# THE LIFE CYCLE OF A RADIOSONDE

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Building a radiosonde with open hardware solutions engages engineering students in meteorological problems and allows them to develop new ideas about probing the atmosphere.

The importance of the radiosonde as a tool for gathering meteorological data is enormous. The radiosonde allows, in a matter of minutes and at relatively low cost, measurement and transmission of data from regions mostly inaccessible to humans. Key advantages of the radiosonde over other observing systems are its relatively low cost, high accuracy, and high vertical resolution in situ vertical profiles of the atmosphere from the surface up to tens of kilometers. The development of the first radiosondes around 1924–31 [see historical discussions on priority and first publication of radiosonde data in DuBois et al. (2002) and Pettifer (2009)] paved the way for numerical weather forecasting and allowed researchers to test the theoretical foundations of dynamical meteorology. Much of what we know about the atmosphere comes from data originally measured and transmitted by one of these instruments, so it is no exaggeration to call the radiosonde the fundamental instrument of meteorological research. Although satellites have filled much of the gaps in our knowledge of the upper atmosphere, there is still the need for radiosondes to provide high-quality and high-resolution data not only for calibration of other observing systems, but also for basic meteorological research, for creating the analyses needed to initialize weather forecasting models, and for detecting climate trends.

Current radiosondes have evolved into a relatively standard and well-developed set of instruments that measure temperature, pressure, and humidity. Wind is currently inferred from the GPS position of the radiosonde, assuming that the carrying balloon acts as a passive tracer with respect to horizontal winds and filtering the pendular motion of the radiosonde package. Several technological improvements of the radiosonde have been led by the Finnish company Vaisala (especially since the 1980s), which produced about 70% of the radiosondes used globally by 2002 (Dabberdt et al. 2002). The World Meteorological Organization has established requirements for the accuracy of the data gathered by a radiosonde (see, e.g., Nash et al. 2011). For instance, operational standards allow for errors of 1 K in the tropospheric temperature and less than 7.5% in the relative humidity (RH). Operational standards are still too relaxed when compared, for

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instance, to the magnitude of the climate trends that we expect to detect from the observational record over a period of decades (observed trends in midtropospheric temperature during the last 30 years range from about –0.1 to 0.2 K decade$^{-1}$; Thorne et al. 2011). Therefore, more stringent requirements are being proposed for climate monitoring that allow for errors of less than 0.3 K in temperature and less than 3% relative humidity in the troposphere (Immler et al. 2010; Nash et al. 2011). Humidity measurements also suffer from low accuracy in the upper troposphere and stratosphere (Miloshevich et al. 2009), regions that provide only a small fraction of the total water vapor in the atmosphere but that have a significant impact on the radiative transfer of longwave radiation (Turner et al. 2012).

Only about 1,000 synoptic radiosonde stations exist around the globe. This is explained by the relatively large operational cost of the ground stations, including the cost of the receiving station, the gas supply, the radiosondes, and the personnel in charge (see, e.g., Douglas 2010). Receiving stations are usually up to $100,000 (U.S. dollars) or at, the lower end, $5,000 for InterMet boundary layer systems that consist mostly of a radio receiver, a modem interface, and the software. Each individual radiosonde costs about $200. The cost of establishing a radiosonde ground station makes it difficult to increase the spatial extent of the radiosonde network, which is particularly deficient in vast regions of the Southern Hemisphere.

Given the relevance of this instrument for research as well as day-to-day operations in forecast centers (weather and air pollution), airports, and other applications, and the availability of inexpensive microcontrollers and sensors, we challenged ourselves to build a radiosonde with commercial off-the-shelf parts and materials within a semester and within reasonable budget constraints. It is fair to ask the question, Why bother reproducing an already well-developed meteorological instrument? The main purpose of our exercise was pedagogical, so even if the radiosonde turned out to be more expensive than a commercial one, there would still be a value in developing it as an engineering project. In addition to the purely pedagogical value of the exercise, building an "open hardware" radiosonde allows for accelerated development by a community of users. Also, we envisioned the prototype of our sonde as a standard platform that could be easily adapted and used by the global community. The possibility of adding and comparing different sensors can potentially lead to improvements in the accuracy, price, weight, and durability of sensors, batteries, actuators, and other components.

We are aware of the existence of projects that bear some similarities to the one we present here. On one side of the spectrum, there are several hobby-oriented projects whose main objective is usually to get images and recordings from the upper atmosphere and usually attempt the recovery of the payload. On the other side, there are several research-oriented projects usually carried out by large labs; they involve the design of specific soundings focusing on a particular research objective. Our project differs from purely hobby-oriented projects in that we attempt to obtain high-quality data; however, our project differs from purely research-oriented projects in that we have a strong pedagogical component. Our project also differs from a commercial radiosonde in that we attempt to have our project to be completely "open" in both hardware and software platforms, so it can be easily replicated and improved.

In the next section we will briefly describe the logistics of the classwork as well as the hardware and software used for building the radiosonde and programming the microcontrollers as well as the graphical interface of the sounding ground station. In section 3 we describe some of the tests carried out using our instrument. In section 4 we ask the question of whether the engineering students learn any meteorology during the building and operation of the radiosonde. Finally in section 5 we discuss some possible uses and improvements of the radiosonde platform.

## BUILDING THE RADIOSONDE.

*Research and development teams.* In the context of a second-year engineering class called Engineering Project Workshop at the University of Chile, the students are asked to "conceive, design, implement and operate an engineering project that gives an innovative solution to a problem in a specific area" (inspired by the so-called Conceive, Design, Implement and Operate (CDIO) approach; Crawley et al. 2007). Like many other meteorology groups around the world, our Geophysics Department is embedded within an engineering school. Many of the faculty in the meteorology group had a background in engineering before moving into the atmospheric sciences and are usually asked to teach sciences to the engineering students. As an applied science, problems in meteorology usually offer a variety of challenges for almost all specialties within a classical engineering school. Therefore, meteorology offers the potential for providing design problems that are interesting for engineering faculty as well as for a large number of students with a breadth of different interests and backgrounds. We believe that the building of a radiosonde is one such problem.

We will illustrate this by enumerating some of the challenges the students faced during the process of building a radiosonde. Some of these issues are usually covered in the typical curricula of engineering as purely theoretical problems; for instance, when studying viscous dissipation in a fluid, students may be asked to calculate the terminal velocity of a balloon filled with a gas lighter than air, or in chemistry students may be asked to find the equilibrium water vapor pressure of a given solution at a certain temperature and pressure. These are usually unrelated problems given in the context of a set of sequential classes in the basic and applied sciences. There is a more meaningful and deep learning when these problems do not appear in isolation and, perhaps even more important, when the resolution of the individual problems is critical for the successful completion of the project. In Table 1, we show examples of some of these tasks and loosely identify them with some engineering specialty. Most of the activities shown in the table were effectively carried out during the semester.

At the beginning of the 15-week semester, we proposed the problem to the 15 students taking the class and initially motivated them about the possible applications of such an instrument. We had the help of six teaching assistants (four students from electrical engineering and two students from meteorology). The class was divided into three groups, each composed of five students and two research assistants, and we gave each group a different task: temperature–humidity measurement, pressure–wind measurement, and radio communications. As the semester advanced, the three groups of students specialized into their designated tasks and were required to interact with the other groups in anticipation of the final integration of the radiosonde components. The student groups suggested two additional features that would distinguish their unit from a commercial radiosonde: 1) a camera to record images during the flight and 2) a release system so that the sonde could be detached from the balloon during the flight and potentially be recovered.

*Hardware.* The computational core of the radiosonde is an Arduino board, an open-source electronics prototyping platform (http://arduino.cc/). Arduino was selected because it provides a complete, flexible, easy-to-use hardware and software platform that is widely used not only by engineers, but also by artists, designers, and hobbyists (e.g., Sarik and Kymissis 2010). The sensors, GPS, transceiver, release linear motor, memory card, and camera in the radiosonde

**TABLE 1. Some individual tasks carried out during construction, calibration, and operation of the radiosonde.**

| Engineering specialty | Radiosonde building and calibration | Sounding |
|---|---|---|
| Computer science | • Programming of the microcontroller<br>• Development of the communication protocols for the radio transmission | • Estimation of the wind from the GPS position<br>• Development of a GUI |
| Chemistry/chemical engineering | • Design and construction of the insulation for the electronics to prevent malfunction of the components at very low temperatures of high humidity<br>• Calibration of RH using air in equilibrium with chemical solutions | • The resistance of the balloon material and the thermodynamics of the sounding determine the burst height and the final diameter of the balloon |
| Electrical/electronic | • Integration of the sensors with the microcontroller<br>• Estimation of the power consumption of the elements in the radiosonde<br>• Development of the communication protocols for the radio transmission | • Design of antennas to allow for a larger range of data reception<br>• Layout of electronics to avoid interference of the data stream and the GPS signal |
| Mechanical/aerospace | • Design of an automatic release system for recovery of the payload | • Calculation of the balloon aerodynamics that determines the rate of ascent and initial filling of the balloons |
| Industrial | • Estimation of the costs and management of the project | • Development of launching mission protocols |

are connected to the Arduino via a customized daughter board, or "shield" in Arduino nomenclature. The ground receiver consists of an Arduino and a transceiver module that are easily connected to a computer where data are stored. Pictures taken by the radiosonde camera are stored internally on the memory card and not transmitted because of bandwidth limitations. Figure 1 shows a view of the components as they were laid out in our final prototype.

The radiosonde and receiver hardware used in our tests were based on the version of the Arduino board called "Arduino Duemilanove." Recently, the source code has been updated to also work with newer versions of the Arduino board: the "Arduino Uno" and "Arduino Mini Pro." The choice of original sensors was made by students in consultation with the teaching assistants and professors. When deciding on sensors we attempted to obtain those that were inexpensive but that could also provide high-quality meteorological data. Table 2 shows a description of the sensors used in building the radiosonde. More detailed specifications of the sensors, parts, and their connections to the Arduino board, as well as circuit diagrams, are available online (at www.dgf.uchile.cl/radiosonde).

*Software.* A summary of the information flow from the radiosonde is as follows: Raw data (voltages) are measured by the sensor/transmitter unit and communicated to the receiver unit which is connected to a computer where the voltages are converted to actual meteorological values. The radiosonde software is divided into three distinct programs: Arduino instructions for the transmitter/sensor unit, Arduino instructions for the receiver, and a computer-based graphical user interface (GUI) to process and display the received data.

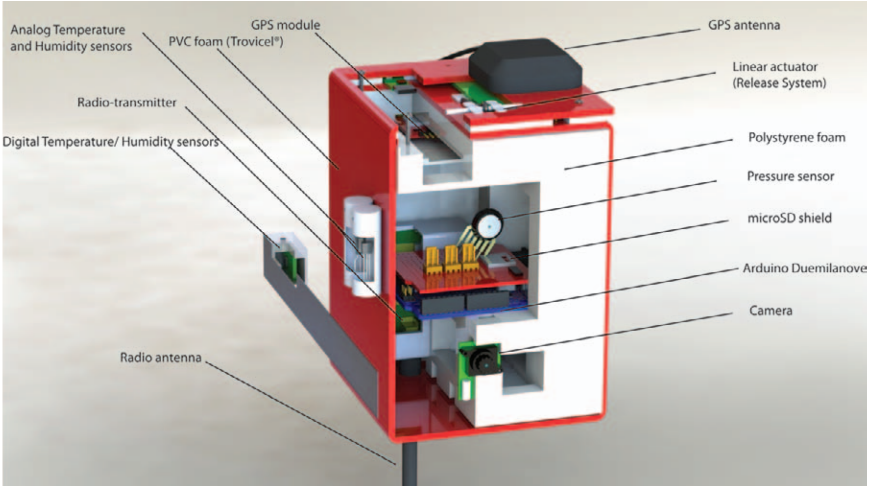


**Fig. 1. Cut-away view of the radiosonde, showing the parts and sensors.**

The Arduino instruction sets are compiled and uploaded to the Arduino boards using a command-line interface and makefile. The rather simplistic Arduino integrated development environment was not used since some compilation errors would occur when certain external C++ libraries were included.

The computer-based GUI, called BaseCamp, has been compiled and run on Windows, Linux, and OS X systems (see screenshot in Fig. 2). All programs and source code will be available for download from the radiosonde project website.

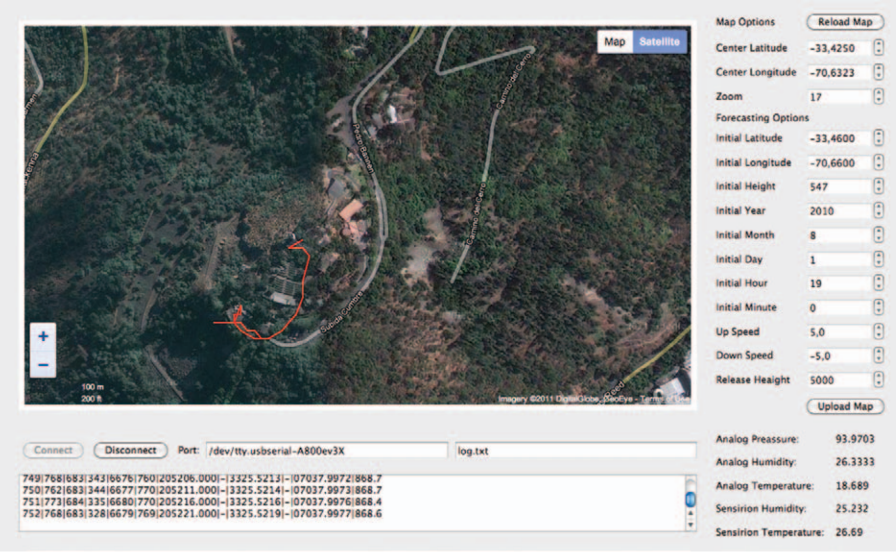
## CALIBRATION AND CROSS COMPARISON.

*Preliminary experiments.* We performed several test experiments in preparation for the main field launch. A tethered balloon campaign was conducted as the end of the semester activity where the radiosonde was first used to transmit meteorological data from an altitude of about 1,000 m above ground level. We also tested the data link from the transmitter to the receiver by communicating between the top of Cerro San Cristóbal (850 MSL) and the top of the Geophysics Department building in Santiago, Chile (520 MSL), about a 4-km line of sight with an unobstructed view of the hill. A successful transmission of meteorological data was completed including GPS data as shown by the trajectory of the team carrying the sonde as they were climbing up the hill in Fig. 2. We also performed a second communication test where successful transmission was established from a park near the Andes piedmont and the top of the geophysics building, about a 13-km line of sight.

*Methodology for release and recovery.* In addition to comparing data measured with our sonde with those obtained with the research-grade radiosondes, we tested the possibility of recovering the equipment. While the notion of recovery was at first a curiosity, it quickly became an important objective of the campaign as the team grew attached to the product of several months of work. Recovery of balloonborne equipment was an essential part of the early attempts to characterize the upper atmosphere. Those balloonsondes only carried registering apparatus and therefore needed

**TABLE 2. Parts, pieces, and sensors used in building the radiosonde. Prices are in U. S. dollars without taxes or shipping.**

| Name | Description | Part number | Vendor/ manufacturer | Variable/ function | Measuring/ operating range | Error | Response time/sampling frequency | Value ($) |
|---|---|---|---|---|---|---|---|---|
| Analogue temperature sensor | 10-K thermistor | 2322 640 | Olimex/Vishay BC-components | Temperature | −40° to 125°C | ~1°C | 15 s | 2.0 |
| Analogue temperature sensor | Two-terminal zener diode with voltage proportional to temperature | LM235Z | Digikey/National Semiconductor Corporation | Temperature | −40° to 125°C | 1°C | 3 s<br>(at 5 m $s^{-1}$) | 1.5 |
| Analogue humidity sensor | Thermoset polymer capacitive sensing element | HIH-4010–001 | Digikey/ Honeywell | RH | 0%–100% RH | ±3.5% | 5 s<br>(slow-moving air) | 20 |
| Analogue pressure sensor | Integrated silicon piezoresistive transducer with analogue output | MPX5100D | Digikey/Motorola | Pressure | 0–1,000 hPa | ±25 hPa | 1 ms | 16 |
| Humidity and temperature digital sensor | Capacitive sensor (RH) band gap sensor (temperature) | SHT10 | Sensirion | Humidity, temperature | 0%–100 % RH<br>−40° to 124°C | ±4.5%<br>±0.5°C | 8 s<br>5 to 30 s | 15 |
| GPS module/ current | GPS Sirf Star III module with internal patch antenna | MOD-GPS | Olimex | Wind, position | −40° to 85°C (<18-km height) | 1–3 m $s^{-1}$ (at 10 m $s^{-1}$) | <1 s | 50 |
| GPS module/ discontinued | SparkFun GPS micro-mini | MN5010HS | SparkFun | Wind, position | −20° to 85°C (<18-km height) | ≤3 m | <1 s | |
| Communication transceiver | Data radio module | HAC-LM12 | Shenzen HAC Technology | Radio transmission | 402–405 MHz | | | 50 |
| Camera/ discontinued | Video graphics array (VGA) module | C328–7640 | COMedia Ltd | Image capture | | | 5 min | 39 |
| Linear actuator | MigaOne−12 linear actuator | | Miga Motor Company | Release system | | | | 40 |
| Switch | Miga analog driver V5 | | Miga Motor Company | Release system | | | | 14 |
| Microcontroller | Arduino Uno | DEV-10356 | SparkFun | Radiosonde brain | | | | 30 |
| Board | Micro secure digital (microSD) Arduino Shield printed circuit board (PCB) | DEV-09802 | SparkFun | Radiosonde sensors board | | | | 15 |
| Battery | Polymer lithium-ion battery 1000 mAh 7.4 V | PRT-10472 | SparkFun/ King Max | | | | | 7 |



Center Latitude -33,4250
Center Longitude -70,6323
Zoom 17
Initial Latitude -33,4600
Initial Longitude -70,6600
Initial Height 547
Initial Year 2010
Initial Month 8
Initial Day 1
Initial Hour 19
Initial Minute 0
Up Speed 5,0
Down Speed -5,0
Release Heaight 5000

Port: /dev/tty.usbserial-A800ev3X
log.txt

```
749|768|683|343|6676|760|205206.000|-|3325.5213|-|07037.9972|868.7
750|762|683|344|6677|770|205211.000|-|3325.5214|-|07037.9973|868.7
751|773|684|335|6680|770|205216.000|-|3325.5216|-|07037.9976|868.4
752|768|683|328|6679|769|205221.000|-|3325.5219|-|07037.9977|868.6
```

Analog Preassure: 93.9703
Analog Humidity: 26.3333
Analog Temperature: 18.689
Sensirion Humidity: 25.232
Sensirion Temperature: 26.69

**Fig. 2. Screenshot of the BaseCamp software showing the trajectory followed by the students around top of the San Cristobal hill in downtown Santiago. The data were received by students located on the roof of the geophysics building about a 4-km line of sight from the top of the hill.**

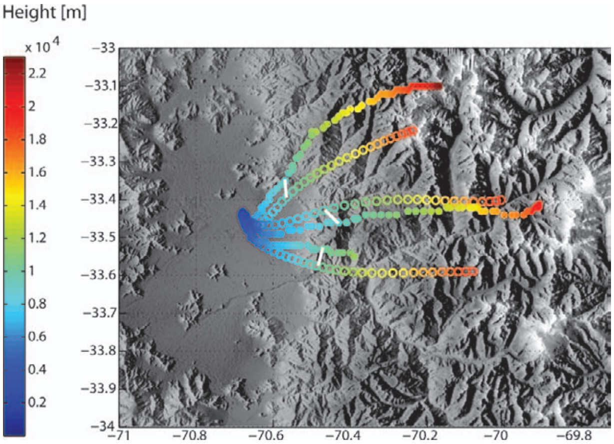


**Fig. 3. WRF-calculated trajectories (open circles) and actual observed trajectories (closed circles) for three consecutive days (16, 17, and 18 May 2011 at 1400 local time). The observed trajectories are the trajectories followed by the radiosondes launched from Quinta Normal station in Santiago. The color bar indicates height above Santiago (in meters). Taking as a reference the Andes piedmont, which nearly coincides with the bounds of the city of Santiago, the trajectories show good agreement (within 5 km to the real ones) for the first 10 km in height, even though they show a separation of about 30 km from one day to the next for this particular case. White segments joining the calculated and real sonde trajectories are about 5 km in length. Several trajectories were calculated from WRF output in a similar fashion for dates for which soundings starting at the main office of the Chilean National Weather Service in Santiago were available, and they all showed a similar agreement.**

to be recovered in order to retrieve the data. For instance, the discovery of the tropopause in 1902 was made using these balloonsondes by Teisserenc de Bort (1902) and Assman (1902) (see, e.g., DuBois et al. 2002).

In order to recover the radiosonde, we took advantage of three features of our sonde, two of them not available to the early balloonists. First, the release system was able to detach a balloon from the sonde at any given pressure level, upon reaching a certain temperature or elapsed flight time, allowing the sonde to travel a predetermined distance in the vertical. Second, the GPS signals from our sonde and one of the commercial sondes allowed us to accurately know their positions. Third, we made use of a Weather Research Forecasting model (WRF; Skamarock et al. 2008) forecast simulation with a resolution of ~6 km in the horizontal and 50 eta levels in the vertical, with 10 eta levels located lower than 0.9 with a top pressure of 50 hPa. The model forecast winds were used to determine the sonde trajectory, allowing a recovery team to be ready near the projected landing zone. Reviewing the literature, we learned that the recovery system devised by the students was not new and was originally called the "multiple-balloon technique" reported by Hugo Hergesell in 1904 (Hergesell 1906; DuBois et al. 2002). Our technique and the original one were effectively the same: two balloons would produce the lift necessary for an ascent of ~5 m $s^{-1}$ of the payload (three sondes weighting in total 1,250 g), and in our case at a given pressure level the linear actuator would release one of the balloons so that the remaining one would carry the payload back to the ground at ~2 m $s^{-1}$ of vertical descent velocity. In the accounts given by the early balloonsonde researchers, they report high rates of recovery mostly based on the willingness of countryside people to return the equipment in exchange for a reward (see, e.g., Clayton and Fergusson 1909). In our case, evidence from comparing WRF forecast and real sonde trajectories showed that the trajectories were sufficiently close to the real trajectories (especially for the region below 10-km height and within the bounds of the city) as to allow a recovery team to be within the range of the radiosonde signals at ground level (much smaller than the range of the reception of the sonde in flight) and perhaps even observe the descent of the sonde (see Fig. 3). The multiple-balloon technique has an additional advantage over the most common approach/technique of using a parachute: if the line attaching the payload to the descent balloons is given sufficient length, it will serve as a marker for the position of the radiosonde package. This was successfully tested by Hergesell (1906) over the ocean.

*Boundary layer sounding.* Our first field experiment was designed to test all sensors in a real flight that included ascent and descent. The flight was launched at 1400 local time 1 October 2011 from Quinta Normal (33.44°S, 70.68°W; 530 MSL) within the city of Santiago. Together with our sonde (which we call FCFM, which is the Spanish acronym for the Faculty of Physical and Mathematical Sciences) we launched two commercially available research-grade radiosondes: a Vaisala RS92 and an InterMet (iMet)-1 radiosonde. The three sondes were attached to a Styrofoam structure. The campaign did not proceed as originally planned because several of the sensors malfunctioned (from the commercial sondes as well as from our own sonde). Three main problems affected the development of the campaign and compromised the recovery of the sonde. First, ascent and descent velocities were computed using a payload weight of 1,250 g. This weight changed during the campaign because of extra batteries and tape being added to attach the sondes together. Therefore, the ascent velocity was smaller than calculated (~3 instead of 5 m $s^{-1}$) and the descent velocity was larger than calculated (~4 instead of 2 m $s^{-1}$). Second, the release did not occur at 500 hPa (~5.7 km) because the time condition for release was not adjusted for the small ascent rate of the balloon and because several minutes were lost during the launch procedure. Instead, the radiosonde was released at about 3.5 km above sea level. Third, we were unable to obtain a signal lock with GPS satellites with the iMet and with our sonde, likely due to interference from a nearby cell phone antenna (the Vaisala sounding system from the Chilean National Weather Service had a dedicated GPS antenna, which may have made the difference). In summary, from the three sondes, we only had a GPS signal during the ascent from the Vaisala sonde. Using the information of the actual release point, we were able to calculate a possible landing point from the WRF wind field. Since the descent velocity was incorrect because of the larger weight of the payload, the recovery team was given a possible landing point approximately 4 km south of the actual landing point. At that point, the batteries were still powering the sondes, and the team realized that the descent velocity was much larger than estimated. Therefore, they decided to turn on the sonde receivers and attempt to triangulate their signals. By iterating along the path calculated by WRF and observing the strength of the signal from the receptors, they were able to determine a small section of about four blocks (within a populated part of the city) where the sonde should have landed. With no visual evidence of the sonde on the street, the team started asking people about the balloon and on the first of these attempts they found the family that recovered the sonde. Figure 4 shows the predicted and the actual trajectory followed by the sonde, as well a picture taken by the sonde near the top of the trajectory.

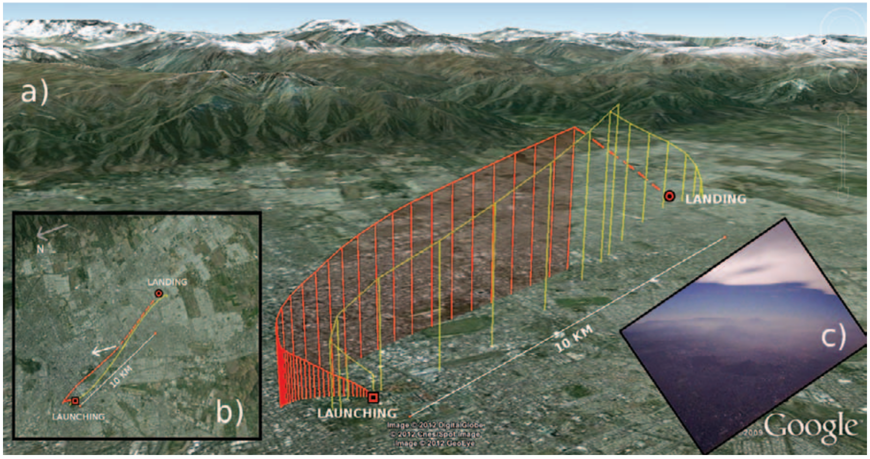


**Fig. 4. (a),(b) Aerial view showing the predicted (yellow) and actual trajectory (red) of the radiosonde during the ascent and descent for the Santiago campaign. The missing GPS data of the descent are represented with dashed lines. The forecast trajectory was made a posteriori, knowing the exact ascent and descent velocities. The forecast was made 24 h before the launch. The separation between the end of the forecast trajectory and the actual landing point was about 700 m. These images were modified from Google Earth. (c) A picture taken by the radiosonde near the top of the sounding and looking in the direction marked by the white arrow in (b).**

Figure 5 shows a portion of the data retrieved by the array of sondes. The Vaisala RS92 stopped transmitting data during descent by the default configuration of the Vaisala receiving station. However, the iMet radiosonde was being inadvertently interfered by another iMet radiosonde that was not the one in the array (we realized this at ~800 hPa into the sounding). The iMet-1 and the Vaisala temperatures show an almost perfect agreement (Fig. 5a). The temperature from the digital sensor in our sonde suffered from a clear time lag. The time in which the sensors reached the minimum temperature is about 70–80 s longer for our digital sensor than for the research-grade radiosondes. Also, the temperature measured by our digital sensor is clearly overestimated during the ascent and underestimated during descent. This can be in part explained by the relatively large range of response time of the sensor (see Table 1) from 8–30 s compared to the much faster bed thermistors used in most of the research-grade radiosondes (which have a time constant of less than 1 s; Nash et al. 2011). However, most of the effect comes from a deficient design of the casing of the digital temperature/humidity sensors (see Fig. 1). Although the main purpose of the casing was to protect the sensor from direct sunlight, we inadvertently increased the stagnation of the flow around the sensor, further increasing the effective response time in temperature. This points to the critical role of the casing design in the total error of the measurement (in this case, the casing accounted for several degrees of error in temperature).

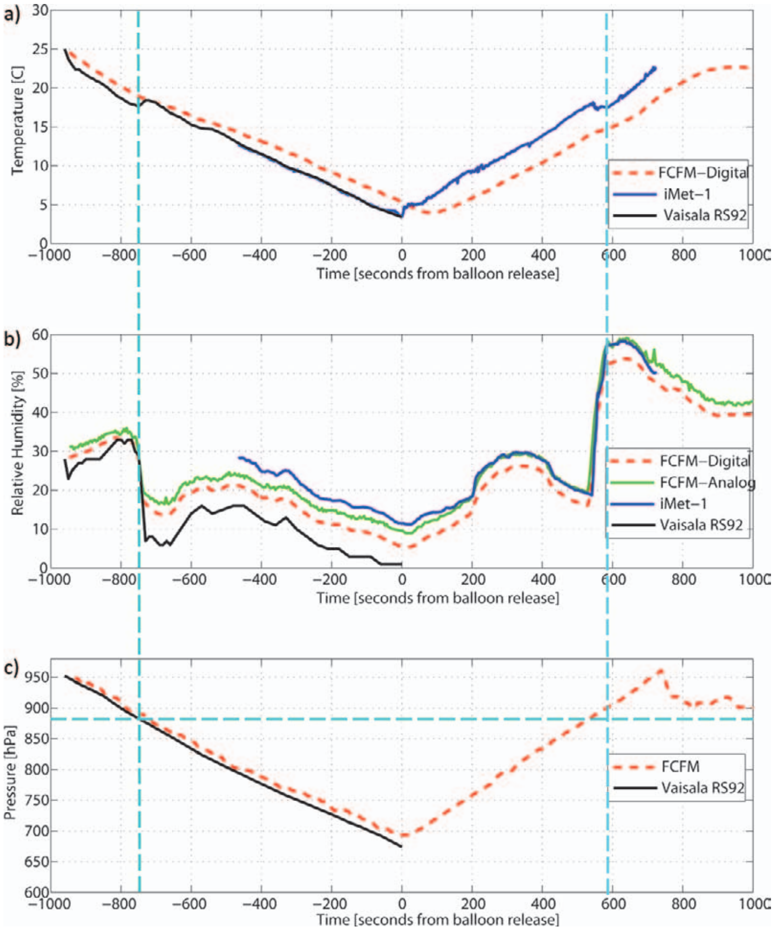


**Fig. 5. Time series data of the different meteorological sensors from the three different sondes during the boundary layer intercomparison campaign for (a) temperature, (b) RH, and (c) pressure. The three sondes are referred to as FCFM, Vaisala RS92, and iMet-1. The light blue dashed lines show the approximate time at which the sonde crossed the top of the boundary layer during the ascent and descent. The horizontal light blue line shows the estimated pressure of the top of the boundary layer.**

The humidity sensors, however, worked reasonably well and took measurements that were in between those of the research-grade radiosonde systems (Fig. 5b). Vaisala humidity measurements during the ascent from the boundary layer to the free troposphere showed humidity values sharply decreasing from about 32% to less than about 8% at the top of the inversion layer. At the top of the sounding, RH dropped to ~1% according to the Vaisala measurement, whereas the iMet sonde registered a minimum of nearly 11% and our digital and analogue RH sensors showed ~6% and ~9%, respectively. Both our digital and analogue humidity sensors showed the sharp decrease of relative humidity at the top of the boundary layer in both the ascent and the descent. Therefore, even in the absence of the research-grade radiosonde temperature, an independent estimation of the height of the boundary layer was obtained by our sonde. Again, the large response time of our temperature sensor filtered out all signal of the boundary layer top in our temperature profile, which is clearly visible in both the Vaisala and iMet temperature data (Fig. 5a). There seems to be a difference in the performance of the RH sensors between the ascent and descent, which might be explained by the different velocity of the sonde relative to the air, and therefore different ventilation of the payload. Also, since the digital temperature had a time lag, the RH measured by FCFM-digital, which has a temperature correction, was also affected by the stagnation of the casing.

The pressure data shown in Fig. 5c are a smoothed version of the raw pressure from the sensor using a moving average window of 10 s. Although a calibration of the pressure was made using equipment provided by the Chilean Meteorological Service, a small bias in pressure is observed, apparently increasing with height. There is a small change in the pressure of the top of the mixed layer between ascent and descent as observed from the horizontal line in Fig. 5c. This may in be in part due to the pressure bias.

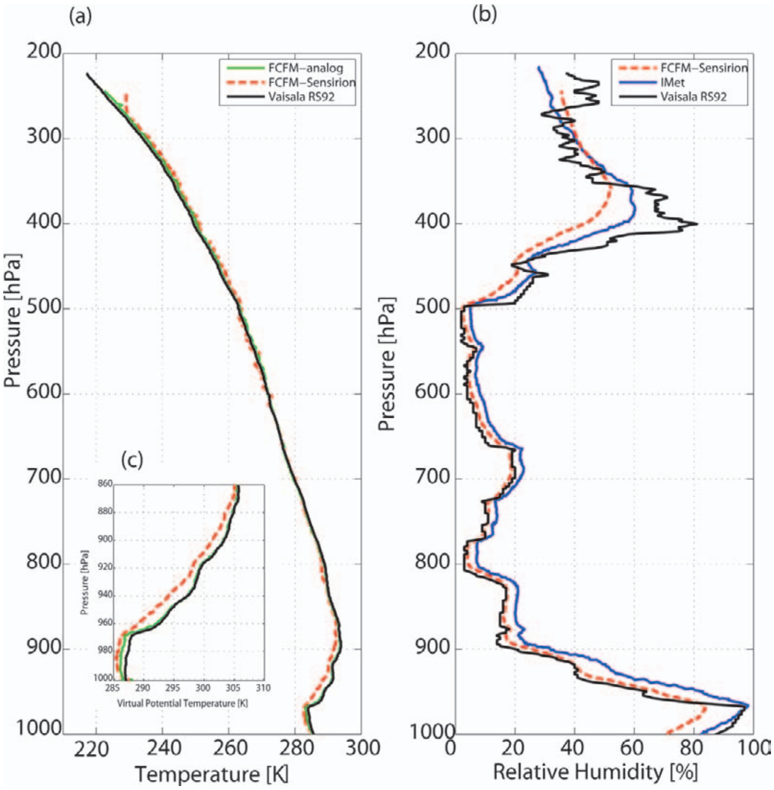


**Fig. 6. Ascent vertical profiles for the free troposphere intercomparison campaign of 4 May 2012: (a) temperature in Kelvins as a function of pressure, (b) RH, and (c) a view of the boundary layer virtual potential temperature.**

*Free tropospheric sounding.* A second campaign was carried out at 1400 local time 4 May 2012 to test the radiosonde electronics subject to conditions in the upper troposphere as well as to test communication over a longer range. The sonde was released at Santo Domingo (33.63°S, 71.65°W; 75 MSL), which is one of the four official sounding stations located in Chile, and the closest to Santiago. Figure 6 shows the comparison among a simultaneous iMet, Vaisala, and FCFM sounding. During this sounding we completely removed the casing covering the digital temperature and relative humidity sensor (FCFM-Sensirion). For this campaign we also added a new analog temperature sensor, which is a thermistor that comes with the most popular Arduino kit distribution, the “Arduino Starter Kit” (see Table 2).

Unfortunately, because of a bad design of the payload, we had interference between the transmitters and the GPS receivers, so no signal from GPS was available from any of the sondes. Individually, the sondes each obtained a GPS signal lock and were transmitting geolocation data to their respective receivers. The lack of geolocation data during flight further resulted in the loss of payload after descending from about 12 km (~220 hPa).

Despite the loss of the payload, the radiosonde transmitted good data even during the descent. Here, we report observations obtained from the ascent part of the sounding. There is a well-mixed boundary layer between the surface and 970 hPa (almost constant virtual potential temperature in the layer; Fig. 6c). Stratocumulus was present at the top of the mixed layer. There is a relatively deep temperature inversion layer from 970 to about 900 hPa. Even without the casing, the FCFM-Sensirion time lag is long enough to smooth out the rapid change at the top of the mixed boundary layer. Figure 6c shows more clearly the lag in temperature by the FCFM-Sensirion; nevertheless, the pressure level of the top of the mixed boundary late could be clearly identified from our sensors. The performance of the analogue temperature sensor was surprisingly good, following very closely the behavior of the Vaisala sounding. The mean absolute error of the temperature was about 0.85 K for the FCFM-Sensirion (mostly due to the large error in temperature within the inversion layer) and only 0.4 K for the FCMF-analog. The FCFM-Sensirion exceeded its operating range and transmitted a fixed temperature after reaching 229 K.

Both the iMet-1 and Vaisla RS92 show relative humidities near 100% at the top of the mixed layer. Our sensor, however, shows an ~15% dry bias within the mixed boundary layer (Fig. 6b). The inversion at the top of the well-mixed boundary layer coincides with a rapid drying from near saturation at the top of the mixed layer to about 20% RH at the top of the inversion layer (about 900 hPa). The performance of our sensor in RH improves for drier conditions compared to Vaisala, consistent with the performance during the first campaign. Near 400 hPa, there was an ice cloud that is apparently detected by the Vaisala sounding as a thin layer of ~100% RH with respect to ice. In this case, both iMet and in particular our sonde have trouble responding to the presence of the cloud and therefore show a much smoother curve (the Vaisala sounding shows a rich structure in humidity), giving also a lower value for the pressure level of the cloud. The slow time response of both iMet and FCFM-Sensirion is clearly seen in the increase of RH above 500 hPa and also in the increase of RH from about 450 to 400 hPa which is the level of the cloud (Fig. 6).

Although we did not recover this first prototype of our radiosonde, the campaign was successful in that it provided us with a wider range of atmospheric conditions to compare and to test the performance of the sensors and the electronics. Also, we were able to receive the signal of the radiosonde over a much longer path than previously tested (about 30 km in a direct line of sight, as calculated from the balloon trajectory inferred from a WRF simulation).

**DID ENGINEERING STUDENTS LEARN METEOROLOGY BY BUILDING AND TESTING A RADIOSONDE?** The main purpose of our original class was to allow students to conceive, design, implement, and operate a radiosonde. The project had an explicit engineering purpose that we believe was largely fulfilled by most of the students. However, we also expected that as an unintended consequence of building a radiosonde, the students would naturally familiarize themselves with atmospheric properties and processes. From conversations with the students at the end of the semester and from the presentations and technical reports that they handed in, we can categorize the students broadly into three equally populated groups that also reflect the students' interests and depth of learning.

- *Students that did not learn any meteorology.* By the design of the class work, students needed to specialize in one of three tasks. The group in charge of the radiosonde communication was only barely in touch with the actual atmosphere we were planning to observe. Some of the best students in the communication group, however, were not in this category.
- *Students that took meteorological observations only as a design constraint on the instruments.* At this level of learning, students were able to take into consideration the range of variables observed in the real atmosphere for the selection of the sensors but did not go much further.
- *Students that took meteorological phenomena into account for the choice of sensors and the design of the radiosonde.* These students revised the design several times in order to comply with the need to observe a particular process. For instance, in order to distinguish rapid changes in the atmospheric variables with height, some students realized that there is a trade-off between the ascent rate of the balloons ($v_{asc}$) and the time response of the sensors; by simply reducing the ascent rate of the balloons, one is also reducing the ventilation of the sensors and therefore increasing the time response. This is an important issue in the local Santiago climate where the height of the mixed boundary layer is a critical parameter for the dispersion of pollutants (e.g., Muñoz and Undurraga 2010). If the depth of the inversion layer is $\Delta h$, the response time of the sensor in temperature needs to be at least $\Delta h/2v_{asc}$ in order to resolve the inversion layer (this can be similarly applied to the detection of a cloud layer from a RH sounding). Solving this type of problem requires interaction between meteorologists and engineers. Other students that fall into this category were interested in knowing the height of the balloon during the trajectory. The height of the balloon was critical to our exercise as it allows for determining whether the ascent and descent rates during the campaign are the ones estimated before the launching. This permits in situ corrections of the radiosonde trajectory calculated from WRF. The need for the height of the balloons led students to study the concept of geopotential height and the hydrostatic and hypsometric equations. The idea of recovering the payload was also a motivation for some students to become interested in numerical weather forecasting models, the calculation of trajectories, and the local meteorology. Several of these students have continued by enrolling in introductory classes in meteorology.

Reflecting on the motivation and performance of the students during the semester, perhaps instead of dividing the groups into particular variables to measure parts of the radiosonde to build, it might be better to assign them to particular phenomena to observe. This would put the students in to a closer relationship with the actual purpose of the instrument and motivate them to come back to the design of the instrument if the data are not satisfactory, as opposed to students thinking that the class is over when the first prototype is ready.

**OTHER SENSORS AND FURTHER DEVELOPMENT.** The lessons learned from the campaigns have led to the development of many improvements to our radiosonde system. Our first two full campaigns were successful in accomplishing some of the main goals that were initially proposed to the students, namely, the transmission of data during flight from most of the depth of the troposphere, the ability to recover the radiosonde, the functioning of the electronics subject to very cold temperatures, and the ability to record and transmit data that compared reasonably well with the operational standards.

Since the end of the semester, some students and most of the teaching assistants have continued working on different aspects of the FCFM radiosonde project. In order to improve the measurement of humidity, we are currently developing a chilled-mirror hygrometer using Peltier cooling elements in part based on the one described by Vömel et al. (2003). Control routines to sequentially cool and warm the Peltier elements can be easily programmed to the Arduino. Also, we are attempting the integration of our system with an ozonesonde, which, being an expensive instrument to begin with (~$1,000 per ozonesonde), makes the possibility of the recovery of the ozonesonde payload much more attractive. Companies that produce electrochemical ozonesondes have designed their instruments to communicate with research-grade radiosondes. Ozonesondes can be reused provided that the reactants are replaced and the sonde is recalibrated.

Equally important for the continuation of the project is to improve the quality of the data obtained from the commercially available sensors, attempting to get as close as possible to the research-grade accuracy and response time in all meteorological variables. Although our comparisons are relative to Vaisala RS92 and iMet-1 radiosondes, these instruments also suffer from biases and random errors [see, e.g., Miloshevich et al. (2009) for a discussion of the errors in the relative humidity measurements made by the Vaisala RS92 sonde]. Improvements in the data come not only from a better instrumentation but also from software corrections due to the time lag of the sensors and possibly improvements in the layout of the instruments in the payload. Attempting to solve some of these challenges makes for interesting ideas for future instances of the workshop class.

If one can prove that radiosondes have errors that are smaller than operational for a significantly large number of soundings, then the idea of adaptive sounding as proposed by Douglas (2010) becomes feasible using our system, given the relatively low cost of implementation of a ground receiving station (the limiting issue then becoming the availability of gas supply). Although the cost of our radiosonde turned out to be on the order of the current commercial radiosondes, the receiver (ground station) is several orders of magnitude cheaper than commercial solutions. In addition to this, the cost of the radiosonde can be of less relevance if we notice two extra advantages of developing a reusable radiosonde, especially as an open software/hardware initiative: 1) open initiatives tend to be developed faster than closed ones because of the community cooperation and 2) specific needs (e.g., radio observatories needing very accurate humidity measurements in the upper troposphere to perform interferometry observations) can be addressed by adding new custom-made sensors in a much easier and more flexible manner.

Other improvements to the system involve the visualization and trajectory software to allow for the real-time correction of the forecast trajectory of the radiosonde to speed up the recovery of the radiosonde package. Also, the Arduino board can be programmed so that in the case of encountering interference at the ground or during the trajectory, the GPS module can be reinitialized and the GPS signal lock can be recovered. Nevertheless, the successful recovery of the payload requires not only having the technology in place, but also a strict set of protocols to be followed by the people participating in the campaign (essential for mission planning engineers).

From a pedagogical point of view, we believe that this exercise is beneficial for both meteorologists and engineers. Meteorologists get a first-hand sense of the data they analyze and study; they recognize the source of errors by looking at amplified versions of the errors relative to what they will encounter in the commercial radiosondes. Engineers, however, learn meteorology (even sometimes inadvertently) by attempting to solve seemingly practical problems. In retrospect, the greatest change we would make to future instances of the class would be to focus the main objective of the class from the beginning on measuring particular meteorological phenomena rather on the construction and integration of the parts and pieces of the equipment.

We have developed a website (www.dgf.uchile.cl/radiosonde) that provides the details of the construction, parts, and programming involved in the radiosonde, so we hope others will attempt the construction of the radiosonde either as a part of the regular curriculum of engineering and meteorology or simply due to enthusiasm. If a community of users and developers flourishes, we hope that many unexpected improvements of the platform that we present here will ensue.

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