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Atmospheric Measurement Techniques
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Return glider radiosonde for in situ upper-air research measurements

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Abstract. Upper-air balloon soundings for weather predictions have been made since the beginning of the 20th century. New radiosonde instruments for in situ humidity-, radiation- and gas-profile measurements in the troposphere and the lower stratosphere, were introduced in recent years for atmospheric research and climate monitoring, but such instruments are often expensive and it is desired they be reused on multiple flights. Recovering instruments that freely descend with parachutes is time consuming, sometimes difficult and even dangerous. Here, we introduce the return glider radiosonde (RGR), which enables flying and retrieving valuable in situ upper-air instruments. The RGR is lifted with weather balloons similar to traditional radiosondes to a preset altitude, at which time a release mechanism cuts the tether string, and a built-in autopilot flies the glider autonomously back to the launch site or a desired preprogrammed location. Once the RGR reaches the landing coordinates it circles down and releases a parachute 100 m above ground for landing. The motivation for this project was to measure radiation profiles throughout the atmosphere with the same instrument multiple times and with a rapid turn-around time. The paper describes technical aspects of the return glider radiosonde and the built-in radiation instruments and shows test flights up to 24 km altitude that are analyzed in terms of flight performance and maximal distances covered. Several successive flights measuring radiation profiles demonstrate the reliability and the operational readiness of the RGR, allowing new ways for atmospheric in situ research and monitoring with payloads up to several kg depending on the specific size of the glider.

1 Introduction

Balloon-borne instruments have been used for in situ atmospheric measurements for more than 100 years (Hoinka, 1997). Instruments that send data from weather balloons to the ground using small radio-frequency transmitters, now commonly known as radiosondes, were invented by the French scientist Robert Bureau in 1929. Some radiosondes are now capable of capturing and transmitting data from other instruments, greatly expanding the measurement capabilities of balloon-borne payloads.

With strong evidence of climate change and a refined knowledge that atmospheric composition in the upper troposphere and lower stratosphere (UTLS) plays an important role regarding radiative effects in Earth's climate system (Forster and Shine, 2002; Solomon et al., 2010), upper-air climate observations have been given more attention in recent years. The Global Climate Observing System (GCOS) Reference Upper Air Network (GRUAN) is designed to produce long-term, climate-quality records of essential climate variables in the troposphere and stratosphere at 20–30 globally distributed sites (Trenberth et al., 2002; GCOS-112, 2007; Seidel et al., 2009; Bodeker et al., 2015).

While the primary objectives of GRUAN are to monitor changes in temperature and water vapor profiles in the lower troposphere and the UTLS (Thorne et al., 2005; Randel et al., 2006), in situ upper-air radiation profile measurements recently revealed interesting insight in the absorption and emission of radiation in the atmosphere in addition to the full radiation budget as a function of altitudes (Philipona et al., 2012). The radiation measurements were made with a double-balloon technique, which reduces the pendulum motion during ascent and provides a slow descent with the

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parachute balloon (Kräuchi et al., 2016). However, despite numerical model calculations to predict flight trajectories, sophisticated GPS (Global Positioning System) technology and the slow balloon descent, the recovery of the valuable payload is still risky, difficult and time consuming, particularly in mountainous terrain or coastal areas.

Here, we describe a ballooning technique that is based on the experience made with the double balloon technique, but uses a new technology to return the payload. The return glider radiosonde (RGR) consists of a flying wing with a built-in radiosonde, a release mechanism, an autopilot and a parachute for autonomous landing. The RGR was conceived for atmospheric radiation profile measurements, but could be used for other atmospheric measurements. Short- and long-wave radiation sensors are therefore integrated in the wings of the glider. In Sect. 2 we discuss general aspects of different flying systems. Section 3 shows the flight procedure and Sect. 4 the glider's hardware and scientific instruments. Section 5 describes the electronics and Sect. 6 the software. Results from the initial flights are presented in Sect. 7 showing flight performance and maximum flight distance. Section 8 presents research measurements with the RGR and Sect. 9 finishes with conclusions and an outlook for new possibilities for this technique in advanced atmospheric research and climate monitoring.

2 Choosing an autonomous flying system

Descending a payload from high altitudes in a controlled manner can be achieved in different ways. Two approaches were considered, namely flying the payload by a parafoil system, or by integrating the payload into a small aircraft. Both systems have advantages and disadvantages, which are discussed in the context of returning the payload to the location where it was launched.

2.1 Parafoil guiding system

Parafoil systems have been used for several years on airplanes to deploy supplies in remote areas safely to the ground (Gupta et al., 2001). Parafoils are compact and similar to currently used parachutes on regular radiosondes, but with additional control over the descending direction. All the electronics and batteries for steering the parafoil fit into a small styrofoam box attached to the radiosonde. The costs of such a system are therefore rather low, and no special training for the sounding operator is needed to launch this system. However, radiosondes fall from altitudes greater than 24 km, where the air pressure is 30 times lower than ground pressure. This low air pressure is the major problem for this technique since a parafoil system relies on the dynamic pressure during flight to keep its shape, inflating the parafoil once released from the balloon. A group from NASA Ames Research Center has made numerous experiments with high altitude parafoil guiding systems with mixed results (Benton and Yakimenko, 2013).

2.2 Fixed-wing aircraft

Small propelled unmanned aerial vehicles (UAVs) have become very popular in the scientific community over the past few years, opening new possibilities in acquiring different data sets in the lower atmosphere. UAVs can have very different payloads and are generally propelled by gas or battery-powered engines depending on payload size and weight. Over the past few years carbon fiber materials became readily available and are currently widely used for building strong air frames which are light weight. Handling and crafting this material needs special know-how and expertise to build strong and rigid air frames.

Expanded polypropylene (EPP), which has gained popularity in the amateur model aircraft scene, is another promising material for building small aircrafts. EPP is very light weight, easy to handle and has good properties in terms of absorbing kinetic impacts while retaining its original shape. Moreover, the material is similar to the expanded polystyrene (EPS) used for radiosonde boxes, hence the knowledge to craft and handling this material already exists.

For fixed wings, different shapes and airfoils are available to best suit our application in terms of flying distance and payload storage. In our case the airframe profile needs to be kept as narrow as possible to not disturb the scientific measurements. However, there are other difficulties which need to be addressed when operating an aircraft at high altitudes. The material used needs to withstand low temperatures in the stratosphere and large and rapid temperature changes reentering the troposphere. Due to the very low air pressure in the stratosphere the aircraft needs to fly much faster to generate the same lift as would be required at low altitudes. Since little information is available about test flights in those challenging regions, air testing starting at low and progressing towards higher altitudes is required to characterize the aircrafts performance.

2.3 Flying wing

In terms of flight performance, even non-propelled aircrafts reach considerably higher forward speeds in high altitude winds than parafoil systems, and can therefore cover greater distances back to the original launch site. Even though the parafoil system has advantages in terms of simplicity, the problems at high altitudes and the lack of flying long distances were crucial and motivated us to investigate a carrier system based on a model aircraft.

Several model aircrafts with a variety of different wing profiles, weight and flight characteristics have been evaluated. Electronic components need to be stored in the payload area and special scientific instruments have to fit into the wings. Therefore, the most suitable fixed wing available to build the return glider radiosonde was a tailless flying wing. The drag of a proper flying wing compared to a regular fixed wing aircraft with a vertical stabilizer is greatly reduced, and the gained structural stability due to the increased wing depth are considerable advantages for our application (Mader and Martins, 2012). The tailless feature was a further benefit since a vertical stabilizer would obstruct the radiation instruments on the glider. To stay within the payload limitations of a balloon-born sounding (which is 2 kg) it was important to keep the weight of the fully equipped aircraft as low as possible. Therefore, the flying wing was designed without a propulsion system to reduce its weight.

3 Flight procedure

Handling the return glider radiosonde is similar to a regular radiosonde, except that due to the radiation measurements the RGR is lifted in controlled horizontal position during the ascent. Weather balloons with a corresponding free lift need to be prepared to raise the glider with an ascending speed of 5 m s^{-1}. Before launch the radiosonde is initialized on a computer and predetermined flight parameters are set in the autopilot for the release altitude, the landing coordinates and the optional emergency landing coordinates. After disconnection from the computer, data transmission at the desired frequency is checked and the RGR is attached to the tether string of the balloon and launched (Fig. 1, left). During the flight the return glider radiosonde transmits its position and all measured physical parameters, but flies fully autonomous without receiving information from the ground.

As soon as the pre-set altitude is reached, the glider detaches itself from the balloon and starts flying back towards the landing site. During the flight back, the autopilot monitors the flight performance and decides whether it is possible to reach the launch station or whether it needs to choose one of the emergency landing sites nearby. After reaching a preprogrammed landing site, a spiral pattern towards the ground is initiated. While spiraling down the altitude is constantly monitored to finally release the parachute 100 m above the ground for landing (Fig. 1, right).

If the glider reaches an altitude of 2000 m above sea level (m a.s.l.) but is still not within 2000 m of any landing site, or if a malfunction with any electronic component or software is detected, the parachute is released for an emergency landing. All decisions made by the autopilot are transmitted via the radiosonde to inform about its next steps.

4 Flight hardware and scientific instruments

4.1 Flying wing hardware

The flying wing has a wingspan of 1.4 m and is made out of the special foam EPP, which is covered with a 100 µm thin laminate film to protect the EPP foam (Fig. 2). The aircraft is controlled by two steering surfaces, called elevons. All electronics except the servos that move the elevons are stored inside the payload area in the middle section of the flying wing. The payload area is made out of two styrofoam boxes, which allow maximum storage space for the radiosonde, batteries, the release mechanism and the navigation devices. The boxes are glued on top of each other and designed for radiosonde application to withstand extreme cold temperatures even under high airflow when descending.

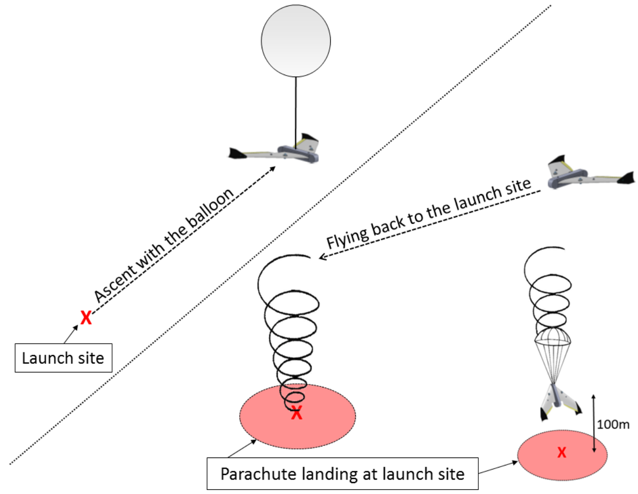

Figure 1. Schematic of ascent with the balloon (left), and descent with the RGR flying back to the launch site (center). After circling down the RGR releases a parachute for landing 100 m above ground (right).

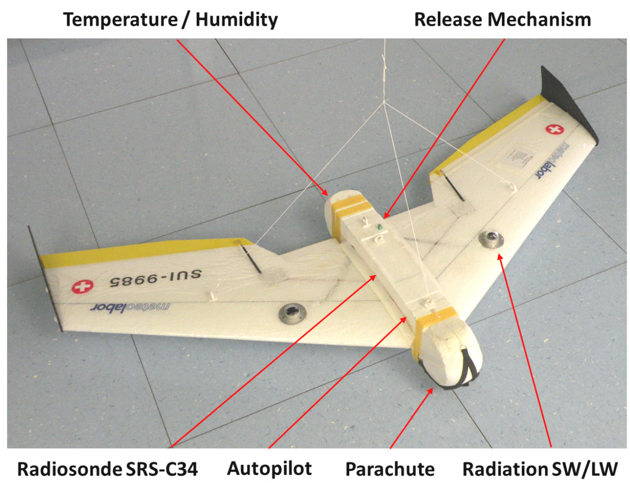

Figure 2. The return glider radiosonde (RGR), with the middle payload section where the radiosonde and the autopilot is stored, and the two upward and downward short- and longwave radiation instruments mounted in the wings. Temperature and humidity sensors are in the back. The release mechanism is above and the landing parachute in front. The wingspan of the glider is 1.4 m and the overall weight 1.9 kg.

The scientific instruments, in this case the short and long-wave radiation sensors, are integrated into the left and right wing. The instrument body has the same height as the thickness of the wing, therefore only the instrument domes protrude, all other cables and connectors are inside the wing, which is connected to the radiosonde in the payload section. Temperature and humidity are measured at the back of the glider with a thermocouple temperature sensor, which extends slightly upward to prevent temperature perturbations from the glider.

In the front of the mid-section is a parachute embedded into a styrofoam half sphere. The parachute is used for the landing and also serves as emergency recovery system if the autopilot detects any malfunction. The total weight of a fully equipped return glider radiosonde with batteries and radiation instruments is under 2 kg and is within the limits of standard balloon born payloads. The current glider could be equipped with heavier payloads up to a takeoff weight limit of 5 kg.

Figure 3. Radiation modules consisting of short- (left) and long- (right) wave radiation sensors. In the glider they are mounted in the left and right wing one upside down as shown here, measuring the four components. They use the same thermopiles and domes as the CNR4 Net Radiometer.

4.2 Scientific instruments

As mentioned above, the motivation to build the return glider radiosonde was to measure solar and infrared radiation profiles. In 2011, the first experiments were made with a CNR4 net radiometer from Kipp & Zonen, which consists of an upward and downward pyranometer to measure shortwave radiation, as well as an upward and downward pyrgeometer for the long wave component. All domes and body temperatures were measured by the thermocouple technique used in the SRS-C34 radiosonde. Measuring the exact temperature on the different parts of the instrument is crucial and allows for corrections of the large temperature gradients between the dome and the body, which can affect the thermopile measurements. The measurements in 2011 showed very promising results (Philipona et al., 2012) and led to further development of the instrumentation to adapt our needs.

One of the major concerns was the size and weight of the CNR4. A new design allowed the instruments to be smaller and lighter. The combination of an upward pyrgeometer and a downward pyranometer allowed a more compact instrument to be built in which all body and dome temperatures are measured inside. Two such instruments, one mounted upside down (Fig. 3) are built into the wings and allow measuring the four radiation components during the ascent, when the RGR is lifted in horizontal position 50 m below the weather balloons, and also during the descent.

5 Electronics

5.1 Radiosonde

The RGR is equipped with a Meteolabor radiosonde, which is similar to the SRS-C34 used for routine operation at the MeteoSwiss aerological station at Payerne, Switzerland (Philipona et al., 2013). Only minor modifications were needed to adapt the radiosonde to measure 10 additional channels from the short- and longwave radiation devices. During the flight, air temperature, humidity, pressure, wind direction, wind speed and all radiation values are transmitted once per second to the ground station. Temperature measurements are made with thermocouples, which have a diameter of only 50 µm and respond very quickly to temperature changes. Humidity measurements are made with a capacitive polymer sensor, whereas pressure and wind components are determined from GPS positions, assuming hydrostatic equilibrium. Additional information from the RGR's flight controller are also transmitted to monitor vital steps during the flight. There is no uplink to the glider, hence all flight configurations are made prior to launch and no remote control over the glider is possible.

The SRS-C34 radiosonde consists of two separate modules connected by a bus system, which are installed separately in the back of the RGR's middle section. The upper module is in charge of all the measurements made by the various sensors and the lower module transmits the measurements to the ground station. The space in the front section is used for the batteries in the lower part and for the autopilot in the upper compartment (Fig. 4).

5.2 Autopilot

In 2013 ETH Zürich together with 3-D Robotics introduced a new autopilot called PIXHAWK, which was developed mainly by the ETH Zürich Computer Vision and Geometry Lab (Meier et al., 2011). The autopilot (Fig. 4) is equipped with all necessary sensors to perform autonomous flights and has two separate attitude sensors, a barometer for altitude measurement and two separated ports to connect

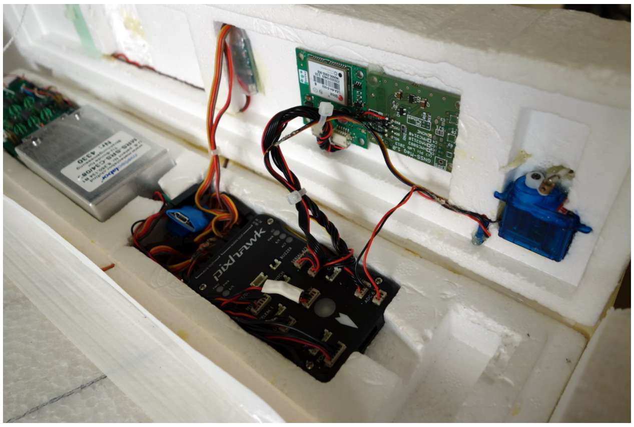

Figure 4. Upper compartment of middle payload section showing the PIXHAWK autopilot in the front part of the main box and the radiosonde module which controls all the data acquisition behind. From left to right in the cover of the upper compartment: balloon release mechanism, two GPS/GLONASS modules, servo for parachute release.

GPS/GLONASS receiver modules for navigation. The system is modular built to add future extensions with new sensors.

The main tasks of the autopilot are to monitor the GPS altitude, activate the release mechanism, fly back to the predefined landing coordinates and spiral down and to release the parachute at the desired altitude above ground. All steps are additionally secured by several fail-safe systems which are internally and externally monitoring the autopilot during the flight, and in addition all flight information is recorded.

5.3 Release mechanism

The release mechanism is controlled by the autopilot and the GPS. It mainly consists of a relay that switches the electric current in a tungsten wire, which heats up and burns the tether string. It is mounted inside the cover of the upper payload section and is connected to insulated wires which go through the cover and follow the central string of the three-point suspension of the RGR up to the tungsten wire, which is wrapped around the tether string. At the pre-set GPS altitude the release mechanism burns the string and releases the balloon.

5.4 Power system

To guarantee an efficient RGR, the power supply on board needs to be properly sized and adapted to the different devices which require various voltages and currents to operate. The power distribution board takes care of this task and monitors at the same time the health of each battery and reports any malfunction back to the autopilot. For safety reason the power system is divided into two completely different power sources.

In normal operation mode the primary power source is capable of powering the RGR for more than 10 hours. If the primary power source fails during operation due to a malfunction, the second power system is used to deploy the emergency recovery system, which releases the parachute. Both power systems are monitored by a temperature sensor since cold temperatures strongly affect the lifecycle of the batteries.

6 Software specifications

6.1 Configuration

The RGR encloses two independent systems and each one needs its own set of configuration software. The SRS-C34 radiosonde is configured by a program developed by Meteolabor AG, and the autopilot by a dedicated software adapted to configure the RGR. Even though both systems can run autonomously they are connected via a bus system and share the same connector at the back of the RGR, allowing various parameters to be configured with an external computer.

Although many parameters can affect the behavior of the autopilot once the RGR is properly tuned and adjusted only three settings may be changed from one flight to another. The most important parameter is the altitude at which the RGR is released from the balloon. This parameter needs to be set well below the burst altitude of the balloon. Furthermore, the main landing coordinates, as well as several additional emergency landing sites, can be set. The emergency landing points are generally selected close to the flight trajectory, which is calculated with a wind forecast model. All parameters are stored and may be used for several flights.

While the parameters for the autopilot can be changed, the SRS-C34 radiosonde is configured once during the preparation for a flight. This way the transmission frequency of the radiosonde is set and the settings of the scientific instruments can be verified before launch.

6.2 RGR attitude control

The attitude control is a complex algorithm for keeping the RGR in a fixed flight orientation with respect to an inertial frame of reference. Accelerometers and gyroscopes are used to guide the RGR to the desired attitude. Accelerometers basically measure the acceleration in the x, y and z axis and adjust the orientation of the RGR with respect to Earth's surface once it is in motion. Gyroscopes are used to compensate for short term noise from the accelerometers. Both sensors are combined to get precise information about the current orientation of the RGR in space.

6.3 RGR navigation

The navigation algorithm relies on a space-based navigation system to determine its location above Earth's surface. The most common navigation system is called the Global Positioning System (GPS) and was developed by the US Department of Defense. It has been in service since 1995 and can achieve a horizontal accuracy of up to 3 m. In 2011, Russia introduced a second system called the Global Navigation Satellite System (GLONASS), which is also available for public use like the GPS.

The newest generation of GPS/GLONASS receivers from the Swiss company u-blox are installed in the RGR. Different receivers from various companies were tested on regular radiosondes. The u-blox was chosen because the altitude limit is 50 000 m a.s.l., and the chip is able to track up to 72 different GPS and GLONASS satellites at the same time. The autopilot is capable of analyzing two different navigation data streams from two independent GPS/GLONASS receivers simultaneously. Hence, two independent navigation receiver modules are currently installed, which further contributes to safety and reliability of the entire system.

6.4 Safety features

Since UAVs are new in scientific research, governments are currently developing plans and safety assessments for a safe operation in the civil airspace. We have therefore been working in close collaboration with the Federal Office of Civil Aviation (FOCA) in Switzerland to operate the RGR as safely as possible. The RGR is a complex system manufactured with different components and sensors working all together to ensure a safe and reliable operation. Since it is not a passive system like a routine radiosonde descending on a parachute, several safety features were integrated to prevent complete loss or failure of the RGR resulting in a fast and uncontrolled descent.

Referring to Sect. 5.4 "Power system" the navigation and operation of the RGR is powered by two individual systems. In case of failure of one system, a passive emergency system is able to safely land the RGR with the parachute. Once the parachute is deployed, the RGR descends at a vertical speed of about 4–5 $m\,s^{-1}$. In addition, an external fail safe device is monitoring the main flight controller and independently triggers the release of the parachute if necessary.

A balloon rupture at any given altitude is another concern and hence correct handling of the balloon is important. The balloon burst can be detected by the RGR's autopilot and leads to an immediate activation of the release mechanism to separate the RGR from the strings and remaining balloon parts. If the ascent rate is too low, or for any reason the balloon cannot reach the preprogrammed altitude, the autopilot releases the RGR after a preset maximum time of flight. All steps conducted by the autopilot are reported to the ground station.

7 RGR test flights

Initial tests were conducted at the MeteoSwiss aerological station in Payerne by lifting the RGR with a tethered balloon up to 150 m above ground. During the first descents from the balloon, the autopilot control parameters, as well as the general flight characteristics, were inspected and tuned. Both release mechanism for detaching from the balloon string and for the parachute release were intensively tested during different wind conditions. Not only was the deployment properties of the parachute analyzed but also the descent speed and landing angle of the RGR. In addition, a motorized version of the RGR was piloted manually to gain information about the glide ratio, which is important to know.

At the same time we worked closely with the FOCA to obtain a permission in Switzerland for doing test flights with a completely autonomous glider. After adding additional safety features we finally received permission for beyond visual line of sight (BVLOS) flights in Payerne. The flights with the RGR were limited to an altitude of 3000 m a.s.l. during nighttime within a safety radius of 2 km around the aerological station. Furthermore, a notice to airmen (NOTAM) with a danger area of 4 km around the station had to be submitted at least 1 day prior.

We first conducted night time flights in Switzerland to test all electronics and software algorithms. While working with FOCA we were also in contact with FINAVIA in Finland, who allowed us to do test flights with the RGR at the Finnish Meteorological Institute (FMI) Arctic Research Center, Sodankylä. The permission included day and night flights up to 30 000 m. The Sodankylä facility is an aerological sounding station in operation since 1949 and has recently become a GRUAN station (Bodeker et al., 2015).

7.1 Test flight in Payerne

To stay within the limits set by FOCA a calm night in terms of wind speed was required for a first test flight in Payerne. The RGR was set to release the balloon at 2200 m a.s.l. and then return to the grassland next to the aerological station. After an 8 min ascent the RGR released the balloon and after a short flight of less than 1 min, the landing coordinates were reached 1 km above ground, where the RGR started to circle down. Only 15 min after the balloon launch, the RGR landed safely with the parachute on the ground.

The flight analysis showed that the autopilot triggered the balloon release mechanism at 1930 m a.s.l., 270 m below the desired altitude. The early release was activated by the maximum time flight safety feature, which triggered because a balloon ascent of under 4 $m\,s^{-1}$was detected. On the flight back the analysis showed an average horizontal speed of 19 $m\,s^{-1}$ while losing altitude at 3.5 $m\,s^{-1}$, which was acceptable. The descending speed with the parachute was measured at 4 $m\,s^{-1}$.

7.2 Test flights in Sodankylä

With the successful flight in Switzerland the goals for the campaign in Sodankylä were to test the RGR at high altitudes, to learn how it handled different wind conditions and to determine from how far horizontal it could fly back to the launch site. Additionally, the overall performance and reliability of the autopilot and the gliders structure were analyzed. The radiation profiles measured during the flights, under very different atmospheric conditions, were both very successful and interesting. A total of seven flights were performed during the first 2 weeks of July to 5 km (1 ×), to 20 km (2 ×) and to 24 km altitude (4 ×).

7.2.1 General weather conditions

According to wind analyses over recent years, summer conditions in Sodankylä are suitable for special balloon launches since wind speeds are rather low throughout the atmosphere. The average horizontal distance from the launch coordinates for July over the past years was generally in the range of 20 to 40 km. However, during our first week distances of up to 90 km were observed by daily routine radiosondes. During the second week the wind decreased. Although flight distances were now shorter, wind speeds in the tropopause regions were still strong, with values up to 43 m s^{-1}. In terms of wind direction the first week was dominated by west winds which in the second week turned south and finally changed to an east wind towards the end of the second week. Fig. 5 shows the last five flight patterns (1 × to 20 km, 4 × to 24 km altitude)

7.2.2 Flight performance under different wind conditions

A major concern are strong winds that can displace radiosondes for hundreds of kilometers. For flights with the RGR it is important to predict the flight trajectories with numerical high resolution forecast models. Since there was no pitot tube installed to directly measure the wind speed during the flight back to the landing coordinates, the wind components are measured during the ascent with the balloon. The recorded information is used by the RGR to fly back after release from the balloon. To learn what maximum wind speeds the RGR can handle, flights during strong wind conditions were performed.

A flight to 20 km altitude with wind speeds of 43 m s^{-1} around the tropopause has been separated into three wind sections and is shown in Fig. 6. After the release from the balloon the RGR gained a forward horizontal speed of more than 80 m s^{-1}. With weak stratospheric winds which gradually increased to 20 m s^{-1}, the glider covered a distance of 40 km before reaching the landing coordinates at 11.4 km altitude. Circling down the RGR entered into the second wind section with maximum recorded wind speeds of 43 m s^{-1}. Under these conditions, the RGR was not able to maintain its circling pattern and was pushed in the wind direction with horizontal speeds of up to 29 m s^{-1}. While flying backwards it maintained the correct horizontal course towards the land-

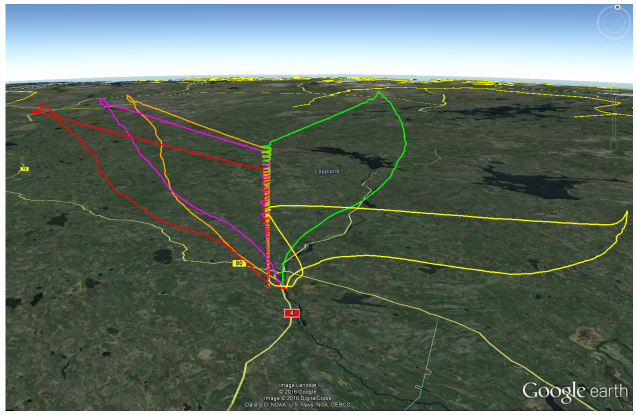

Figure 5. Flight path from five soundings to an altitude of 20 km (1) and 24 km (4) performed in Sodankylä, Finland. The 20 km flight (yellow) was 40 km away from the launch site at the top. Flying back it reached the launch site at an altitude of 11.4 km, where it started to circle down. Very strong winds around the tropopause pushed the RGR to the east until the winds slowed down and it made it back to the launch site.

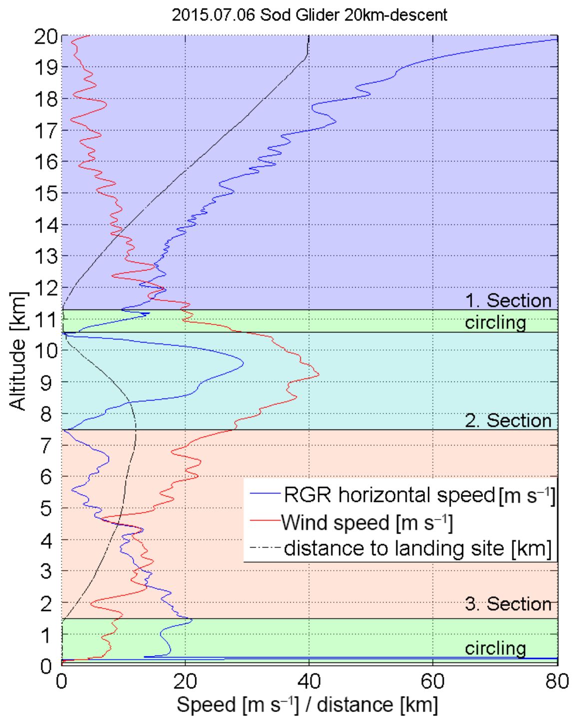

Figure 6. Wind speed analyses from a flight from 20 km altitude. Three sections of very different wind speed and horizontal flight speed are shown. Wind speeds of up to 41 m s^{-1} and horizontal flight speeds of more than 80 m s^{-1} were recorded. The circling down happened in two phases. The black, dotted curve shows the distance to the landing site. The wind speed is recorded with the radiosonde and the horizontal speed of the RGR with respect to ground.

ing site. Losing altitude, the wind slowed down to around 28 m s^{-1}, where the RGR came to a stop, but it had already been pushed 12 km away from the landing site. With further decreasing winds the RGR regained forward horizontal speed and covered the distance back to the landing site at an altitude of 1.5 km, where it circled down to the ground.

The flight shows, that the RGR can fly against headwinds of up to 20 m s^{-1}. At higher wind velocities, the glider is pushed back but maintains its course towards the desired location. This information and pre-calculated trajectories allows for precise estimates of the landing location.

7.2.3 Maximum flying distance

The first goal of the return glider radiosonde is to fly research instruments safely back to the ground. The question then is from how far can it fly back once it is released from the balloon. The value we are looking at is the glide ratio, which is the ratio of the gliders horizontal distance covered over the vertical descent. The glide ratio is usually calculated during calm air, since the flight distance with respect to ground changes when the air is moving. In order to achieve an optimum glide ratio, precise control of the airspeed as well as minimizing the drag generated by deflecting the steering surfaces is necessary.

During the first flight in Switzerland an overall flight distance of 6.2 km, while losing 1.3 km altitude, results in a glide ratio of 4.7. In the section where the RGR is heading back to the landing coordinates the head winds were less than 5 m s^{-1} and a glide ratio of 5 results.

In Sodankylä only the four flights performed from 24 km altitude were used to analyze the glide ratio. Also, only data from 22 to 19 km altitude with low head-wind speeds of 5 to 10 m s^{-1}, were processed. Although the required calm wind conditions were not really fulfilled, the calculated average glide ratio is 5.5, which from an altitude of 24 km results in a theoretical maximum flying distance of more than 130 km. Looking at all flights performed from 24 km altitude, an average flying distance of 105 km (circling down included) was recorded. The maximum flight distance achieved during an average wind speed of 6.7 m s^{-1} was 122 km and is close to the theoretical 130 km.

7.2.4 Temperature

The RGR is equipped with several temperature sensors monitoring vital electronic components inside and outside the glider. Air temperature decreases from ambient to −60 °C or even lower around the tropopause and is accurately measured by the integrated SRS-C34 radiosonde thermocouple. Batteries and autopilot are monitored by separate temperature sensors. During the ascent, the temperature inside the electronic bay increased during the first part of the flight and remained above 10 °C at high altitude. The coldest temperatures were measured during the initial phase of the descent, but stayed above 0 °C in the electronics bay.

7.2.5 Icing through cloud passes

In Sodankylä, the RGR passed different clouds at various altitudes. The humidity measured on board indicated whether the RGR directly passed a cloud or just a region with high water content. During ascent, cloud passes are not a concern since water droplets deposited onto the wings are evaporated at higher altitudes. Moreover, the RGR comes from warmer regions passing colder clouds. However, flying back from the cold stratosphere into the warmer troposphere with high water content, freezing may occur especially in cumuliform clouds with large droplets. This effect has not been observed in Sodankylä since no cumuliform clouds were formed, and only flights through stratiform cloud structures were conducted. Although the flexible structure of the RGR due to the EPP material helps preventing ice buildup during descent, icing cannot entirely be excluded.

7.2.6 Parachute landing

Once the RGR reached the desired landing coordinates, it circled down and released the parachute 100 m above ground, allowing for safe landing. Due to the weight distribution, the parachute is stored in the front of the glider inside a styrofoam case, which is not an optimal place for releasing due to the fast forward flight speed. Therefore, once the string closing the capsule is released, a spring inside the case and a special flight path lift up the nose of the RGR, which helps to deploy the parachute. The parachute reliably opens within a second after it drags alongside the aircraft, and the descent speed is slow enough to not damage the RGR. The parachute landing is very convenient since during nighttime operation, manual landing would be difficult. Additionally, in case of an emergency due to a failure of the autopilot or other components, the parachute is deployed and the RGR lands safely on the ground, at no risk to third parties.

7.2.7 Successive flights

The last test flights to 24 km altitude were all made in rapid succession to examine repeatability with the same instrument. After successful landing the RGR needs little maintenance for its next flight. The parachute is folded and restored inside the front case of the glider and the three-point suspension and the release mechanism is readjusted. The internal batteries are either charged through the connector at the back of the RGR or are exchanged with a new set. For the four flights the batteries were always charged through the connector which allowed flights every 6 hours.

The RGR opens new possibilities for atmospheric research and climate monitoring, allowing the use of the same instrument over many successive flights. With the RGR as an instrument carrier, the repeatability of an experiment can be

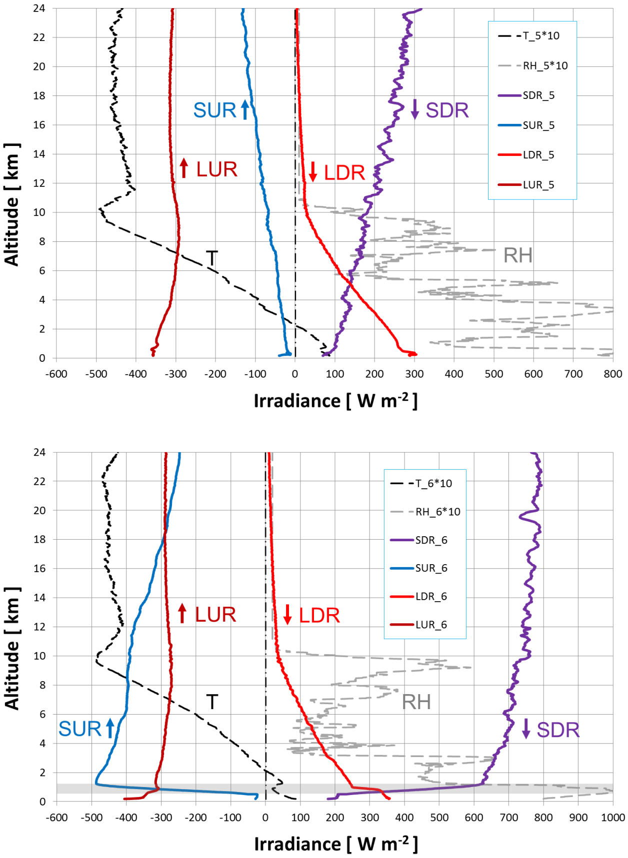

Figure 7. Temperature, relative humidity and radiation profile measurements with the RGR from the surface to an altitude of 24 km. Flight #5 (above) started in the early morning and flight #6 (below) 6 hours later. The morning flight was cloud free, whereas at noon a thin cloud layer between 500 and 1200 m shows the strong influence of clouds on shortwave and also longwave radiation. Downward SDR and LDR fluxes are positive and upward SUR and LUR fluxes are negative. Temperature and relative humidity signals are multiplied by a factor of 10.

increased significantly and the time between each flight can be further decreased by using two RGRs alternately.

8 Research measurements with the RGR

As mentioned above the motivation to build the RGR was to routinely measure radiation profiles through the atmosphere for climate change investigations. Fig. 7 shows radiation profiles measured from the surface to 24 km during two successive flights within 6 hours at Sodankylä. The first flight was in the early morning showing small downward and upward solar irradiance. During the second flight around noon a thin cloud layer between 500 and 1200 m led to a temperature inversion, and to a large increase of shortwave down- and upward radiation through the cloud as well as the influence of the cloud on the longwave radiation profiles. These new results will be shown more in detail in a separate publication. Comparing radiation profiles that were taken under different weather conditions allows us to study effects of air temperature, water vapor, clouds, ozone and other greenhouse gases on solar and thermal radiation.

There is presently also much interest in using dew/frost-point humidity sensors to study water vapor in the UTLS, and AirCore sampling devices to measure gas profiles through the atmosphere. Dew/frost-point hygrometers are valuable instruments, and AirCores need to recover as quickly as possible for the gas analysis, which has to be made right after the flight. Such measurements could be performed from the RGR.

9 Conclusions and outlook

The return glider radiosonde is a flying wing made out of EPP foam with a built-in operational radiosonde, a commercial autopilot, a release mechanism, a parachute for landing and the necessary safety and power systems. Its purpose is to fly upper-air research instruments multiple times and to fly the payload autonomously back to the launch station. This new capability opens up several new possibilities for climate change studies.

During several test flights from 24 km altitude the RGR proved to reliably control itself, and to maintain its flight even in the presence of very strong winds. Analyses showed that the RGR maintains a forward flight path with head winds of up to 20 m s^{-1}. The overall glide ratio during flights from various altitudes is 5.5, which from 24 km altitude results in a flight distance of roughly 130 km. This maximum flight distance can only be achieved during calm wind conditions and is reduced once the RGR passes different wind speed layers. Typical horizontal flight distances back to the launch station are on the order of 100 km. Emergency landing points along the flight path allow flights even during strong winds since the autopilot is capable of detecting unfavorable wind conditions and reacting accordingly.

Using the concept of traditional radiosondes with a RGR allows for connecting different upper-air research instruments, and transmitting measured physical values and all important information from the autopilot continuously to the ground station. Moreover, the system is fully autonomous, relying only on preset values without receiving information from the ground. The RGR has successfully been used to measure radiation profiles through the atmosphere, but many different in situ research or climate-monitoring measurements can be made that rely on multiple flights with the same instruments, or use specific sensors that need post processing analyses after the flight. Projects to fly back advanced humidity sensors and AirCores to measure atmospheric gas profiles are presently under investigation.

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