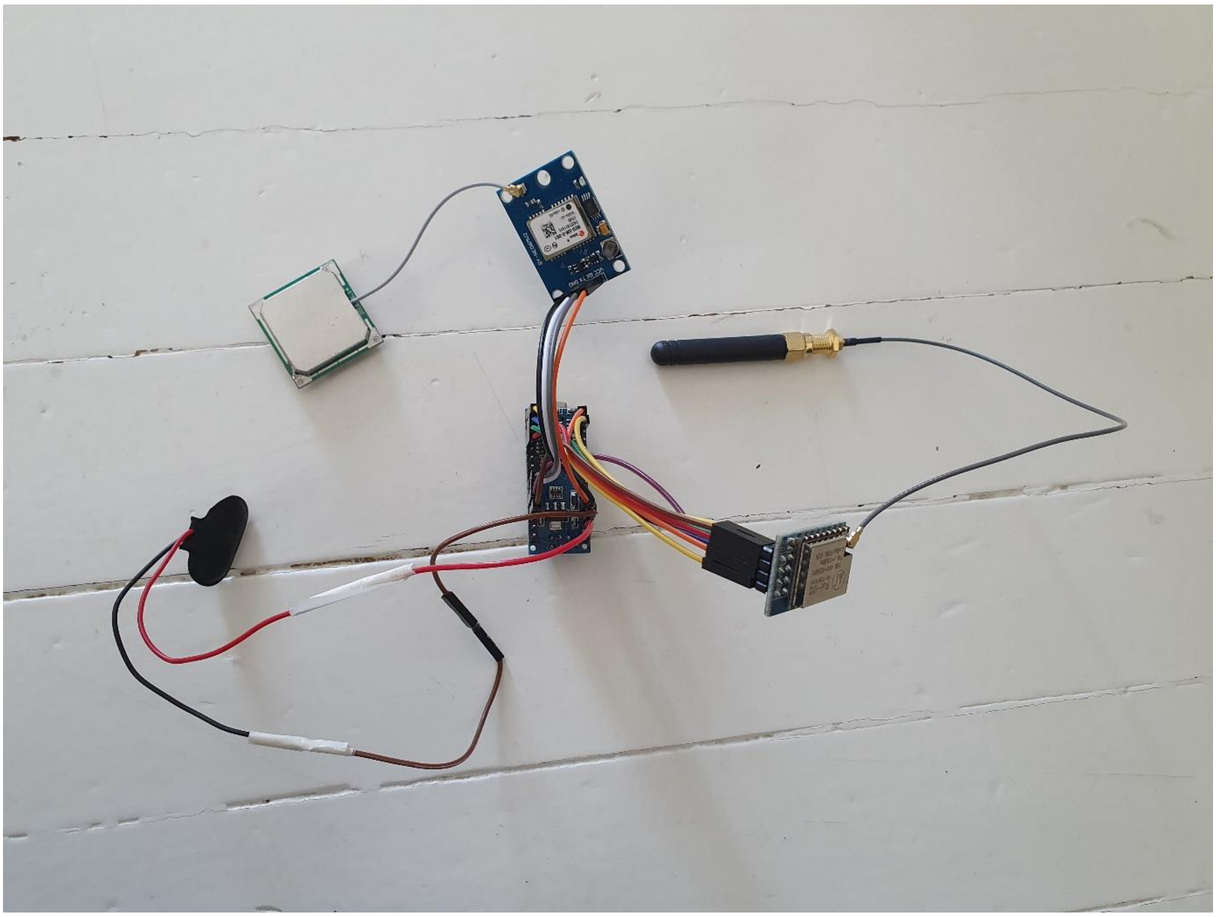

**Figure 8:** LoRa tracker with attached components

Arduino Nano: 15,30 € (any version of Arduino Nano would work, bringing the cost down)

Neo-6M GPS: 2,97 €

SX1278 LoRa module: 3,72 €

433MHz antenna: 2,02 €

Energizer Lithium 9V battery: 7,95 €

TOTAL: 31,96 €

### 5.1.6 Prototype GSM tracker

A prototype GSM tracker was produced as a proof-of-concept, demonstrating that a properly functioning, reliable tracker can be manufactured at a very low cost. This would not only allow any meteorological organization to accurately track any equipment they send out but also incorporate these tracking capabilities to their daily operations without major investments. As such, a reliable microcontroller was needed, with Raspberry Pi Pico being selected as the ideal platform. Soldered to a SIM800L module and a Neo-6M GPS tracker, the Pico had the ability to take power directly from either the Radiosonde's auxiliary port or from three AA batteries. As the input power could vary from 1,8 volts to 5,5 volts, a separate step-down or boost module was not needed, as the Pico could be run directly from the AA pure lithium batteries, with each producing 1,4-1,8 volts (4,2-5,4 volts in total) (Pounder, 2021), or from the auxiliary port of the radiosonde producing 3,7 volts (±3 %). However, the auxiliary port output is limited to a maximum of 50 mA, thus making it incompatible for GSM operations, where burst draw could be as much as 2A (Vaisala, 2015). Adding a capacitor between the radiosonde's aux port and the GSM module could allow the burst draws to occur at predefined intervals, which would require further investigation on the feasibility of such a design. Additionally, the TXD port of the radiosonde does not feed any useful data to the additional sensor, which in theory could have been used to feed the radiosonde's own GPS signal to the tracker module. Because of the power and data limitations, the internal solution for running all modules from the batteries proved most stable.

The Pico can be programmed with either Python or C++ language. As the Pico is a relatively new product, at the time of this research the Python libraries were missing proper support for the GPS and GSM modules. Therefore, C++ over Arduino IDE was used to program the microcontroller (Claussen, 2021; Muchika, 2019; SurtrTech, 2020).

A challenge with Pico is that it only has two UART peripheral connections, UART0 and UART1. This means that once the Pico is connected to a programming platform, such as an Arduino IDE running on a PC, if the code instructs the Pico to print a notification to the Serial Monitor of the programming software, Pico defaults to using UART0 for the serial connection, effectively reducing the available UART channels to one. In short, any active connection to another computer via the Pico's USB port will reserve the UART0 for that purpose. However, in order to use both the GPS and the GSM modules, both UART ports are needed to transfer data back and forth these modules. With the default serial channel reserved by the USB virtual monitor, using two other components on the Pico while receiving feedback from the board was not possible at this stage. Therefore, the code was developed, compiled and tested by generating the required code components for each module separately and in the end combining them without the USB virtual serial connection. The code of the module excluded the use of a serial monitor, thus running “blind” to the programmer. The only confirmation of the service running was the initial SMS message, which was sent once both the GPS and the GSM modules had been initialized. The programming of each module required parsing NMEA GGA sentences from the GPS unit as well as passing the information to the GSM module for transmission in a predefined format (Lefebure, 2020; Arduiniana, 2021; Alselectro, 2018).

With the Pico being released in 2020 and this research being conducted on the following year, the Arduino IDE was not completely ready for programming Pico. It did not inherently specify the GPIO pins used by each UART and at the time of writing the libraries did not specify this either. The only way around this problem was to open up the pins_arduino.h file of the hardware library and inject lines, which would define the pins used for each UART (Teja, 2021). The code added to Arduino IDE is available in Appendix 2.

The functional programming of the Pico featured the same 2000-meter limits for accessing the mobile phone network as the primary GSM tracker. The prototype tracker also used the same gateway at 4-minute interval and was programmed to send the message to the backup phone at the same 4-minute interval as well, with 5-second pause between the transmissions. This enabled higher accuracy in the final trajectory. Because the Pico does not inherently have a microSD card slot, a permanent log was not saved.

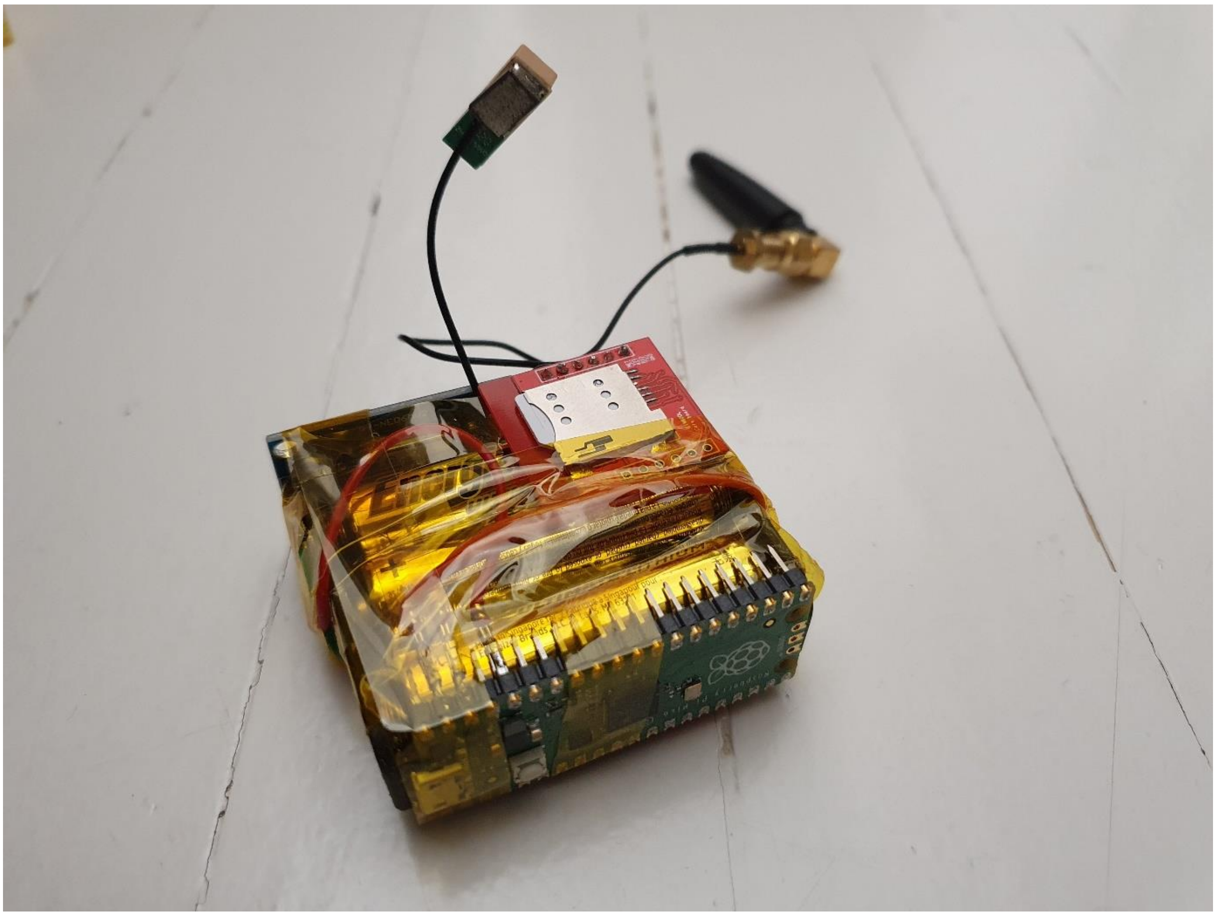

**Figure 9:** The prototype GSM tracker

The insulative shell was produced with commercially available wood pulp sponges, originally designed as biodegradable cleaning products. In the later climate test in a laboratory setting, the insulation capabilities of porous wood cellulose products proved to be as good if not better than polystyrene, albeit 30% heavier than EPS, at approximately 24 kg/m3.

As the sponges were manufactured to absorb moisture, they had to be protected by a biodegradable waterproof shell. While wood pulp does not conduct electricity, water captured in larger quantities within the wood product can do so to some extent (BLR, 2015). As wood products are typically good insulators, a waterproof paper provided optimal features for both protecting the insulation as well as providing another layer of insulation on top of it while being water resistant. For this prototype, the outer shell was made of Rite in the Rain 8518 75g/$m^2$ paper, with samples obtained from both the Rite in the Rain headquarters in Tacoma, USA as well as their local supplier FPW Firmaservice in Finland (J. Mattingly, Rite in the Rain / JC Darling LLC, private correspondence, July 23, 2021; P. Westerlund, FPW Firmaservice, private correspondence, July 22, 2021). As the laws and regulations concerning international shipments outside of the European Union were put in effect in July 2021, it was not guaranteed that the samples obtained from the manufacturer would reach the researcher in time for the field experiments, therefore requiring an additional local contact. The 8518 paper was one of the lightest within the Rite in the Rain production portfolio, while offering outstanding heat and water resistance as well as being antistatic (Rite in the Rain, 2021). It is also basic and affordable. While not having any research done on how long exactly this type of paper would withstand being submerged in water or discarded in nature, from material point of view it was considered likely that it would perform well under the circumstances it was going to be used (J. Mattingly, Rite in the Rain / JC Darling LLC, private correspondence, July 23, 2021)

The prototype GSM tracker, with antennas included, weighted approximately 85 grams and the shell another 45 grams, equaling 130 grams in total. A Vaisala RS41 radiosonde weights 80 grams, out of which 55 grams is electronics and 25 grams the shell. This would indicate that the GSM tracker was not as optimized for weight as it could have been, but for an initial field experiment these were acceptable figures. A standard 350-gram balloon would be easily able to carry both a radiosonde and the tracker, with a combined weight being approximately 205 grams, with the recommended payload limit being 250 grams (UKHAS, 2017), although capable of lifting 400 grams as well (High Altitude Science, 2021).

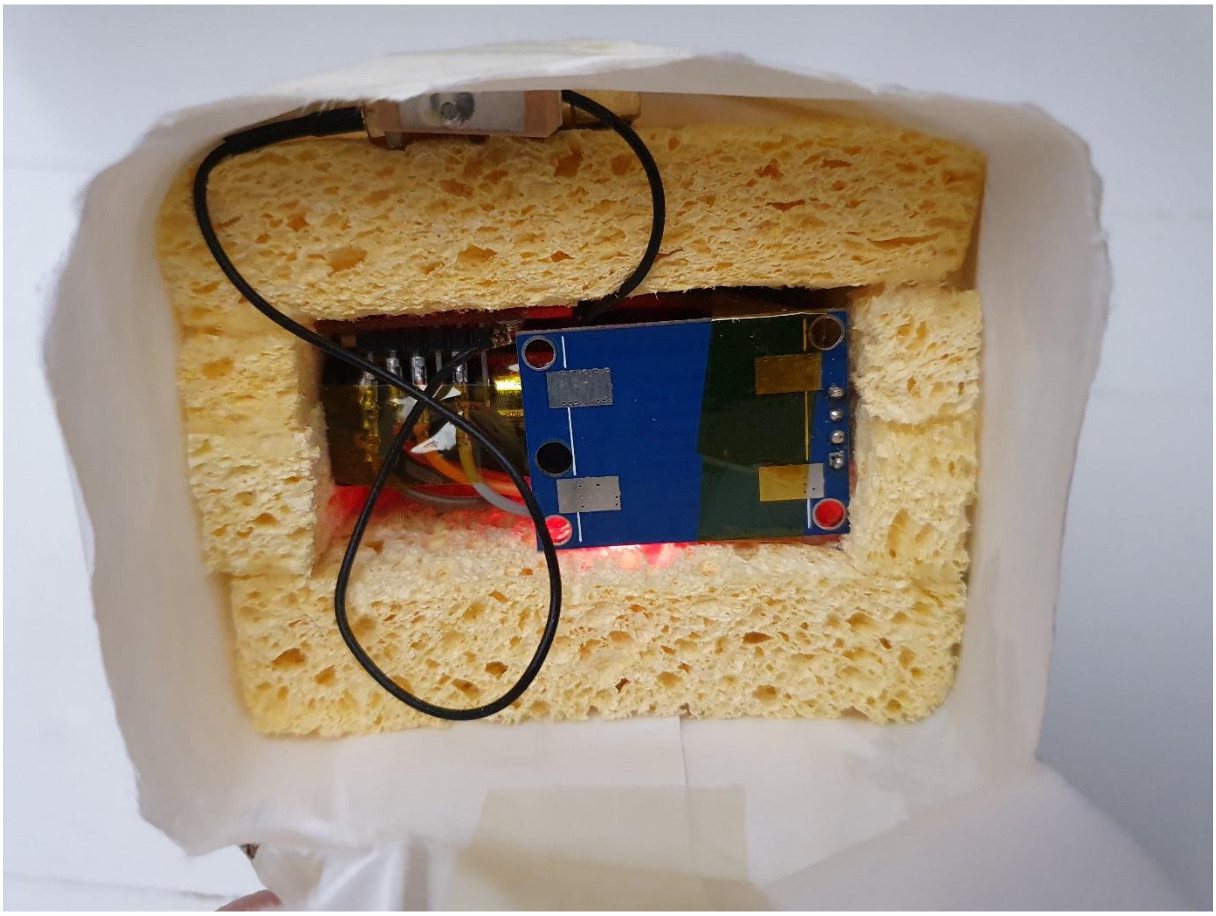

**Figure 10:** The prototype GSM tracker within the biodegradable shell after retrieval

Cost of equipment:

Raspberry Pi Pico: 5,84 €

Neo-6M GPS: 2,97 €

SIM800L: 2,12 €

GSM antenna: 1,42 €

Battery compartment: 0,24 €

3x Energizer Lithium AA: 6 €

Wood pulp sponge: 0,99 €

Rite in the Rain paper: Free samples, usually 13 € for 50 pcs.

TOTAL: 19,58 €

Although the current total retail store cost exceeds the limit of 10 euros per tracker, with 0% VAT, wholesale purchasing and bulk industrial order amounts the price would fall well below this threshold. If the module would be manufactured as one custom-made system, the cost of the equipment would likely fall within 5 euros per unit, excluding the shell and the batteries. With everything included, the price of the finished product should still be well within the 10-euro limit per unit. However, due to limited margins, this would likely require the product to be manufactured in larger quantities by global electronics producers such as Avnet (Avnet, 2021), with the certification of the product being covered by the quantity of these trackers being produced and purchased. Nevertheless, with prototype costs being below 20 euros, the manufactured cost of less than 10 euros can be reasonably expected, which means the tracker is feasible to be used in daily operations.

## 5.2 Laboratory climate test

After the payloads had been produced, they were exhaustively tested in a Vötsch VC 4018 climate test chamber at the LUT Voima facility of the Lappeenranta-Lahti University of Technology. The freezer can reach a -40 °C environment, with temperature sensors measuring the conditions inside the payload boxes.

With all the modules running, the larger polystyrene box was capable of maintaining a -20,4 °C internal temperatures. In contrast, the biodegradable box with a paper shell had a stable -3,4 °C, which can be attributed to the porous structure of the wood pulp sponge, with the air pockets insulating well. The outer paper provided another insulative layer. Moreover, the tracker was sitting very tightly within the box, with the waste heat of the modules and batteries being effectively transferred to the internal walls of the shell. The polystyrene box, on the other hand, had a larger cavity, with plenty of air between the modules. Nevertheless, with similar wall thickness, the wood pulp box seemingly outperformed the polystyrene box.

## 5.3 The field experiment

The Finnish Meteorological Institute offered their assistance in conducting the field tests from their meteorological observatory in Jokioinen, Finland. The original agreement was to launch in August/September 2021, but due to the global COVD-19 pandemic preventing public access to the observatory, this launch date was pushed back, until the restrictions were lifted mid-October 2021. FMI provided the balloons, the gas and one Vaisala RS41 radiosonde (ID

T0830083) for the experiment. Vaisala provided another RS41, thus allowing the different areas of the research to be tested during two consecutive launches on the same day. The researcher had acquired one large 160V-05 parachute, two small 5012-05 parachutes as well as an additional TA500 balloon from Totex's representative in Europe, Sys-Infor in Belgium (A. Lemarchand, Sys-Infor, private correspondence, February 25 – September 27, 2021). Totex is a global provider of weather balloons, parachutes and other meteorological equipment (Totex, 2021). The 160V-05 is a parachute designed to be used with Vaisala Ozonesonde, having an elastic hanger, which connects well to Vaisala's cord unwinder. This parachute is designed for payloads of 1000 grams. The 5012-05 parachute is a radiosonde parachute, designed for smaller 300-gram payloads. As being designed for generic radiosondes, the 5012-05 features a plastic buckle instead of an elastic one (Totex, n.d.).

Appropriate licenses were acquired from the Finnish Transport and Communications Agency Traficom well in advance, with the license validity period being extended to six months, however allowing operations for one day only within that period, pending notice of the confirmed launch date. The licenses included the use of airborne GSM devices in test use as well as airborne LoRa device in test use. Traficom handled the negotiations and approvals with the mobile network operator DNA, whose prepaid subscriptions were used with the GSM devices. The prepaid nature of the SIM cards made it possible to remotely configure the available balance and active/passive status for the days when the devices were in use, as well as remotely shut the connections down if the payloads would have been inaccessible, for example due to landing in a lake.

The launch date was agreed on November 4, 2021. The date was picked as having the most favorable winds, even if the day had been forecasted to be cloudy, with a little bit of rain in the morning. The surrounding dates had either heavy rainfall or heavy winds, which would have sent the payloads far from the launch site, even across the border to Russia or Estonia. Because the smaller payload featured a biodegradable, water-resistant shell, relatively high humidity provided fitting conditions to test the shell's capabilities.

### 5.3.1 The first launch

Because FMI's equipment can only track one manual sounding at a time, it was agreed to send the smaller payload first and try to purposefully end the sounding faster. This would allow more time for the larger payload to be sent out. The time limit for manual sounding is five hours, from first launch to the touchdown of the last launch, including approximately ten minutes of systems operations after touchdown. In order to provide comparable data, both launched had to be measured from start to finish with FMI's equipment. As the first launch contained only the RS41 radiosonde as well as the prototype GSM tracker, the highest altitude of the flight had very little importance, thus allowing the flight to be purposefully sabotaged without any effect on the research results. Therefore, multiple strips of duct tape were applied on the surface of the balloon, with the logic being that once the balloon starts to expand, the duct tape would tear the balloon apart. Moreover, limonene is known to dissolve rubber, *id est* latex, which the balloons are made of (Kuntzleman *et al*., 2015). Therefore, pure lime juice was applied to the surface of the balloon, in order to weaken the chemical structure of the latex.

FMI's Jokioinen site uses the frequency 403.00 for automated daily radiosonde launches and frequency 405.00 as backup, in case of a manual sounding. However, the listening stations at Vähikkälä, Lempäälä and the local car, had been tuned to listen frequencies ranging from 402.00 to 404.00. Therefore, it was agreed to modify the RS41 frequency to 404.00. The FMI personnel configured the RS41 few minutes before the launch. At the same time, the researcher turned on the prototype GSM tracker, received the startup signal on his mobile phone, and sealed the package. The tracker was taped to the back of the RS41 radiosonde and brought outside for better GPS signal. Once the RS41 indicated large enough number of satellites visible, and the GSM tracker sending first coordinates to the backup phone, the package was ready to be sent out.

A standard 350-gram balloon used for daily radiosonde sounding was filled with helium, which makes the manual operations safer than using the volatile hydrogen. The CUSF Landing Predictor indicated that the payload would land approximately 100 kilometers east of the launch site (UKHAS, 2021b). With the RS41 ID T0830083 and the prototype GSM tracker ready, the payload was launched at 10:09 EET / 08:09 UTC. The balloon rose at a standard rate of 4,9 m/s and was soon pushed north by the southerly wind, until at an altitude of approximately 15 kilometers the balloon turned south-east due to the wind conditions in stratosphere and the rotation of the planet. Reaching an altitude of 20195 meters approximately 30 kilometers northeast from the launch site, the balloon burst and the payload started descending.

Unfortunately, tracking data indicated an unnaturally slow descend, likely caused by an unsuccessful burst. After below 15 kilometers in altitude, the balloon started drifting north, heading finally northeast with a descend rate of 3,8 m/s. The payload finally landed in a forest 78,6 kilometers northeast of Jokioinen.

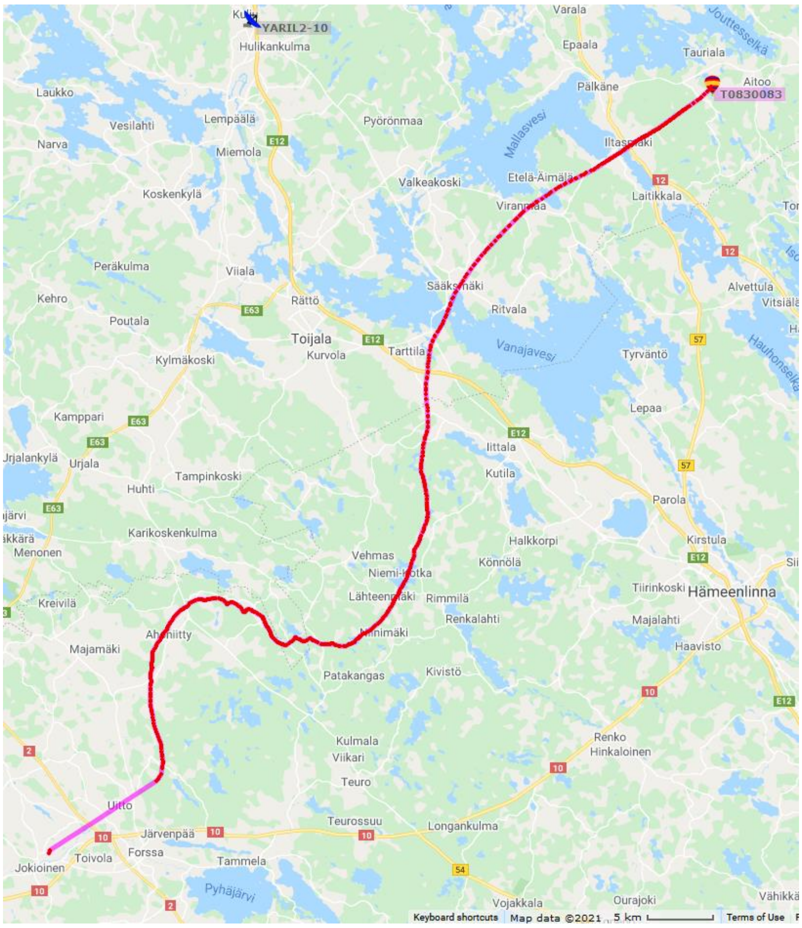


**Figure 11:** Flight trajectory of radiosonde T0830083 (APRS.fi)

The GSM tracker had been configured to search for and contact a ground tower at an altitude of 2000 meters or below. However, the first message from the tracker came at an altitude of just 765 meters at coordinates 61.3256 24.4088. The delay was either caused by the limited gain and range of the antenna attached to the SIM800 module, or the lack of network coverage in the heavily forested area, or some of the modules being offline due to freezing temperatures in the stratosphere, having rebooted closer to ground. However, considering the successful freezer test earlier on the insulation capabilities of the payload box, the most likely culprit is the antenna used for sending the data. The range of the simple antenna is limited to just few kilometers, which in the area of landing could have caused issues with network coverage, as the region is mainly composed of forests and lakes (Laud, n.d.). Moreover, vertical antennas operate in a donut-shaped radiation field, which limits the altitudinal reach of these antennas (Zufferey, 2013).

Below the altitude of 765 meters, the GSM tracker operated flawlessly, sending out coordinates and altitude data to both the backup phone and the gateway module at the predefined four-minute interval. The final coordinates recorded by the FMI equipment in Jokioinen were 61.32534 24.40803 at an altitude of 775,2 meters at 11:42 EET / 09:42 UTC (T. Laine, FMI, private correspondence, November 5, 2021). The final coordinates recorded by the APRS listening station set up in Lempäälä, Vähikkälä and in the car were 61.3274 24.4137 at an altitude of 702 meters (this final location being heard by the Lempäälä station, due to optimal line of sight), and the entire amateur APRS network recorded coordinates 61.3359 24.4303 at an altitude of 286 meters (Radiosondy.info), from a tower in south of Hämeenlinna run by the Hämeenlinna radio amateur society (Hämeenlinnan Radioamatöörit ry, 2021). Finally, the touchdown coordinates recorded and reported by the GSM tracker were 61.3380 24.4331 at an altitude of 120 meters, which is the ground level. The GSM tracker continued to report the same coordinates for several hours, indicating a successful and safe landing.

The difference in location coordinates between the official FMI equipment and the GSM equipment was 1593 meters on the horizontal plane and 655 meters on the vertical. This equals approximately 1722 meters distance in total. The APRS network had the obvious advantage of having receivers much closer to the landing location, thus having very negligible obstruction from the curvature of the Earth. The differences were 203 meters horizontally, 166 meters vertically and 262 meters in total. The images of the tracking systems, including retrieval locations, are available in Appendix 1.

Due to the five-hour manual sounding time limit, as well as limited daylight in late autumn, the first payload was temporarily abandoned to its landing location. Because of issues sending out and retrieving the second payload, the retrieval attempt for the first was eventually postponed until the next day. The November 5 had heavy rainfall from early morning, setting further challenges for the biodegradable shell. Nevertheless, the tracker continued to transmit coordinates up until midnight between the 4$^{th}$ and 5$^{th}$ of November, having worked flawlessly for the entire 14 hours.

The first payload was finally retrieved on the next morning at 10:46 EET / 08:46 UTC, at the exact coordinates reported by the GSM tracker, with no variation in either reporting the coordinates or the actual coordinates as recorded by the cell phone used for navigation. Any navigation software would have been able to pinpoint the location based on the coordinate data. The payload hung from a tree 20 centimeters off the ground, with the cord running along the treetops to the landing trajectory.

The balloon itself was retrieved approximately 30 meters away from the payload, hanging from a tree as well. Further inspection confirmed that the balloon had experienced a minor tear (3mm in diameter at ground level) next to a duct tape, which had caused the helium to escape in a controlled manner and the balloon to deflate at a slow rate. The balloon is relatively thick, designed to stretch ten-fold and therefore the altitude of 20 kilometers had not yet pushed the balloon's structure to its bursting point. Instead, the duct tape had teared a hole but otherwise provided stable structure above the tear to keep it from spreading further. The limonene had very little effect on such a thick balloon and would have likely required longer time to react. Moreover, the balloon is covered in a protective dust, hindering any chemical reaction. Retrospectively, the most effective way to burst the balloon fast would likely be to overinflate the balloon, causing it to rise quickly and ensuring an early burst, albeit high, or to attach a burning fuse to the balloon, which was not available at the time of launch (T. Laine, FMI, private correspondence, November 5, 2021).

The payload box was in good condition, despite the freezing temperatures in stratosphere, 23 hours of exposure to the elements of nature and 6 hours in heavy rain, as seen in Figure 12. To much of the researcher's surprise, the tracker was still running, reading coordinates but due to lack of internal storage space not saving them to a log file. The three AA batteries were still producing a total of 4,9 volts, which indicates a healthy charge, good enough to keep the components running (Energizer, n.d.) despite sending messages for 11 hours straight after landing. As the tracker was using a prepaid SIM card, each message sent reduced the available balance, until running out close to midnight. If a different kind of a subscription model would have been selected, the tracker would have been sending the data for several days, far longer than the battery capacity of the radiosonde itself.

The biodegradable shell had only slightly passed moisture through, which had not reached the interiors of the box, leaving the electronics completely dry and running relatively warm. Further inspection confirmed that the wood pulp sponges had attracted some moisture, but not enough to reach the internal walls of the container. The "Rite In the Rain" paper had protected the insulating material and continued to do so in the rain.

The first test was a complete success, with the prototype GSM tracker reporting precise landing coordinates and the biodegradable shell protecting the internal electronics from both the -60 °C temperatures and the heavy rainfall. A proof of concept for replacing the plastic structures of current radiosonde as well as adding extremely low-cost but highly effective tracking capabilities to the equipment.

**Figure 12:** The biodegradable shell of the GSM tracker attached to RS41 after retrieval, with the external black GSM antenna barely visible through the “Rite in the Rain” paper.

### 5.3.2 The second launch

The second payload was much heavier, containing a GSM tracker based on Raspberry Pi Zero W, protected GPS antenna, an electric USB heater, a 10 000-mAh power bank for the tracker and heater, a LoRa module with 9V lithium battery, a Canon Ixus camera scripted for still pictures at 5-second interval, a Denver action camera within a waterproof enclosure scripted for still pictures at 3-second interval, a Raspberry Pi Zero video camera with four AA lithium batteries, and Honor 6A mobile phone for video pointing downwards. The heaviest components were placed at the bottom and the payload balanced through optimal layout of the lighter equipment. The total weight of the package was 1195,8 grams, with 1200 grams being the maximum allowed payload for manual observations at FMI’s Jokioinen site. The original payload also contained a backup GSM tracker as well as a video camera pointed at the balloon, but those had to be stripped off before the launch, due to the weight restriction. This also meant moving the GPS antenna and its wires to the opposite corner, to balance the payload.

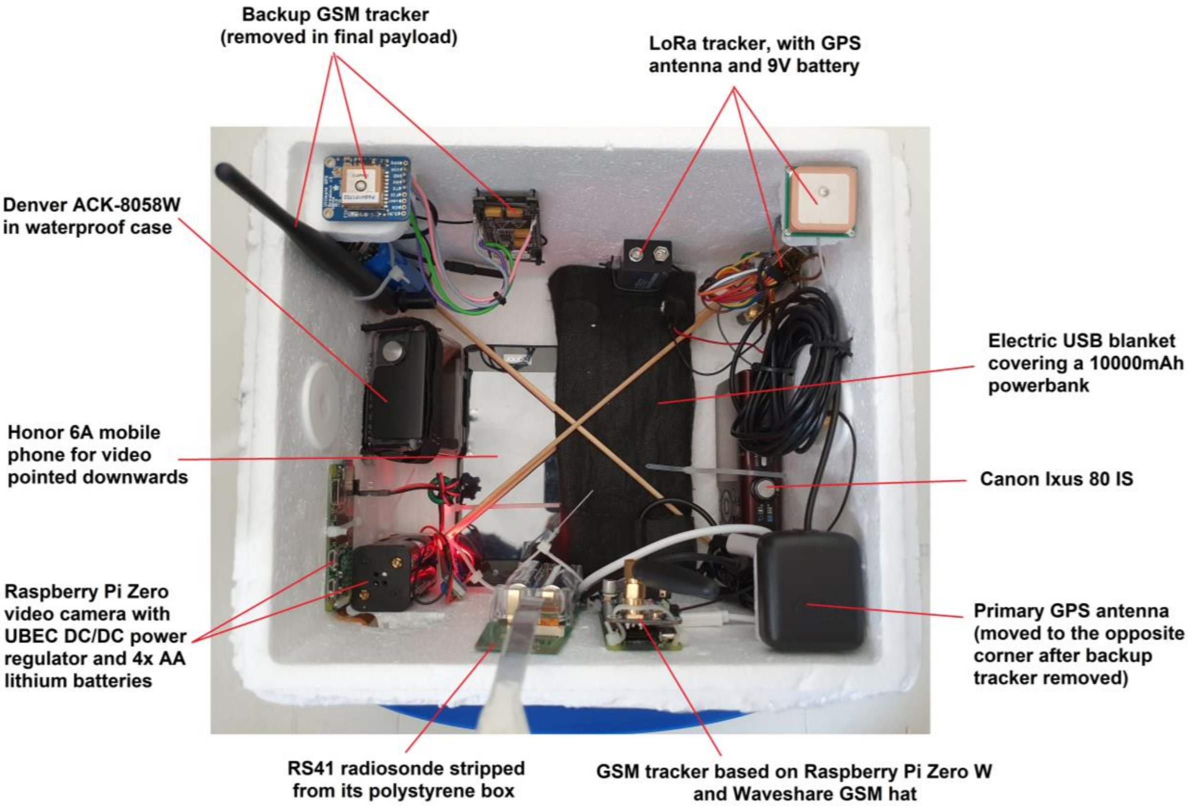


**Figure 13:** The payload box for the second flight

The second experiment focused on several key areas. First, the GSM tracker was based on commercially available products and therefore more expensive. Moreover, the tracker used a much more accurate and more protected GPS antenna. Secondly, the box contained another tracker with the communications based on LoRa technology, to test the range and feasibility of LoRa in tracking the balloons. Finally, the package was meant to be sent as high as possible and as far as possible from the launch site (which the first launch almost surpassed due to the unforeseen drifting), therefore providing opportunities for visual imagery from the stratosphere, to be used by the university, FMI as well as other parties involved in the project, but also to stress-test the trackers.

A typical styrofoam box was used for the flight, as the researcher was unable to produce a box large enough for all the components from biodegradable alternatives, which would have required more industrial manufacturing processes. The use of biodegradables in this experiment was considered secondary, as the primary focus was on tracking capabilities in remote locations.

The frequency of 404.00 was also used on the second radiosonde. Once having received confirmation of a successful touchdown of the first flight, the second payload was prepared for launch. The modules had to be booted up as close to the actual launch as possible, to keep the batteries in proper working condition. Once outside, the RS41 took a long time to find satellites, which should not have been influenced too heavily by the other equipment inside the box. Because of the delays of the first flight and the preparations for the second, an automated daily radiosonde operation at 11:30 UTC was launched between the experiments.

At 13:35 EET / 11:35 UTC, the second payload was ready for launch. A large 1200-gram balloon was filled with helium and the 160V-05 parachute attached to the balloon. Standard Vaisala unwinder was attached to the elastic buckle, with the unwinder’s beam attached to the payload. Although the cord contained by the unwinder is generally used with much lighter 75-gram radiosondes, the same unwinder has been designed to attach to the heavier parachute, for heavier payloads. The CUSF Landing Predictor indicated similar path for the second payload as the first one had had.

At approximately 11:45, the balloon was released. Unfortunately, the forceful and sudden lift produced by the large balloon as it jerked the parachute’s cords on the way up ripped the unwinder’s hook off from the elastic buckle and caused the payload box to smash to the ground. Upon further inspection, the unwinder’s hook was bent sideways, indicating a point of failure. The payload box seemed to suffer only very minor damages outside and all the equipment inside was deemed functioning through receivers. The payload box was not opened at this stage, as that would have caused a very long delay in the flight and daylight limit was approaching fast. Unknown to the operators until box retrieval, the battery pack of the Raspberry Pi video camera had been somewhat dislodged by the sudden impact, ripping out the wires from the DC/DC regulator and thus breaking the power source of the camera. The Raspberry Pi camera had been programmed to restart if in states of failure, but without a functioning power source this was obviously not possible. At the same time, the impact had caused the Honor 6A to reboot, which did not have a video restart script. Therefore, the flight produced only still images and no video.

Moreover, the accident caused the balloon to carry the sole heavy-duty 160V-05 parachute to the sky.

Another balloon was prepared and a much lighter spare 5012-05 parachute meant for 300-gram payloads attached to the balloon, fortified by additional cords to survive the weight of the payload. As the small parachute featured a plastic buckle instead of an elastic one, the connection between a new unwinder and the buckle had to be reinforced with cable ties. Carefully lifting the radiosonde train one piece at a time, therefore preventing any sudden jerks to the joints, and by attaching a wider base to the unwinder to allow a slower cord unwinding process, the second payload with radiosonde ID T1820157 was successfully launched at 14:06 EET / 12:06 UTC.

The pickup crew appointed by the researcher headed immediately towards the predicted landing site. The southerly winds had ceased and the payload flew almost directly east, as evident in Figure 14. At 27295 meters, the balloon burst and the payload started to drop at 50 m/s with very little atmosphere to break the fall. At post-flight inspection, it was determined the burst to be particularly violent, as both of the still cameras had abruptly shut down at that point, without any photos captured or stored at the point of or after the burst. With the components of the flight train stretched to their limits, the force of the burst would have affected the payload directly. However, the cameras had managed to take photos all the way up to the highest altitude. Moreover, the log file stored by the GSM tracker shows that the Raspberry Pi was able to continue operating throughout the flight, although it had been programmed to have the watchdog module to reboot the device in case of failures.

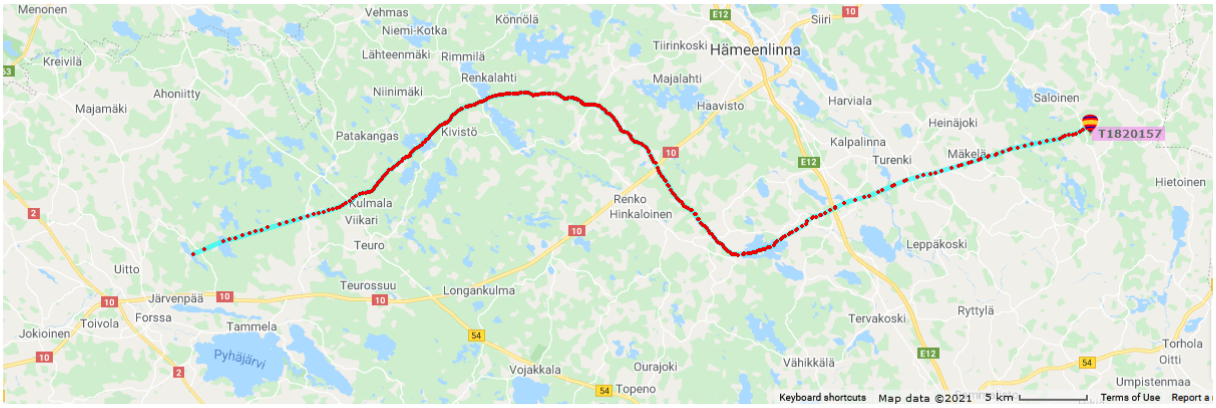


**Figure 14:** Flight trajectory of radiosonde T1820157 (APRS, 2021)

The small parachute acted first as a drogue, only slightly slowing down the fall, with an average descend speeds of 8 m/s below 10 km altitude. However, the flight still drifted far east, to a heavily forested area, with the final descend speed of 5,9 m/s near ground level, indicating a working parachute.

The GSM tracker had been designed to send messages to the gateway once every 5 minutes and to the backup phone once every 20 minutes. The total descent from 27 kilometers to ground took only 40 minutes, with the first message sent to both the gateway and the backup phone from an altitude of 296,48 meters. The prior altitude five minutes before had been 2354,25 meters, which was not reported due to the limitations of activating the service only below 2000 meters. At this stage the payload was so close to the ground that the next message was the final landing position, 79,4 kilometers east of Jokioinen.

The FMI equipment in Jokioinen were better able to pinpoint the landing than with the first flight, projecting final coordinates of 60.94042 24.9099 at an altitude of 522,3 meters at 15:27 EET / 13:27 UTC (T. Laine, FMI, private correspondence, November 5, 2021). The APRS listening stations had more trouble tracking this, with Lempäälä station receiving the final message at an altitude of 4119 meters, and the Vähikkälä station being blocked by terrain behind the antenna towards this particular direction. However, the Hämeenlinna radio amateur tower OH3AA-1 was able to track the balloon to an altitude of 220 meters at coordinates 60.9430 24.9175 (APRS, 2021; Lewiński, 2021). The touchdown coordinates reported by the GSM tracker were 60.943376 24.918169 at an altitude of 123,76 meters, which is ground level, once again indicating a successful landing.

The difference between official FMI-provided coordinates was approximately 345 meters horizontally, 399 meters vertically and 527 meters in total. The APRS network was off only 25 meters horizontally, 96 meters vertically and 99 meters in total. Naturally, the horizontal difference is the most important in terms of locating the payload, in which the APRS network came quite close. The visualizations of the locations are available in Appendix 1.

For the LoRa module, the final coordinates reaching the receiver were 60.82351 23.53882, which is 2,43 kilometers northeast from the launch site of Jokioinen. Once close to the final landing site, the LoRa receiver was again able to pick up the signal, but only after the payload had already been recovered and was being transported back to the vehicles.

Unfortunately, the landing site was in the middle of a forest, five meters from a lake. The surrounding area was mainly soft marsh among pine trees, blocked from the nearest road by an extremely thick forest. However, the trees did not block the signal from the RS41, which the handheld radio signal tracker was able to pick up and project on a map (MySondy GO). This method was used as a backup for pinpointing the payload, but the coordinates sent by the GSM tracker, projected on Google Maps along with current location and heading of the phone, proved to be functioning well.

When the pickup crew arrived at the coordinates, it was already dark. However, the payload was located once again exactly at the coordinates reported by the GSM tracker. The box rested among the marsh hummocks, suspended marginally by the cords, with the parachute invisible in the treetops. Upon retrieval, the devices were one-by-one shut down.

The payload was in good working condition, except for the minor damage to the video cameras caused by the accident during the first launch attempt. Despite adversities, in terms of experimentation goals this second test was a success. The GSM tracker worked flawlessly, enabling a reliable low-cost method of pinpointing the landing position as well as providing a communications channel for the elevations not reachable by radio towers. Additionally, images from stratosphere were obtained for the use of the university, participating organizations and the researcher.

# 6 DISCUSSION

With alternative materials for components proposed in chapter three, alternative systems analyzed in chapter four and field tests conducted in chapter five, the findings of each can be used to identify the most suitable changes for transforming the current weather balloon system to a more environmentally friendly one. This chapter concludes these findings and proposes the most promising solutions. As the presented changes together can have varying impacts on the entire system, these alternatives and their total impact in comparison to the current model are further analyzed and presented. This enables a comprehensive and thorough overview of these solutions.

## 6.1 Findings on biodegradable materials

Radiosonde operations worldwide depend on two key features of the current operating model; minimal design leading to minimal module cost, and maximum scientific benefits without compromises on data quality.

The literature, patent and TRIZ method studies provided several applicable solutions for these systems, some of which are currently being developed and some that have potential to be used in this target application. From the overview on alternative solutions, it has become evident that there is no technology or process that can entirely replace the radiosonde. The penetration capabilities of both ground-based profilers as well as weather satellites is not yet at the level of being the only providers of weather data, even if working together. Specific layers of the atmosphere can only be reliably reached using a radiosonde.

Nevertheless, there are certain changes proposed by this research to the overall design of the radiosonde. While the latex balloon cannot be changed to an alternative, being the most degradable solution available at the moment, the color used in the balloon can be switched to, for example, blue at no additional cost. If the change in color can reduce accidental digestion by wild animals even by a small margin, with no cost impact it is well worth implementing.

The other components of the balloon train could be replaced with materials having a faster degradation rate. The highest impact towards nature in the current design comes from the EPS styrofoam shell, which can break down into small particles at relative ease but remaining at nanoparticle level for hundreds of years. Those particles are digested by animals, either through smaller animals such as insects or through vegetation. The protein corona surrounding the polystyrene nanoparticles enables penetration through internal membranes, with the plastic molecules ending up on our plates (Kik *et al*., 2020). Switching to a biodegradable alternative would bring major benefits to the entire environmental impact of the radiosonde structure, as evident in chapter 6.3.

While the rigging is usually also made of non-biodegradable plastic, from an environmental perspective it could be argued that the current requirements for the rigging are too high, considering the tensile strength of the current string. While the cord needs to withstand the weight of the radiosonde and the turmoils in the atmosphere, it only needs to do so for a very short period of time. The target utilization area is the journey up, lasting approximately an hour in extreme conditions of thunderstorms, +50 °C to -90 °C degrees and 8 G-forces. In cases where parachutes are used, the use range is extended to two hours. As such, it would be beneficial to investigate which materials would withstand the weight of a 100-gram module for two hours in such an environment but beginning to degrade faster over time. This of course brings challenges to logistics and shell life, but with proper storage the risk of contaminating the rigging early could be minimized. Therefore, there is very little harm in investing in storage solutions to keep the disposable, single-use units at ideal condition.

The parachutes are currently getting an overhaul, from non-biodegradable nylon to biodegradable polybutylene-succinate. This change is pending trials with the Bureau of Meteorology in Australia, but so far the results have been promising. Worldwide interest in biodegradable parachutes is evident in more and more supplies becoming available. Moreover, the radar targets could also be modified to specifically act as drogues, in areas where they could act as cheaper alternatives to the less risky parachutes.

Finally, the radiosonde itself can have only very little modifications, aside from the abovementioned shell replacement. With the dawn of biodegradable plastics, it might be worth to consider offering a more biodegradable version of the standard radiosonde, as an additional product. Such a device could feature biodegradable PCB boards, battery holders and a biodegradable shell, possibly colored brightly to repel animals as well as to stand out for retrieval. With further field tests and continued usage, the solutions onboard the radiosonde could be improved sooner, rather than waiting for ideal solutions to be born first. With climate change approaching fast and concern over the environment on the rise, it would be reasonable for businesses and manufacturers to start offering less permanent product versions, especially where the product itself is essentially a consumable. Naturally, there would be increased costs involved, which would need to be transmitted to the funding organizations, as demands for investments in a cleaner environment.

## 6.2 Findings on tracking and retrieval

The technologies behind external and internal tracking solutions were introduced and the applicability of these technologies tested in two field tests. From the data obtained through the experiments, it became evident that either type (or both) of tracking capabilities would need to be enhanced, to enable the retrieval of radiosondes. While many tracking and communication technologies has already been used, most of them are too expensive for daily operations. Therefore, the focus was to find a budget-friendly solution, which can be applied to every radiosonde flight.

In order to provide scientifically accurate weather data, radiosondes are absolutely necessary at the moment. However, from an environmental point of view, the most ecological radiosonde would be the complete absence of a radiosonde. As this cannot be achieved without compromising scientific data collection, the best solution would be to have the radiosondes in operation for the required time and then being collected. While none of the meteorological organizations can afford to travel the world in search of lost radiosondes, utilizing the public, such as hobbyists, travelers, and nature organizations, would be beneficial for both the environment as well as all parties involved. By openly declaring the landing locations of the radiosondes, the meteorological organizations would gain transparency and access to a vast network of innovators and logistics methods. The concerned would be able to effectively clean up their surroundings. Finally, the manufacturers could start recycling their units at higher efficiency, with higher degree of units being returned.

However, this recommendation also includes specific prerequisites. As a minimum, all meteorological organizations should enable descent tracking and transmission of the data. Not only does it bring scientific benefits, it enables better tracking of the radiosonde. Moreover, following in the footsteps of the Finnish Meteorological Organization, it has been evident that openly releasing the data, the benefits greatly outweigh any risks or concerns. If weather organizations truly wish to enable the mass retrieval of radiosondes, the data could quite easily be published on an international map service, using for example Google Maps, OpenStreetMap or Drupal as a baseline for reading the data from a public server. This could be achieved with as little as a single SQL server providing coordinates to an OpenStreetMap layer. As radiosondes can easily drift across country borders, an international cooperation providing global tracking solutions would be ideal. For inventory management, once a balloon is returned the founder could simply send the balloon's ID as an international text message or an automatically deciphered email to a central system which would remove the found radiosonde from the database and the map. It would be even possible to officially gamify the finding of lost radiosondes, similar to what Radiosondy.info has done.

The two field experiments provided useful data on the accuracy of using the current solution with a single antenna tracking the radiosonde, using several receivers at strategic points, and using an internal tracker communicating via existing mobile phone networks. The results of these flights are seen in the two images below, with the red pointers indicating the final coordinates received by the radio tower at the launch station, the green pointer indicating the final coordinates received by the APRS radio tower network around the region, and the blue pointer indicating the final coordinates transmitted via GSM network. These latter coordinates were also the points in which the payloads were found and collected.


**Figure 15:** Differences in final coordinates of T0830083 between current FMI receivers (red pointer), APRS network (green) and on-board GSM tracker (blue) (OpenStreetMap, 2021)


**Figure 16:** Differences in final coordinates of T1820157 between current FMI receivers (red pointer), APRS network (green) and on-board GSM tracker (blue) (OpenStreetMap, 2021)

The travelled distances between the two experiments were relatively similar, with 78,6 km with the first and 79,4 km with the second. However, the official FMI equipment lost contact with the first radiosonde at 775 meters' altitude while they were able to track the second balloon down to 522 meters. A topographical map of the region indicates areas of higher ground elevation between Jokioinen and the first landing site than along the trajectory towards the second landing site, therefore affecting radio communications (OVH SAS, 2017).

Because the final landing position and the last radio communication between the radiosonde and the launch site varies by ground elevation differences, wind conditions, descend speed, humidity and temperature, it is not possible to generate a straight-forward theoretical model for any standard deviation in relation to the distance travelled. For example, the two launches on November 4 produced two different final communications from two different altitudes, with distances to the final coordinates varying from 345 meters to over 1,5 kilometers. Therefore, as a generalization the coordinates provided by the last communication received by the meteorological organization are always off, from roughly hundred meters up to several kilometers in scale. Such a difference makes the radiosonde impossible to locate and retrieve if using radio communication alone for guidance, unless using specialized equipment to catch the radio transmission close to the predicted landing site.

While such methods have been commonly used by amateur balloon hunters in densely populated regions (Lewiński, 2021; MySondy GO, n.d.), it is not easily available for the general public, therefore requiring additional methods if the radiosondes are to be extensively retrieved.

As evident from the maps above (Figure 15 and Figure 16), depending on descend speed the network of receivers comes relatively close to the final coordinates, which has good potential for being used to track the radiosondes more accurately. Moreover, these trackers could be installed on ground weather stations around the country, therefore providing better coverage and therefore better accuracy in pinpointing the landing location. The RTL-SDR modules used in this experiment would be usable low-cost options for such a network, with the exception of the FC0012 module, which proved to be insensitive enough not to receive any good signals, despite a good antenna. The R820T2 and R828D tuners proved to be reliable and accurate.

In these two experiments the external network was only able to reach approximately 25-200 meters' accuracy, which may not be enough to reliably locate the radiosonde. Therefore, a GSM-based tracker would bring the highest benefits. While 2G networks are being decommissioned around the world, 4G has almost an equal coverage as 2G. Moreover, 4G modules are backwards compatible with older mobile networks, making a 4G module ideal for future use in such a tracker. With the dawn of the 5G network, the module costs for 4G are becoming reasonably low (Remmert, 2021; Alexiou, 2020).

Finally, the LoRa technology proved to be interesting, but in this price range not a viable option, as any workable solution would require more powerful transmitters, which still have the same challenge as current radio technology of being blocked by the curvature of the Earth on ground level. The LoRa network currently has a lot of holes in certain regions, therefore not having the same coverage as a mobile network. With the unit costs currently above any GSM technology, it does not seem a viable option for tracking the radiosondes, except in the absence of a radiosonde. For pinpointing the package close to the landing site, one might as well use the existing radiosonde signal and a receiver tuned to its radio frequency, rather than switch to another, relatively similar LoRa technology, unless LoRa would at some point in the future replace the currently used radio technology of the radiosondes.

### 6.2.1 The prototype tracker

The prototype shell and tracker produced for this experiment proved to be fully applicable candidates for enabling tracking below the horizon. The tracker system itself was capable of obtaining a signal fast and transmitting that signal reliably over a long period of time, being limited only by the subscription plan.

Upon collecting the tracker from its landing location, the three AA batteries were still producing a total of 4,9 volts, which indicates a healthy charge, good enough to keep the components running (Energizer, n.d.). The device had been sending messages for 11 hours straight after landing and the batteries were still in relatively good shape, which means that in terms of capacity they were oversized. For this experiment, they were selected for their capacity as well as capability to provide the 2A in burst required for a transmission (Pujar, 2020). However, smaller AAA batteries would have worked as well (Lygte-Info, 2020), which will be selected for future iterations of the tracker to reduce the overall weight by approximately 20 grams with smaller case included (Energizer, 2021) as well as to reduce the overall environmental impact of these batteries. With the tracker module weighting 85 grams with antennas, the change in battery size would reduce it to just 65 grams. This could be further reduced by replacing the relatively heavy 10-gram GSM antenna with a lighter version, or simply removing the plastic outer shell from the antenna. Moreover, if eSIM modules for 2G and 4G networks would become available in this price range, the overall weight of the module could be reduced to mere 60 grams. By embedding a 4G microchip to a microcontroller or a GPS module, the overall weight could be reduced even further.

Added weight to the radiosonde means slower ascend when using the same amount of gas. This in turn translates to increased drift, which could in theory cause the radiosonde to fly outside of the intended zone of operations and out of reach for retrieval personnel. If more gas is used, the balloon will burst sooner at a lower maximum altitude (T. Laine, FMI, private correspondence, November 8, 2021). However, the impact of doubling the weight of the payload, from current 75 grams to 205 grams, does have some effect on the performance of the balloon train. With the same amount of gas used, the lift is reduced, translating to a loss of approximately half a meter per second in ascend rate (at 4,5 m/s) and ten minutes longer flight time, while reaching the same altitude. If targeting the same ascend rate, approximately 200 liters of gas would need to be added to the balloon, resulting in balloon burst at lower altitudes (High Altitude Science, n.d.). Using Finland as an example, with current operations using around 900-1000 liters of hydrogen per sounding, costing 15 000 euros a year, the added gas would mean a 20% increase in gas purchasing, totaling 18 000 euros a year (T. Laine, FMI, private correspondence, November 11, 2021).

If eSIM subscriptions and modules became more affordable, they could be used as well, but for the time being it would be beneficial to negotiate deals with local and global mobile network operators for providing a single-use subscription SIMs, which would be activated when the device was turned on and had registered itself on the network. With the subscription active only for 24 hours, the operational costs could be kept at an absolute minimum.

Combined with the relatively good lambda values, *id est* insulating well as evident by the freezer test, the shell of the tracker had been oversized as well. The current shell had a weight of 45 grams, which could easily be reduced to 35 grams by using thinner walls. In terms of weather resistance, the biodegradable shell performed extremely well. Not only was the shell capable of keeping the internals well-insulated within a -60 °C environment, the waterproof paper prevented water from reaching the tracker module despite being left into the forest for almost 24 hours, out of which six were spend in a constant rain. For this experiment, the electronics were taped together with thin insulative tape, but most biodegradable alternatives would have worked as well.

With the changes proposed to the prototype tracker, the overall weight of the product could be reduced to less than 100 grams, from the current 130 grams. Moreover, with industrial manufacturing processes, the overall cost of the module, including batteries and the shell, could be well within the 10-euro threshold, making it a viable product to be used in radiosonde operations, at least for the most promising launch stations.

Additionally, if the mobile network capabilities were embedded to the radiosonde, as part of a product line offering environmentally friendly alternatives, the costs of using this technology would be even lower. In theory, it might be even possible to share the antenna between the modules, although this would cause complexity to the end product. Naturally, the development work and certifications are the most expensive parts of any new product, which can be reduced with mass production. Considering that a fully functional 4G smartphone can today be produced at a retail price of 20 euros (Alcatel MyFlip, using Qualcomm Snapdragon 210-SoC) (Alcatel, 2021), a 4G radiosonde tracker could easily be produced for less than 10 euros, including development, certification and peripheral costs. With enough orders for mass production, the final wholesale cost could potentially be closer to five euros per unit.

Considering the loss of the current radio signal at an altitude of 500-1000 meters, a tracker covering the rest of the way to the ground could additionally be used to provide scientifically relevant data. With constant tracking of the GPS location and by enabling faster communication rate, the wind conditions on ground level can be assessed very accurately, thus contributing to the overall model. The added benefit can mitigate the increased cost of the radiosonde operations, in addition to bringing transparency to the operations and promoting environmentally friendly processes. If the radiosonde would communicate measurements to the auxiliary port, this information could in theory be used as added content for the GSM communications, providing temperature and humidity data from ground level in potentially uncovered locations. Furthermore, the data could provide GPS coordinates for the tracker, therefore replacing the additional GPS module used in the current iteration.

### 6.3 Environmental impact analysis

In order to assess the “environmental friendliness” of these solutions, they were also compared and analyzed against the current model. This analysis draws from the findings of both the material alternatives as well as the technological solutions, in order to evaluate the impact of each current or proposed element as an integral part of the whole system. In this comparison, each component of the radiosonde train gets a weighted average impact value (WAI) which compares the weight of the component against the average biodegradation time in years, as sourced from literature. Therefore, the environmental impact in this analysis does not cover the manufacturing processes, as those are already considered and developed by the manufacturers, but rather seeks to consider the post-consumption impact when majority of these radiosondes and relevant components are discarded in nature.

Naturally, while the density and size of these components are not the same, the gram weight can still be used as an indicator to the overall impact of the specific component against the overall material amount. Adding density or size calculations into the model would cause marginal changes, affecting the weighted average impact only little. This is because while density of, let’s say, EPS is relatively low and the overall size of the product larger than with lithium batteries, on particle level the overall weight of the object gives the most comparable figures, close enough to be used for component impact comparison. It could be argued that one cannot easily calculate the biodegradation rate of “this” particular shell construct, but the given figures are estimates, approximations, using the best available knowledge so far.

Table 1 considers the average biodegradation times of a RS41 radiosonde. A WAI figure is calculated by dividing the weight of the component with the overall estimated weight of the radiosonde train multiplied by the degradation time. While rudimentary, it gives an indication and a comparable figure to be used to assess the impact of different scenarios. This is particularly useful, as currently there are no universally agreed methods for measuring environmental friendliness.

**Table 1:** Biodegradability of the current RS41 radiosonde (Ciriminna, 2020; Davis, 2019; IBC-M, 2019; Ioakeimidis *et al.*, 2016; Kimukai *et al.*, 2020; Smith, 2019; Vaisala, 2017c).

| **Component** | **Weight (g)** | **Average Biodegradation Time (y)** | **Weighted Average Impact (WAI)** | **Comments** |
|---|---|---|---|---|
| Latex balloon | 350 | 10 | 8 | |
| Unwinder | 10 | 32 | 1 | PET: 16-48 years |
| Unwinder's cord | 15 | 25 | 1 | Polypropylene cord: 20-30 years |
| EPS shell | 25 | 500-never | 28 | EPS Polystyrene: 500-1 000 000 years |
| Lithium battery | 29 | 100 | 6 | |
| PCB board + battery holder | 12 | 500-never | 13 | Plastics: 500 years, epoxy resin and fiber glass: never |
| Electronics + wires | 12 | 250-never | 7 | Silicone: 250, plastics: 500 years, copper: never |
| **TOTAL** | **453** | **500** | **9,0** | |

As evident from Table 2, the GSM tracker would only need to achieve a 10% retrieval rate to reduce the overall impact of radiosondes lost in wilderness, even if all of them would contain the tracker as well. This can be attributed to the biodegradable shell as well as the retrieval of electronics in larger quantities.

**Table 2:** Biodegradability of a radiosonde coupled with the prototype GSM module achieving higher retrieval rates (Ciriminna, 2020; Davis, 2019; IBC-M, 2019; Ioakeimidis *et al.*, 2016; Kimukai *et al.*, 2020; Plasser & Rahbaran, 2017; Smith, 2019; Vaisala, 2017c).

| **Component** | **Weight (g)** | **Average Biodegrada-tion Time (y)** | **WAI with 5% retrieval rate** | **WAI with 10% retrieval rate** | **WAI with 15% retrieval rate** | **WAI with 20% retrieval rate** | **WAI with 25% retrieval rate** |
|---|---|---|---|---|---|---|---|
| Latex balloon | 350 | 10 | 6 | 6 | 6 | 6 | 6 |
| Unwinder | 10 | 32 | 1 | 1 | 1 | 0 | 0 |
| Unwinder's cord | 15 | 25 | 1 | 1 | 1 | 1 | 1 |
| EPS shell | 25 | 500-never | 22 | 21 | 20 | 19 | 17 |
| Biodegradable shell | 35 | 0,5 | 0 | 0 | 0 | 0 | 0 |
| Lithium battery | 54,5 | 100 | 10 | 9 | 9 | 8 | 8 |
| PCB board + battery holder | 27 | 500-never | 24 | 22 | 21 | 20 | 19 |
| Electronics + wires | 24 | 250-never | 11 | 10 | 9 | 9 | 8 |
| **TOTAL** | **540,5** | **500** | **9,2** | **8,8** | **8,3** | **797** | **7,4** |

Table 3 below considers the impact of switching the current EPS shell and PCB board to biodegradable alternatives. As evident from the WAI figure, the impact is immediately reduced to less than half of the previous iteration of the product.

**Table 3:** Biodegradability of the current radiosonde utilizing biodegradable alternatives (Ciriminna, 2020; Davis, 2019; IBC-M, 2019; Ioakeimidis *et al*., 2016; Kimukai *et al.*, 2020; Kumar *et al*., 2010; Plasser & Rahbaran, 2017; Smith, 2019; Vaisala, 2017c).

| Component | Weight (g) | Average Biodegradation Time (y) | WAI |
|---|---|---|---|
| Latex balloon | 350 | 10 | 8 |
| Unwinder | 10 | 32 | 1 |
| Unwinder's cord | 15 | 25 | 1 |
| Biodegradable shell | 25 | 0,5 | 0 |
| Lithium battery | 29 | 100 | 6 |
| Biodegradable PCB board + battery holder | 12 | 1 | 0 |
| Electronics + wires | 12 | 250-never | 7 |
| **TOTAL** | **453** | **250** | **3,2** |

In table 4, the above scenario is coupled with the prototype GSM tracker.

**Table 4:** Biodegradability of the current radiosonde utilizing biodegradable alternatives, coupled with the prototype GSM module achieving higher retrieval rates (Ciriminna, 2020; Davis, 2019; IBC-M, 2019; Ioakeimidis *et al*., 2016; Kimukai *et al.*, 2020; Kumar *et al*., 2010; Plasser & Rahbaran, 2017; Smith, 2019; Vaisala, 2017c).

| Component | Weight (g) | Average Biodegradation Time (y) | WAI with 5% retrieval rate | WAI with 10% retrieval rate | WAI with 20% retrieval rate | WAI with 30% retrieval rate |
|---|---|---|---|---|---|---|
| Latex balloon | 350 | 10 | 6 | 6 | 6 | 6 |
| Unwinder | 10 | 32 | 1 | 1 | 0 | 0 |
| Unwinder's cord | 15 | 25 | 1 | 1 | 1 | 0 |
| Biodegradable shell | 60 | 0,5 | 0 | 0 | 0 | 0 |
| Lithium battery | 54,5 | 100 | 10 | 9 | 8 | 7 |
| Biodegradable PCB board + battery holder | 27 | 1 | 0 | 0 | 0 | 0 |
| Electronics + wires | 24 | 250-never | 11 | 10 | 9 | 8 |
| **TOTAL** | **538,5** | **250** | **4,0** | **3,8** | **3,5** | **3,2** |

From the above analysis, it is evident that enabling mobile network tracking can have major impact on the environment, with just 10% retrieval rates bringing benefits to nature. With 20% retrieval rates recorded in USA, 10% retrieval rate worldwide should be possible, even easy to achieve. If the shell and PCB board materials are switched to fully biodegradable alternatives, then the GSM tracker would need to achieve 30% recovery rates to justify its use. Therefore, it might be worthwhile to test the feasibility of added tracking capabilities, to promote the locations to the public through easy-access map services and meanwhile move to biodegradable alternatives. Moreover, by embedding the capabilities to, for example, alternative variations of the current radiosonde product, the overall impact is reduced by even low retrieval rates offering high environmental value. This would in essence mean that radiosondes could have 4G-enabled versions, with built-in GSM trackers and biodegradable shells, or standard radio versions with biodegradable shells designed for remote locations, as environmentally friendly alternatives.

Finally, if biodegradable alternatives would emerge in the market soon, a GSM tracking module could be replaced by a prediction model, which uses the open data of the soundings to calculate a probable landing location. With a network of receivers, the final landing path could be accurately plotted, as the final received coordinates would be close enough to the ground to be usable for retrieval purposes. The predicted landing coordinates, along with the trajectory of the flight, could be published online on a map service by the meteorological organization for anyone to use. Therefore, instead of investing in onboard tracking solutions, the focus would be on external tracking, although as evident from the above research cannot be as accurate as internal tracking systems. It is therefore a matter of reliability of the given information as well as the speed at which radiosondes turn “green”, whether to invest in tracking the radiosondes accurately and enabling their retrieval, or to invest in predictive models with less accuracy and slightly lower retrieval profile.

# 7 CONCLUSIONS

This research focused on providing answers to the following question: In what ways is it possible to reduce the environmental impact of weather balloon operations?, as well as three sub-questions: 1) Can biodegradable materials be reliably used in scientific research or weather observations in Earth’s atmosphere?, 2) which technologies and materials would reduce the environmental impact of atmospheric sounding, considering the limited budgets of meteorological institutes?, and 3) what investments in infrastructure could prevent atmospheric sounding from harming the environment?

The research found that by replacing some of the plastic components of a radiosonde with biodegradable or relatively less robust alternatives as well as using alternative colors, the environmental impact of weather balloon operations could be reduced significantly. By field experiments, one feasible alternative was tested and proven efficient enough to be used for scientific research. For easier collection of used radiosondes, different tracking methods were analyzed and the most accurate one identified as on-board trackers utilizing existing mobile networks, due to the almost complete coverage of populated land with any kind of cellular network. Such trackers can evidently be made cost-efficient, suitable for the budgets of meteorological institutes. Moreover, they can be used to provide weather data near ground level in locations not covered by any weather station network, adding scientific value to the module.

In terms of infrastructure, by investing in electric profiling technologies, to satellites, to a radio signal receiver network and especially to open access to data, weather organizations around the world can have a direct impact on the environmental friendliness of their daily operations. This can be achieved by enhancing the current research on remote sensing. Moreover, by improving the external tracking of the current radiosonde, by installing low-cost receiver nodes at weather stations or mobile towers, predictive models could be used to indicate the landing location of the payload within a radius of few dozen meters and less. The tighter the network, the more accurate the prediction.

The end goal is to enable radiosonde retrieval, rather than allowing the equipment get lost with every launch. Organizations have the option to either invest in onboard consumable-type cellular tracking systems, therefore utilizing the existing networks for receiving highly accurate location data, or alternatively invest in a more permanent receiver network, by adding low-cost radio receiver nodes to existing infrastructure. Both models should be reinforced with an open-access cloud database and a prediction model based on the actual data, with the final coordinates published on an international map service. The investments would effectively allow anyone to locate and retrieve the radiosonde.

Future research would be required to assess additional biodegradable solutions. Moreover, improvements to the GSM tracker would need to be tested for the product to become valuable in daily operations. This can be achieved in collaboration between meteorological organizations, radiosonde manufacturers and electronics producers. Finally, predictive models would need to be developed based on open data currently available through the FMI Open Data network, to assess the accuracy of such models in wider use.

This research has contributed to the available academic literature on the subject through various research methods. Moreover, by giving an overview of the key aspects related to the research field, managerial decisions can be made in terms of investments as well as Research and Development efforts. By generating discussion around the subject, new kinds of solutions and innovations can be achieved. Finally, photos from the stratosphere were produced to be used in education by the relevant parties (Figure 17).

As evident by the current climate crisis, the environment requires actions, the sooner the better. Both academic and scientific communities are at the front seat producing solutions to combat this threat. With up to a million radiosondes being lost in nature every year, bold managerial decisions are required. By “right-sizing” the current operations, by offering alternative products suited for the target environment rather than utilizing one heavy-duty solution for all, the overall impact of these operations are reduced. Radiosonde composition can be altered with biodegradable solutions, to be used in regions where they are best suited. For weather research, this may mean a minor increase in failures, but if the total environmental impact is reduced with very little effect on the mass of data obtained otherwise, the tradeoffs would be rational. For producers and end users, the addition of alternatives biodegradable models may incur added costs, but such cost increases are inevitable if environmental responsibilities are upheld. As the public demands more actions, weather organizations have the opportunity to answer this call and offer solutions, such as those presented in this research.


**Figure 17:** A sunset at an altitude of 27,3 kilometers (private photo, November 4, 2021)

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Appendix 1. Images of tracking systems' output

**FMISID:** 101104
**Luotaus ID:** 432893
**Observation ID:** 3058

**Luotausaika:** 04.11.2021 08:00
**Laukaisuaika:** 04.11.2021 08:09
**Päättymisaika:** 04.11.2021 09:16
**Kestoaika:** 68 min
**Tietokannassa:** 04.11.2021 08:59
**Tallennusviive:** 59 min
**Julkaisuaika:** 04.11.2021 08:59
**Julkaisuviive:** 59 min

**Figure 18:** T0830083 launch data packet from FMI system

**FMISID:** 101104
**Luotaus ID:** 432894
**Observation ID:** 22240

**Luotausaika:** 04.11.2021 09:00
**Laukaisuaika:** 04.11.2021 09:20
**Päättymisaika:** 04.11.2021 10:53
**Kestoaika:** 93 min
**Tietokannassa:** 04.11.2021 11:07
**Tallennusviive:** 127 min
**Julkaisuaika:** 04.11.2021 11:07
**Julkaisuviive:** 127 min

**Sondimalli:** Tuntematon! (141)

**Figure 19:** T0830083 final data packet from FMI system

**Valitun luotauksen havainnot:**

**Näytä** ◉ **vain merkittävät luotaustasot** ○ **kaikki luotaustasot**

| Taso | Tila | Aika (s) | Korkeus (m) | Paine (hPa) | Lat | Lon | Merkittävyys | S1 | S2 | S3 | S4 | S5 | S6 | S7 | TAP | TDP | RHP | UAP | WSP | WDP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 5566 | 775.2 | 911.58 | 61.32534 | 24.40803 | 14336 | | | | | 1 | 1 | 1 | 3.46 | 3.46 | | | 12.1 | 234 |
| 100 | 0 | 5370 | 1339.1 | 850 | 61.31428 | 24.37584 | 65536 | | 1 | | | | | | -.14 | -.23 | | | 9.3 | 232 |
| 292 | 0 | 4986 | 2344.5 | 748.68 | 61.29613 | 24.31741 | 12288 | | | | | 1 | 1 | | -6.45 | -6.45 | | | 11.3 | 240 |
| 300 | 0 | 4970 | 2387.8 | 744.57 | 61.29534 | 24.31445 | 12288 | | | | | 1 | 1 | | -4.24 | -13.96 | | | 11.7 | 239 |
| 393 | 0 | 4784 | 2871.7 | 700 | 61.28446 | 24.28065 | 65536 | | 1 | | | | | | -7.38 | -19.71 | | | 11.3 | 237 |
| 493 | 0 | 4586 | 3426.8 | 651.47 | 61.27363 | 24.23948 | 2048 | | | | | | | 1 | -10.56 | -36.57 | | | 14.6 | 243 |
| 498 | 0 | 4576 | 3455.5 | 649.05 | 61.27305 | 24.23707 | 12288 | | | | | 1 | 1 | | -10.73 | -36.41 | | | 14.6 | 243 |
| 644 | 0 | 4284 | 4334.8 | 577.87 | 61.25355 | 24.17148 | 8192 | | | | | 1 | | | -18.54 | -36.64 | | | 14.5 | 232 |
| 706 | 0 | 4160 | 4681.9 | 551.53 | 61.24114 | 24.14499 | 4096 | | | | | | 1 | | -19.68 | -48.54 | | | 17.5 | 224 |
| 708 | 0 | 4156 | 4692.6 | 550.73 | 61.24069 | 24.14408 | 12288 | | | | | 1 | 1 | | -19.73 | -48.55 | | | 17.7 | 224 |
| 719 | 0 | 4134 | 4750.8 | 546.42 | 61.23807 | 24.13904 | 2048 | | | | | | | 1 | -20.18 | -48.73 | | | 18.2 | 222 |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | | | | | | [illegible] | [illegible] | | | [illegible] | [illegible] |

Appendix 1. Images of tracking systems' output

**Figure 20:** T0830083 landing observations from the FMI system

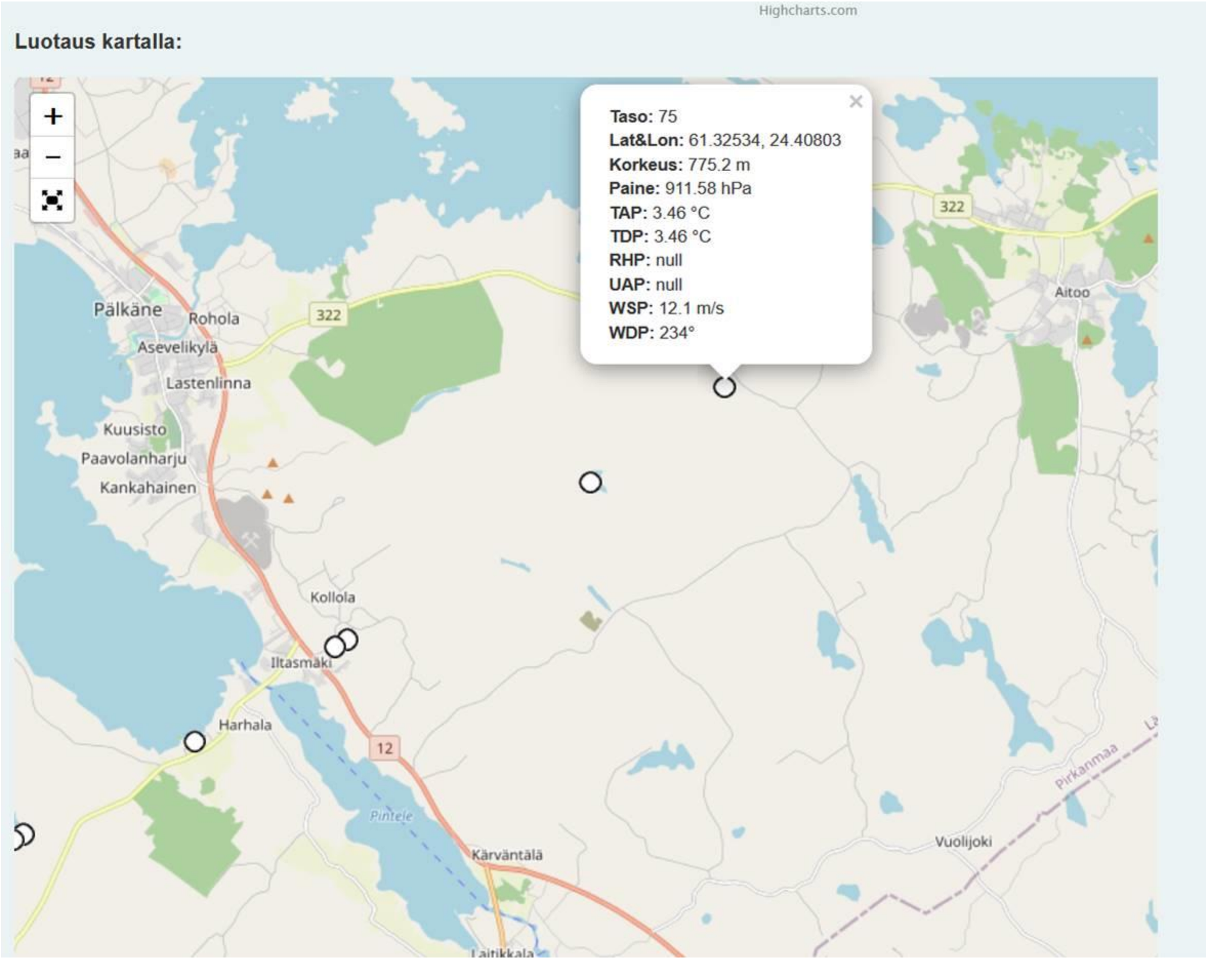


**Figure 21:** Visual representation of the T0830083 landing from the FMI system

**Valitun luotauksen metatiedot:**

**FMISID:** 101104
**Luotaus ID:** 432936
**Observation ID:** 3058

**Luotausaika:** 04.11.2021 12:00
**Laukaisuaika:** 04.11.2021 12:05
**Päättymisaika:**
**Kestoaika:**
**Tietokannassa:** 04.11.2021 12:55
**Tallennusviive:** 55 min
**Julkaisuaika:**
**Julkaisuviive:**

**Figure 22:** T1820157 launch data packet from FMI system

Appendix 1. Images of tracking systems' output

**Valitun luotauksen metatiedot:**

**FMISID:** 101104
**Luotaus ID:** 433022
**Observation ID:** 22240

**Luotausaika:** 04.11.2021 13:00
**Laukaisuaika:** 04.11.2021 13:27
**Päättymisaika:**
**Kestoaika:**
**Tietokannassa:** 04.11.2021 14:14
**Tallennusviive:** 74 min
**Julkaisuaika:**
**Julkaisuviive:**

**Figure 23:** T1820157 final data packet from FMI system

**Valitun luotauksen havainnot:**

**Näytä** ◉ **vain merkittävät luotaustasot** ○ **kaikki luotaustasot**

| Taso | Tila | Aika (s) | Korkeus (m) | Paine (hPa) | Lat | Lon | Merkittävyys | S1 | S2 | S3 | S4 | S5 | S6 | S7 | TAP | TDP | RHP | UAP | WSP | WDP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 2026 | 522.3 | 928.73 | 60.94042 | 24.9099 | 14336 | | | | | 1 | 1 | 1 | 4.05 | 4.05 | | | 9.9 | 237 |
| 3 | 0 | 2024 | 555 | 925 | 60.94025 | 24.90957 | 65536 | | 1 | | | | | | 3.89 | 3.58 | | | 10 | 237 |
| 23 | 0 | 1984 | 871.9 | 889.54 | 60.93835 | 24.90349 | 2048 | | | | | | | 1 | 1.98 | 1.98 | | | 10.4 | 239 |
| 45 | 0 | 1940 | 1141.7 | 860.22 | 60.937 | 24.89584 | 2048 | | | | | | | 1 | .33 | .33 | | | 8.8 | 259 |
| 53 | 0 | 1925 | 1237.7 | 850 | 60.93673 | 24.89366 | 65536 | | 1 | | | | | | .01 | -.7 | | | 8.7 | 255 |
| 99 | 0 | 1834 | 1849.3 | 787.09 | 60.93506 | 24.87949 | 2048 | | | | | | | 1 | -4.19 | -4.19 | | | 7 | 244 |
| 106 | 0 | 1820 | 1966.6 | 775.46 | 60.93456 | 24.87808 | 12288 | | | | | 1 | 1 | | -4.88 | -4.88 | | | 8.5 | 240 |
| 123 | 0 | 1786 | 2226.6 | 750.31 | 60.93346 | 24.87141 | 8192 | | | | | 1 | | | -3.86 | -10.75 | | | 14.4 | 259 |
| 128 | 0 | 1776 | 2295.5 | 743.78 | 60.93317 | 24.86851 | 4096 | | | | | | 1 | | -3.89 | -12.35 | | | 15.4 | 262 |
| 129 | 0 | 1774 | 2307.2 | 742.68 | 60.93315 | 24.86783 | 2048 | | | | | | | 1 | -3.92 | -12.37 | | | 15.5 | 262 |

**Figure 24:** T1820157 landing observations from the FMI system

Appendix 1. Images of tracking systems' output

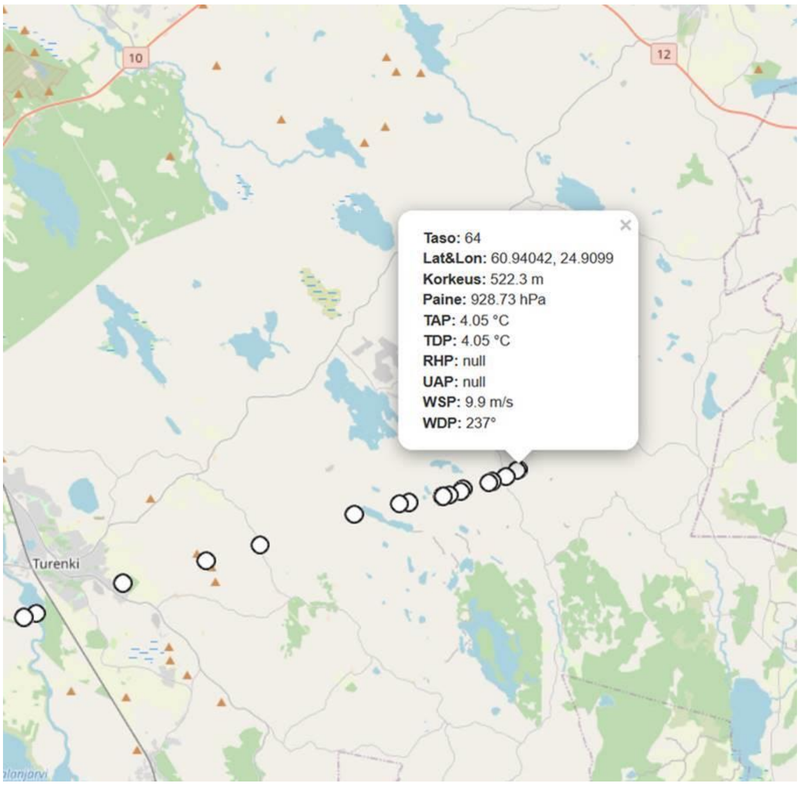


**Figure 25:** Visual representation of the T1820157 landing from the FMI system

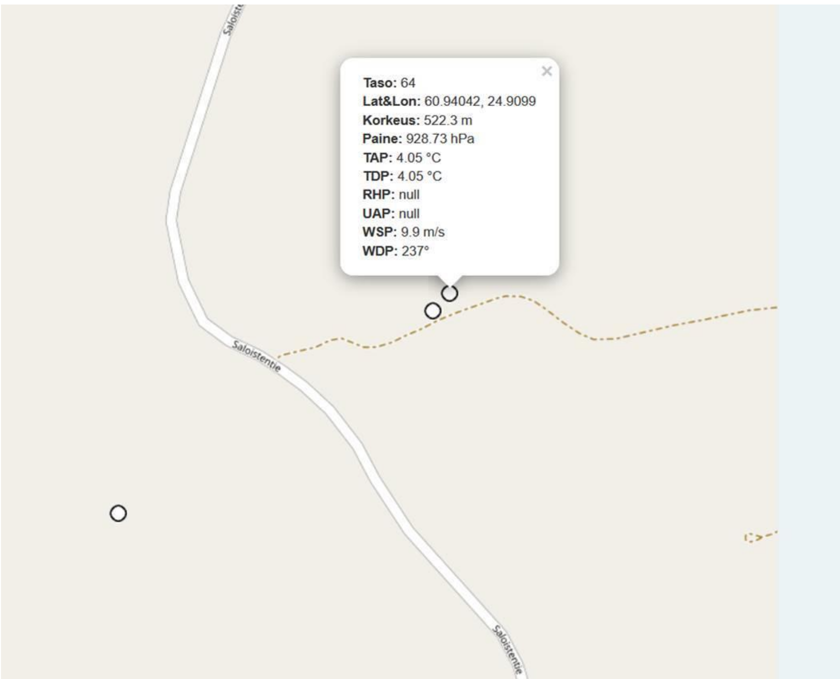


**Figure 26:** Visual representation of the final T1820157 landing site from the FMI system

(T. Laine, FMI, private correspondence, November 5, 2021)

Appendix 1. Images of tracking systems' output

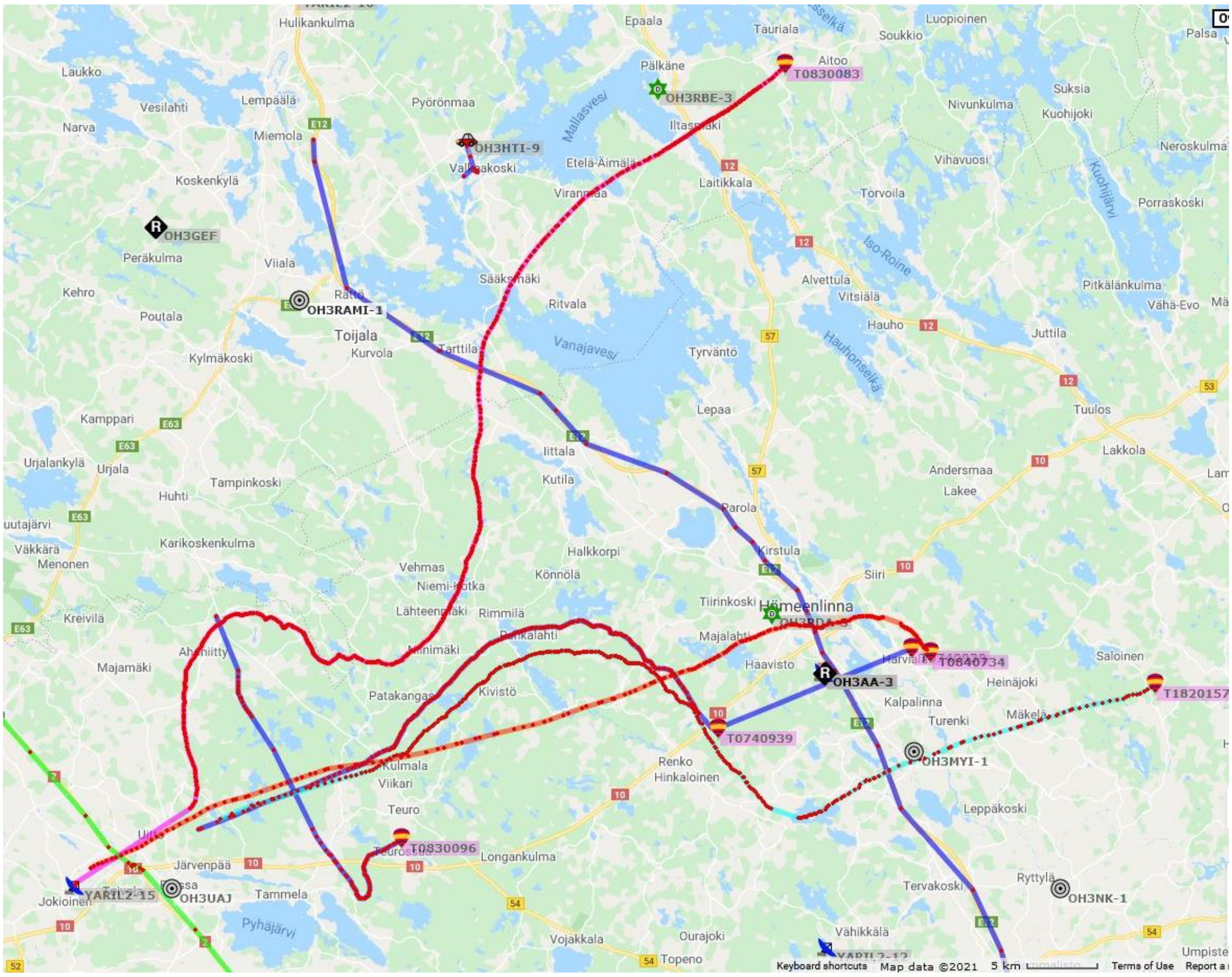


**Figure 27:** APRS map with trails of balloon launched on November 4, 2021 (APRS, 2021)

Appendix 1. Images of tracking systems' output

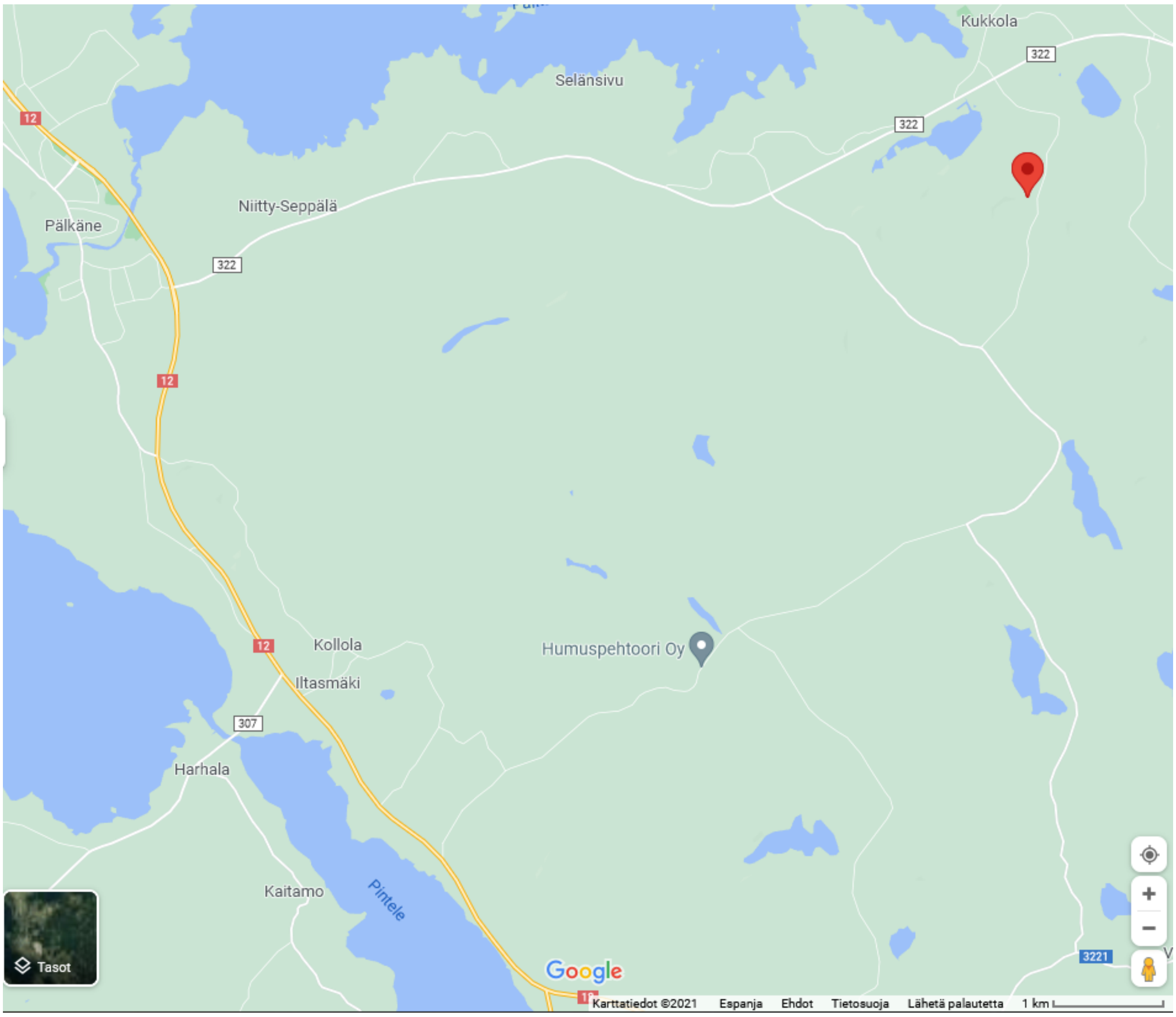


**Figure 28:** The coordinates of T0830083 as reported by the GSM tracker (Google, n.d.)

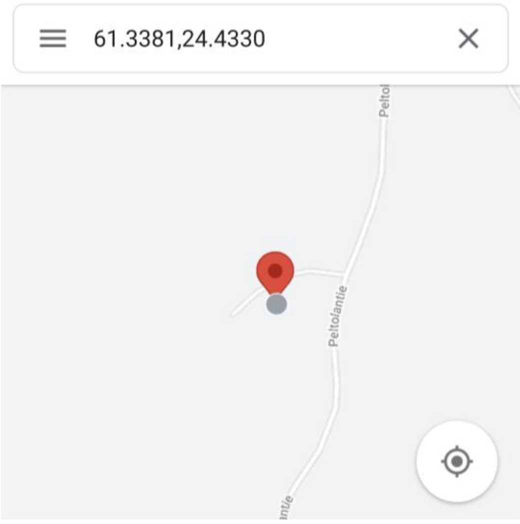


**Figure 29:** Close-up of the GSM tracker's reported coordinates for T0830083 and the physical location of the phone used for navigation (gray dot) at the point of retrieval (Google, n.d.)

Appendix 1. Images of tracking systems' output

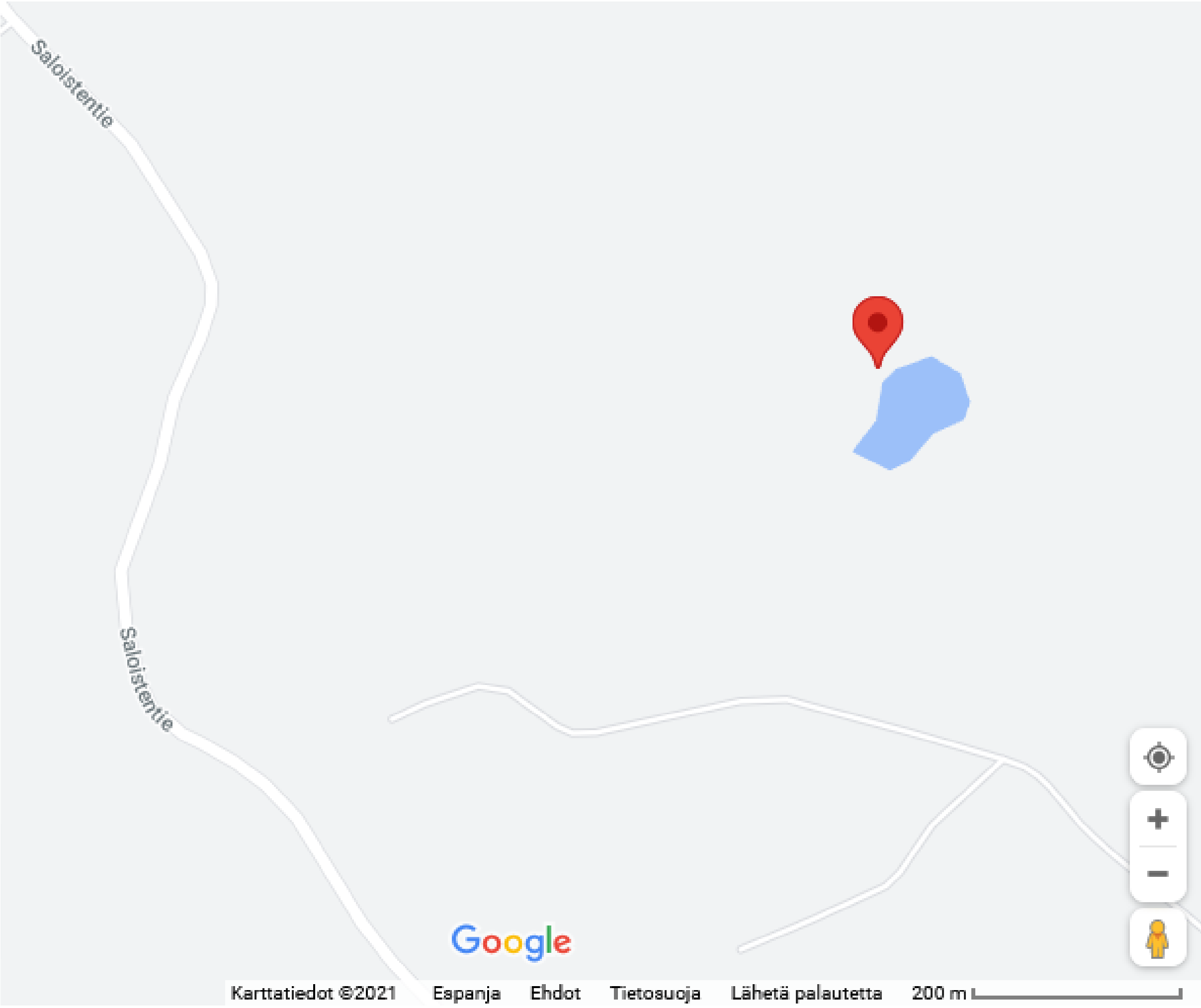


**Figure 30:** The coordinates of T1820157 as reported by the GSM tracker (Google, n.d.)

Appendix 1. Images of tracking systems’ output

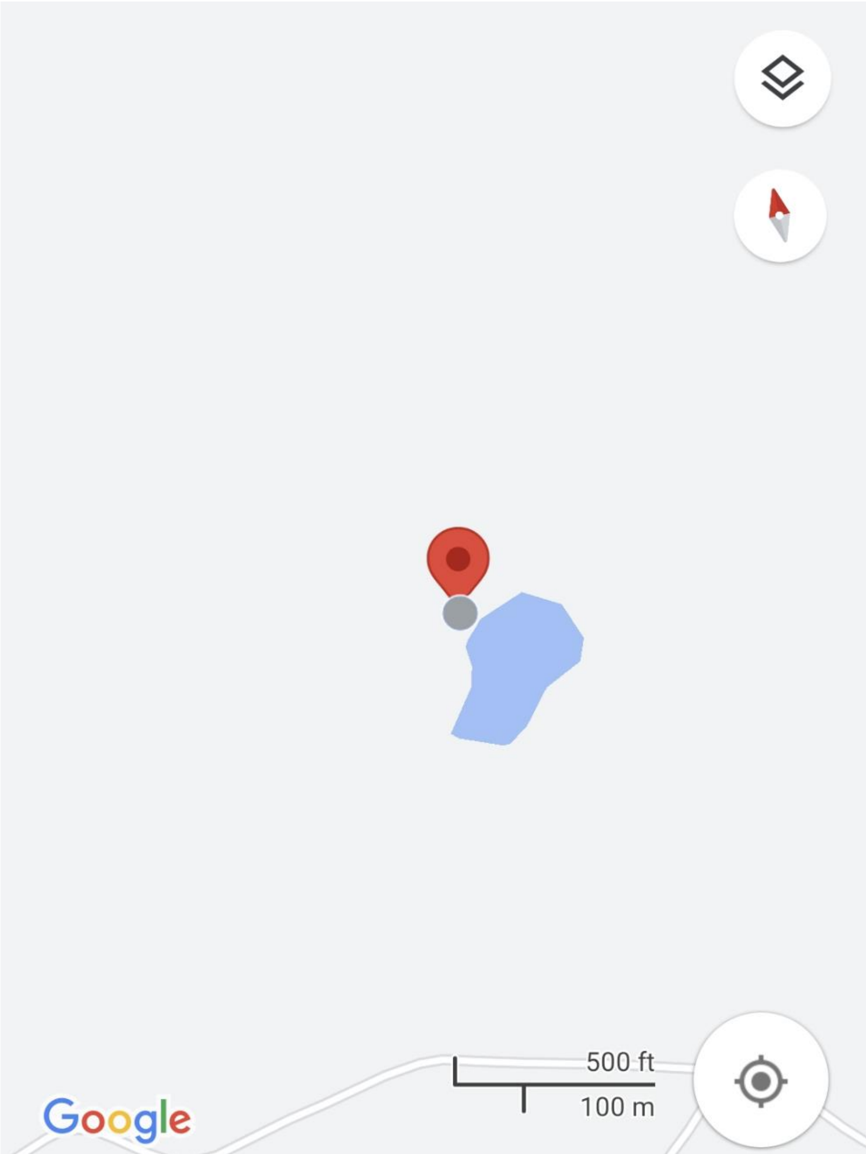


**Figure 31:** Close-up of the GSM tracker’s reported coordinates for T1820157 and the physical location of the phone used for navigation (gray dot) at the point of retrieval (Google, n.d.)

Appendix 2: Raspberry Pi Pico GPIO pin configuration for Arduino IDE

Location of Arduino pin source file:
%UserProfile%\AppData\Local\Arduino15\packages\arduino\hardware\mbed_rp2040\2.2.0\variants\RASPBERRY_PI_PICO\pins_arduino.h

These rows had to be added or modified:

```
#define SERIAL_HOWMANY                    3
#define SERIAL2_TX      (8u)
#define SERIAL2_RX      (9u)

#define SERIAL_PORT_HARDWARE1       Serial2
#define SERIAL_PORT_HARDWARE_OPEN1  Serial2

#define SERIAL3_TX      (12u)
#define SERIAL3_RX      (13u)

#define SERIAL_PORT_HARDWARE2       Serial3
#define SERIAL_PORT_HARDWARE_OPEN2  Serial3
```