SkySense: Terrestrial and Aerial Spectrum Use Analysed Using Lightweight Sensing Technology with Weather Balloons

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ABSTRACT

Given the availability of lightweight radio and processing technology, it becomes feasible to imagine spectrum sensing systems using weather balloons. Such balloons navigate the airspace up to 40 km, and can provide a bird's eye and clear view of terrestrial, as well as aerial spectrum use. In this paper, we present SkySense, which is an extension of the Electrosense sensing framework with mobile GPS-located sensors and local data logging. In addition, we present 6 different sensing campaigns, targeting multiple terrestrial or aerial technologies such as ADS-B, AIS or LTE. For instance, for ADS-B, we can clearly conclude that the number of airplanes that are detected is the same for each balloon altitude, but the message reception rate decreases strongly with altitude because of collisions. For each sensing campaign, the dataset is described, and some example spectrum analysis results are presented. In addition, we analyse and quantify important trends visible when sensing from the sky, such as temperature and hardware variations, increased ambient interference levels, as well as hardware limitations of the lightweight system. A key challenge is the automatic gain control and dynamic range of the system, as a radio navigating over 30km, sees a very wide range of possible signal levels. All data is publicly available through the Electrosense framework, to encourage the spectrum sensing community to further analyse the data or motivate further measurement campaigns using weather balloons.

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CCS CONCEPTS

• **Networks** → *Network monitoring*; *Mobile and wireless security*.

KEYWORDS

HAB,spectrum sensing,balloon,skysense

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1 INTRODUCTION

With the advent of flying base stations, spectrum regulations and dynamic spectrum access become more challenging [2, 19, 20]. This challenge is mainly due to the wider coverage range of aerial base stations, making them a stronger interferer than a similar base station on the ground. In fact, the wider range makes spectrum scanning more critical and hence, increases the required scale of spectrum scanning.

With the availability of low cost, and lightweight, software defined radios (SDRs) and embedded processors, spectrum sensing at large scale becomes possible. Electrosense [21] is a crowd-sourced initiative to unlock the spectrum sensing potential and give massive access to data to the crowd in general, and to the spectrum research community specifically. In Electrosense, all data is sampled by static low cost sensors, that compress the data that is then stored and analysed in a data center. Due to these ground-based measurements, the sensing range is small, as they are often deployed indoor, and therefore, miss a lot of signals.

Companies like [1] launch sensors in space for measuring signals from up there, and it is even possible to design a nanosatellite for this purpose. However, these devices move far away from transmitters, and the sensitivity of these devices needs to be tremendous to detect the smallest signals. Furthermore, the radio horizon is in the order of several 100 kilometers, such that wireless signals cannot be located accurately. However, this information is crucial, as spectrum access is always a local action.

As technology scales, and power consumption decreases further, our vision is that eventually extremely light-weight, battery powered, spectrum sensing with local data storage and processing will become possible. We even envision those tiny *extreme edge sensors* to be light enough so they can be carried by balloons or drones.

In this paper, we propose SkySense, which is a light-weight, battery-powered solution for spectrum sensing using weather balloons. Using this prototype system, initial measurement campaigns were carried out, and this data can be used to quantify the case of aerial spectrum sensing. Indeed, our results show that high altitude spectrum sensing significantly increases the number of overheard messages, and as a result, increases the spectrum use knowledge.

In addition to an increased view of terrestrial spectrum use, high altitude sensing also enables to monitor the spectrum use in the region between satellites and the ground. These balloons measure the signals while going up and provide statistics of spectrum use, spectrum occupancy, and the potential of dynamic spectrum access and monitoring from the sky. In parallel, we are interested in knowing the proper altitude for monitoring signals. Furthermore, we like to understand how many sensors we need to cover a particular area and whether SkySense is feasible in the first place given the extreme weather conditions at high altitudes.

The contributions in this paper are (1) a low power and low-cost mobile spectrum sensing platform using generic probes to measure all frequencies below 1.8 GHz, (2) a data set from 6 measurement campaigns containing signals at different altitudes, (3) an initial analysis of these signals, and (4) the lesson learnt from our experience. We observed that balloons are an interesting platform for measuring signals, but that the optimal altitude depends on the frequency, the protocol, and the number of wireless devices that it can sense.

This paper is structured as follows: In the next section, we discuss the need and the motivation to send high-altitude balloons in the air for sensing the spectrum. Section 3 elaborates on the design of the balloon, and Section 4 discusses the different balloons launched and the technologies we have measured. The next section then demonstrates the obtained results. Finally, we conclude this paper with a discussion, where we provide do's and don'ts for launching spectrum measuring balloons.

2 MONITORING SPECTRUM WITH BALLOONS

The Electrosense project [21] provides a platform for large scale spectrum analysis with low-cost sensors. This spectrum analysis is done through crowd-sourcing, which allows a wide and distributed spectrum sensing over the globe. Currently, all sensors are connected to the main grid, however, it is not mandatory. Recent developments in single-board computers allows sufficient computational power and decent storage space with low-cost and low-power consumption. These characteristics enable spectrum measurements for a few hours, without being online, i.e., connected to the internet. Such an offline period opens exciting new opportunities, such as launching the wireless spectrum analysis tools to the sky with balloons, or other moving vehicles. In this work, we propose SkySense, a mobile and battery-powered wireless spectrum monitoring payload for high-altitude balloons to measure signals from above. This measurement framework forms an interesting approach for the current platform to cover blind spots in spectrum measurements. To be successful in covering these blind spots, it is important that we can effectively measure more signals when going higher and that we can prove a larger radio horizon.

2.1 New aerial technology sensing opportunities

Spectrum measurements from the sky open unexplored opportunities for spectrum sensing and analysis. Many applications use the spectrum at higher altitudes. Avionics uses a tremendous, but scattered amount of spectrum for coordination and connectivity, including Automatic Dependent Surveillance - Broadcast (ADS-B), Air Traffic Control (ATC) and Aircraft Communication Addressing and Reporting System (ACARS). With the ever-growing numbers of airplanes, it is an open question to see how this congestion looks like at higher altitudes. Additionally, we are curious about what levels of interference they can tolerate.

Another example is Internet connectivity provided by balloons. Alphabet's project Loon [19] is probably the most renowned project. It is important to quantify what such technologies are capable of at higher altitudes and what type of interference they may observe. More importantly, many of these technologies aim at using Industrial, Scientific and Medical (ISM) bands, however, little is known about low-power communications at higher altitudes.

Similarly, there is the satellite industry that wants to connect the world. Examples in this category are Starlink [28] and Hiber [4]. Both companies want to connect thousands of users or sensors with high-speed link or low power wide area link, respectively. Balloons provide cheap solutions to measure the performance and signal strengths at a considerable portion of the altitude of satellites. Therefore, it can give a good indication of the achievable performance.

2.2 Advantages of high-altitude sensing

As mentioned before, balloons are a cost-efficient way to measure signals at high altitudes. It is an excellent platform for both hobbyists [26] and school projects [17] as well as professional equipment [5], primarily for measuring meteorological and climatic activities. The advantage of measuring at high altitudes is the larger coverage area compared to ground-based receivers. For this reason, weather balloons have been been selected as a platform from measuring seismic activity [13] to lightning activity [15], or more related: electrosmog [11]. One sensor can easily cover a few 100 square-kilometers, while an indoor sensor is restrained to a much smaller area.

Similarly, wireless signals propagate better at higher altitudes because of the higher probability of *Line-of-Sight* at higher altitudes. This effect has been studied both theoretically with drone

Table 1: A comparison between different spectrum sensing platforms

Platform	Lifespan	Accuracy	Coverage	Price	Reference
Mobile spectrum sensor	+	++	- -	-	
Collaborative spectrum sensing	++	-	-	++	[21],[12]
Drone based platform	- -	+	+	- -	[8]
Balloon based platform	-	-	+	+	**Skysense**
Satellited based platform	+	++	++	- -	[1]

models as well as experimentally [22, 24]. It is important to note that the works presented in these papers do not assume kilometer altitudes but just in the order of 10 to 100's of meters.

In addition to the larger coverage area, balloons also fly at altitudes comparable to airplanes. This proximity makes them an interesting vehicle to transport measurement equipment to measure the effect of altitude on avionics communications. As a result, [3, 6, 7, 14] have looked into measuring ADS-B messages. Besides ADS-B, more protocols are used in avionics such as air traffic control bands to check interference and congestion on these channels. Measuring these bands can give information about the amount of traffic, congestion of the wireless medium, proper cell planning of airport control, etc.

A similar effort has been done by [16, 18] for AIS. These authors tried to make a monitoring platform as well targeting Automatic Identification System (AIS). It should be mentioned that all papers for both ADS-B and AIS only measure the performance at the maximal altitude, ignoring the ascent time.

Inspired by these pioneering works, we would like to present our contribution: a general purpose and low-cost software defined radio in the sky to measure wireless spectrum at higher altitudes. This probe allows to monitor and decode all frequency bands, not only when it is hoovering at its highest altitude, but also during the ascent to unravel the effect of altitude on different protocols.

2.3 Comparison with other spectrum sensing frameworks

When introducing a novel spectrum sensing framework, it is important to highlight the strengths and weaknesses of such a framework. Specifically for a spectrum sensing framework, this platform needs to work for long time, measure accurately with a high coverage, and with as low price as possible.

We highlight each of these in

- **Lifespan:** The percentage of time a sensor is scanning the spectrum. Ideally, this is continuous.
- **Accuracy:** The accuracy of the data, how high is the noise floor. A measure of the quality of the receiver.
- **Coverage:** The coverage is the amount of surface that is covered by the framework. This is depending on the radio horizon.
- **Price:** The price to deploy a sensor.

A mobile sensor mounted on a car for foxhunting allows for great flexibility, turns on whenever needed and is highly accurate as it needs to find even the smallest signals [27]. The coverage however is limited as there is only one sensor, which typically is circumvented by software, making the whole setup expensive.

Collaborative spectrum sensing (like [12, 21]) is the other type of the spectrum sensing. Many users share the deployment price by placing a small sensor in their house. Each user covers a small area, hence full coverage is obtained by combining the sensing of multiple sensors. However, because these sensors may be deployed indoor to ease the setup, the quality of the data could be rather low and the coverage of each sensor not optimal.

A drone-based spectrum sensing framework exists in the form of a mobile sensor mounted on a drone. Aerial sensors provide better coverage, however, the battery life of the drone largely limits its applicability. Furthermore, considering the price of the drone and the pilot time, this setup is expensive.

Launching satellites to measure spectrum is an interesting approach. The sensors are always sensing whenever they are above a certain location. Moreover, their hardware is carefully designed and placed. This makes their coverage nearly perfect. However, launching satellites is costly, the hardware needs special care to resist the space environment and cannot be repaired in case of failure, generating additional space junk.

Motivated by the above discussion, we propose our balloon-based network. This is the cheaper version of the satellite as it gives a wider coverage by flying high, while being less expensive than launching a satellite. A summary of these platforms is written in Tab. 1. Notice that a balloon-based platform nicely augments the collaborative spectrum sensing. By flying over an area, an overview of the signals can be obtained, while small area granularity can be obtained by placing ground receivers. Therefore, we argue that this new framework should not work standalone, but complement existing platforms to enhance them.

3 DESIGN OF THE PROBE

The probe consists of a balloon filled with helium, and a payload encompassing all the measurement hardware. It was designed by the company SkySquitter[1], who is specialized in custom measurements from the sky. In this section we give further insights on the hardware design and the software, which allowed running the experiments.

3.1 Hardware

Fig. 3 shows the components building the payload. The `Control and sensing unit (FRCU)` is at the heart of the hardware platform, as it controls all the other components. It is responsible for measuring the physical environment, such as the pressure-altitude, the temperature, the humidity and the GPS position. All this information is sent through telemetry to ground stations through

[1] http://www.skysquitter.com

the Radio Teletype (RTTY) protocol on 434MHz, and also made available to the software running on the Raspberry Pi Zero W. The FRCU handles the power management as well, and gracefully shuts down the host system when the 2700mAh battery reaches a certain threshold. In the case that the FRCU would fail and that as consequence no more telemetry information could be sent, an independent GSM tracker is automatically activated.

The `Host system` on the other hand includes all the required equipment for performing the RF measurements. Its design relies on the Electrosense sensors, used for spectrum monitoring. Due to weight and power constraints, it was opted for a Raspberry Pi Zero W instead of the 3B+ version. The Raspberry runs the measurement software and receives environmental data from the FRCU. The well-known `RTL-SDR` allows spectrum measurements from 24MHz to 1766MHz with a stable bandwidth of 2.4MHz. In order ensuring the decent reception of signals at high altitudes and to avoid noise generated by the SDR's gain control, a Low Noise Amplifier (LNA) was used.

The hardware was put into a styrofoam box, which served as thermal protection and allowed absorbing the shock of the crash on the ground. The entire payload including hardware and styrofoam weights only 870g, with dimensions 260x210x192mm. The payload without the styrofoam box is shown in Fig. 1.

Similar as in rocket science, every gram of energy which has to be carried impacts the system. In our experiment, a trade-off had to be made regarding the embedded battery powering the systems. As we wanted to achieve high altitudes, its weight had to be limited. For that reason, measurements were only performed during the ascent, which allows reducing the battery size, and therefore the overall weight. An additional advantage of only measuring during the ascent is that the telemetry can be broadcasted continuously during descent, simplifying the recovery of the balloon.

The launch of our balloon probe is visualized in Figure 2. The figure on the left shows a human as comparison for the size of the balloon. This person is also holding the payload. The second figure shows the balloon and the payload flying. Notice that the balloon is completely passive. Steering the balloon is left to the environment, being the wind and thermal effects in the atmosphere.

3.2 Software

The software of the FRCU was entirely developed in C and is proprietary. The Host system relies on the Electrosense software available on GitHub [2]. The `essensor` executable interfaces with the RTL-SDR and takes simple parameters such as center frequency, bandwidth, the measurement type (In-phase & Quadrature (I/Q) or Power Spectral Density (PSD)) and the output file. Measurements data is stored locally on the SD card of the Raspberry Pi. The balloon carried a SD card with a storage of 64 GB. This was however too much, the balloon samples around 2 MB/s of raw IQ data. For a flight of 4 hours, the total amount of data occupies around 28 GB of space when sampling continuously. But due to the telemetry broadcast and the landing phase, the balloon was not always sampling.

In order to allow various types of measurements (I/Q and PSD) at different altitudes during the ascent, users specify what should be measured when in a dedicated configuration file. Each line consisting of a measurement definition has to include the altitude above mean sea level when the measurement has to start, its maximal duration, and the es_sensor command to run (or any arbitrary command). An excerpt of such a configuration file is shown in Listing 1.

[2]https://github.com/electrosense/es-sensor/wiki/Usage

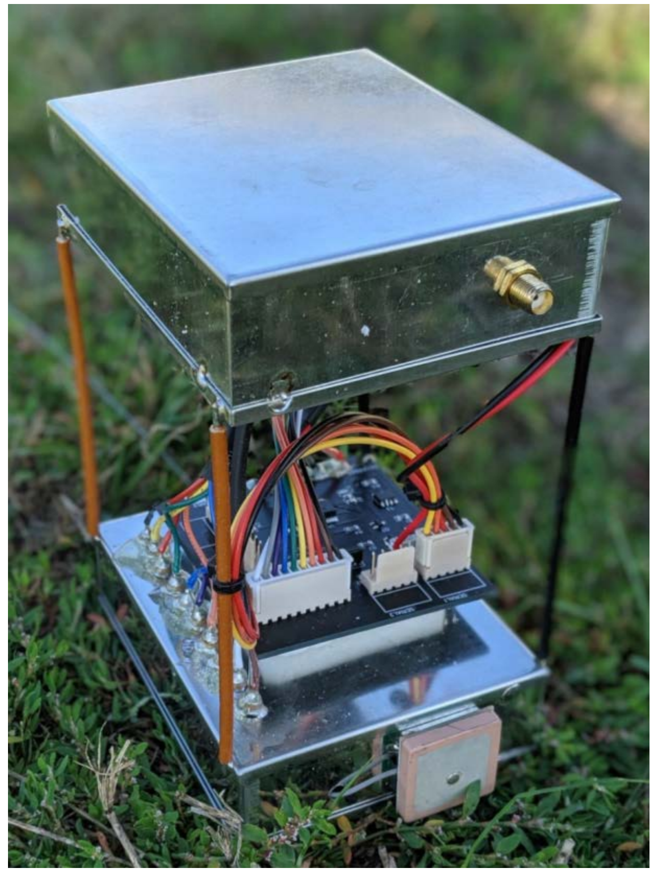


Figure 1: Balloon payload encompassing all the hardware required for spectrum measurements in the stratosphere.

A Java application on the host system takes the configuration file as input parameter and executes the commands when the target altitude has been reached. The altitude information is received every second from the FRCU. Furthermore, a log CSV file stores following information: timestamp, latitude, longitude, altitude, vertical speed, speed, satellites and pressure.

4 MEASUREMENT SETUP

With the balloons, described in the previous section, we measured the spectrum occupancy and usage of a variety of frequency bands in a region west of Frankfurt. In this regard, we targeted three different scenarios.

The first scenario was focusing on avionics. Airplanes typically fly on an altitude between 0 and 10 kilometers. The balloon would therefore allow to monitor these frequencies amongst these planes

Figure 2: SkySense payload launched on August 20, 2019 from a small airfield close to Frankfurt Main Airport.

Listing 1: PSD and IQ commands are executed at 1000, 2000 and 30000m above mean sea level.

```
1000,60,es_sensor 24000000 170000000 -z PSD -s 2400000 -u /tmp/psd_1000.csv
2000,15,es_sensor 806000000 806000000 -z IQ -s 2400000 -u /tmp/iq_2000.raw
...
30000,60,es_sensor 109000000 109000000 -z IQ -s 2400000 -u /tmp/iq_30000.raw
```

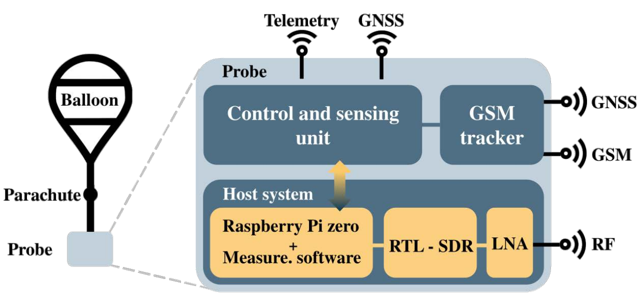


Figure 3: Hardware design of the probe, consisting of the FRCU, a Raspberry Pi Zero W, an RTL-SDR along with a LNA

and see how occupied the channel is, how many aircraft can be seen, along with the potential horizon limit.

The second scenario is similar, but looked for ships. In contrast with airplanes, ships use AIS which comes with a flavour of satellite communication as well as peer-to-peer connections.

The last scenario is linked to user connectivity and terrestrial mobile broadband communication technologies. People are more connected these days, from FM radio stations to Digital Video Broadcasting - Terrestrial 2 (DVB-T2) for video and even GSM and LTE for bidirectional communications. The effect of altitude has been shown in multiple theoretical works for lower altitudes (up to a few 100m), but this scenario is interested in higher altitudes.

For these measurements, we launched several balloons from the airstrip in Reinheim. The measurements from the different balloons are summarized in Table 2 and their respective flight paths are presented in Fig. 4. Notice that due to similarity in wind patterns, the balloons' paths are similar. The exact landing time of the balloons is not always known as the battery drained before the balloon reached the ground and the logging ended. In Table 3, we list the most important technologies we measured during our measurement campaign. The data itself is publicly available at [3].

Before going into the measurements itself, we add here the typical conditions in which a balloon has to work. These conditions are summarized in Figure 5. The figure shows that the environmental conditions can be considered harsh, as the outside temperature was below the typical range of commercial hardware. Second, the pressure inside the box drops to 7 hPa at the highest achieved altitude. These values make sense when leaving the troposphere to the stratosphere. A remarkable observation from this figure is the small voltage drops. These occur when the low-noise amplifier is turned on, and therefore, when measurements are being performed. When the measurement successfully finishes, the amplifier is turned off and the battery voltages goes back to the higher state. Looking at the measurements, we did not see any issues with this except for the final day when battery drained. The reason of the empty battery was the LNA that did not turn off as expected. Lastly, it is important to note that we did not have GPS issues unlike [14].

An issue that we did encounter was DVB-T signals leaking in the receiver. These strong signals clip the first amplifier and generate harmonics. This was observed during the measurement when measuring the GPS signals. As a reference we include the locations of the DVB-T2 transmitters in Fig. 6 to compare with the flight paths above in Fig. 4.

[3]https://electrosense.org

Table 2: High-altitude balloon parameters

Name	Antenna Length	Technologies measured	Launch time	Landing time
SKY-BEAR	7 cm	ADS-B	10:40	13:05
SKY-BULL	9 cm	LTE,DVB-T,ISM	11:50	13:15
SKY-PUSH	35 cm	ADS-B,Radar,AIS,weather satellites	08:43	11:55 **(est.)**
SKY-DATA	9 cm	LTE,DVB-T	10:20	13:00
SKY-TRON	48 cm	AIS	11:10	14:30
SKY-KING	18 cm	ISM,ATC,ADS-B uplink	09:21	11:00 **(est.)**

Table 3: Measured protocols

Frequency	Altitude	IQ/PSD
ADS-B	0-40 km	IQ
AIS	0-30 km	IQ
ATC	0-30 km	IQ
DVB-T	0-30 km	IQ/PSD
PMR	0-40 km	IQ
PPDR	0-40 km	IQ
LTE	0-10 km	IQ
NOAA	0-30 km	IQ
satellite uplink	0-30 km	IQ
Telemetry	0-30 km	IQ
433 MHz ISM	0-30 km	PSD
868 MHz SRD	0-30 km	PSD

5 MEASUREMENT RESULTS

In this section we describe and comment the measurements obtained through several balloons. The results are split between ADS-B, AIS, DVB-T2, Long Term Evolution (LTE) and telemetry/amateur radio bands.

5.1 ADS-B

5.1.1 Measurement setup. For measuring ADS-B data, we used SKY-BEAR for all altitudes until 30 km, where the balloon burst. Above 30 km, SKY-PUSH has filled our data set up to 42 km. SKY-BEAR was only measuring ADS-B data and therefore measured the ADS-B band every 300 m for 30 s. SKY-PUSH has been configured to measure ADS-B data every 3 km for 30 s.

5.1.2 Measurement results. The results of this measurement are published separately in [23]. For completeness, we will discuss the most important results here as well. In Fig. 7, we show the amount of airplanes that can be seen from the balloon. The amount of aircraft is rather stable over all distances but the reception rate shows a lot of variation ranging from 150 kilometers to 480 kilometers. This variation might be explained because of the lack of airplanes, which we doubt as Frankfurt is rather close and the number of aircraft is constant. However, we believe that the ADS-B system is full of collisions and noise. This is backed by Fig. 8 where we can see that the noise always goes up. This is remarkable as we will see later that the noise power goes down at higher altitude. Additionally, we noticed a big difference in the distribution of messages we see compared to the amount of planes we observe, shown in Fig. 9. We clearly notice a significant amount of planes close by, but few messages coming from flights far away. This makes us believe that due to collisions many ADS-B messages are dropped.

The measurements between 5 and 12 km show the most stable results, the reception rate remains constant and the maximal distance increases. Altitudes higher than 12 kilometer show a high variation in the reception rate. This variation is caused by collisions and is better to be avoided.

5.2 AIS

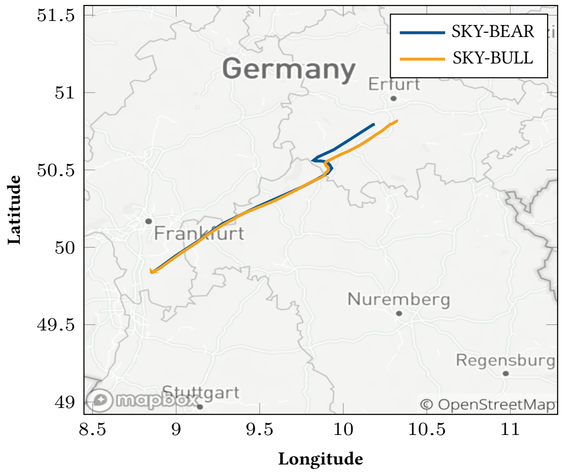
5.2.1 Measurement setup. With SKY-TRON we collect raw AIS I/Q samples with a period of 100 s. For both Terrestrial-based AIS (T-AIS) and Satellite-based AIS (S-AIS), the sampling rate was set to 1.6 MHz.

5.2.2 Measurement results.

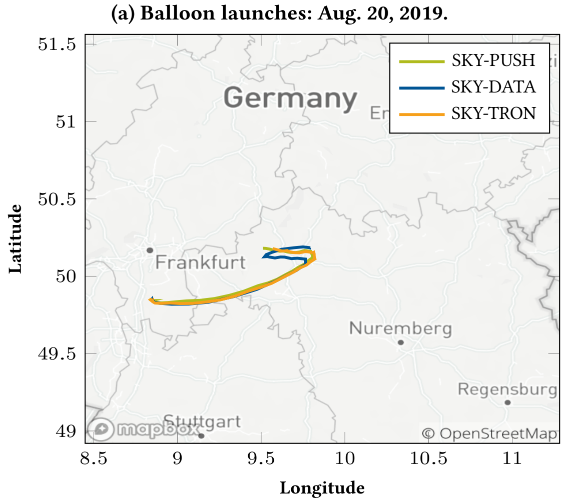
AIS Message Type Frequency of Occurrence: AIS messages frequency of occurrence depend on type of message. The AIS Technical Standard ITU-R M.1371-5 lists out 27 different types of AIS messages [10]. We counted the number of occurrence for each type of AIS messages within the captured time window. Fig. 10 summarizes the number of frames for the message types we observed during measurements. Messages of type 1 and type 27 are the most frequent as it is shown in Fig. 10. Messages of type 3 and 8 are the next most frequent, while other types of messages (types 4, 5, 6, 7, 15 and 18) have a very low frequency. The other types of messages are not observed within the captured time window. At higher altitudes a low number of messages transmitted on T-AIS frequencies is sensed. On contrary to T-AIS messages, with higher altitude more messages of type 27 are sensed.

AIS Channel Load Management: AIS system operates in Very High Frequency (VHF) band and four channels have been designated for its use worldwide: AIS 1 (channel 87B with a center frequency of 161.975 MHz), AIS 2 (channel 88B with a center frequency of 162.025 MHz), channel 75 (used only for S-AIS with a center frequency of 156.775 MHz), channel 76 (used only for S-AIS with a center frequency of 156.825 MHz).

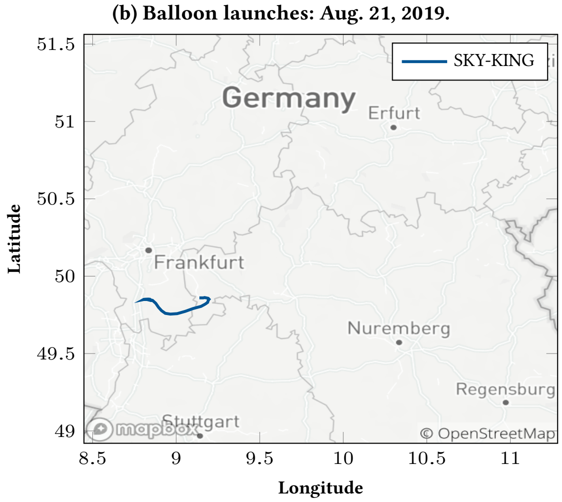
Each channel has bandwidth of 25 kHz and channel spacing is equal to 25 kHz. AIS by default operates on channels 87B and 88B for T-AIS. Base stations could alternate AIS messages between those two channels in order to increase link capacity, to balance channel load and to mitigate the harmful effects of Radio Frequency (RF) transmissions [10]. For this function an efficient channel management is needed. S-AIS transmissions should alternate between channel 75 and channel 76, as well so that each channel is used once every 6 minutes. Fig. 11 shows that the channel load is very



(a) Balloon launches: Aug. 20, 2019.



(b) Balloon launches: Aug. 21, 2019.



(c) Balloon launches: Aug. 22, 2019.

Figure 4: Flight paths of the balloons on 3 consecutive days (Aug. 20, 2019 - Aug. 22, 2019).

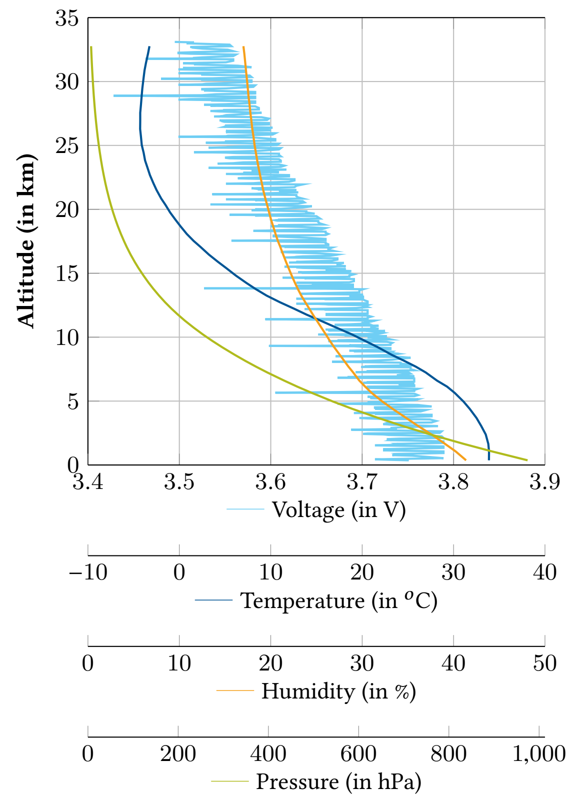


Figure 5: Typical measurement results of the on-board flight computer in one of the flights.

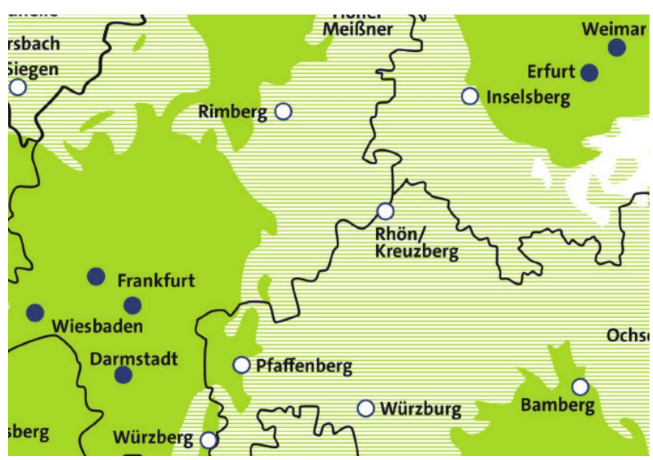


Figure 6: Locations of DVB-T2 broadcasters. Both blue and white circles. (Source: [9])

well balanced between channel 87B and channel 88B, as between channel 75 and channel 76. Thus, the measurements prove that both systems, T-AIS and S-AIS have deployed channel management which works very well in practice.

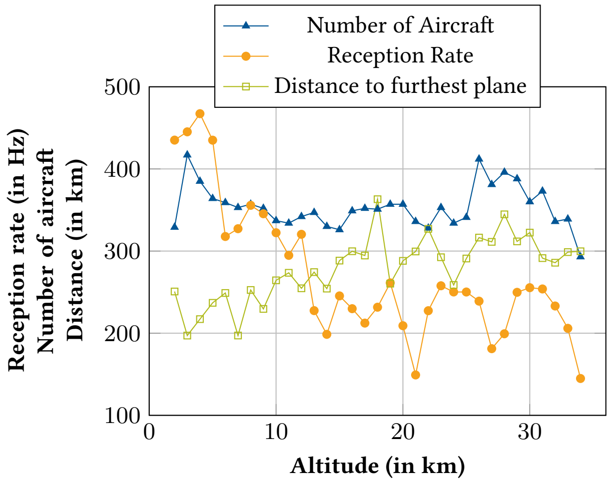


Figure 7: Amount of aircrafts picked up by the balloon at various altitudes compared to the reception rate of ADS-B messages.

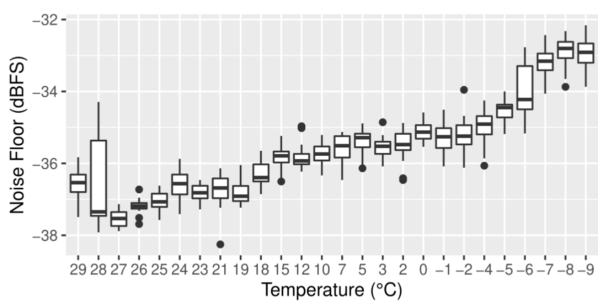


Figure 8: Noise level of the ADS-B messages in the balloon.

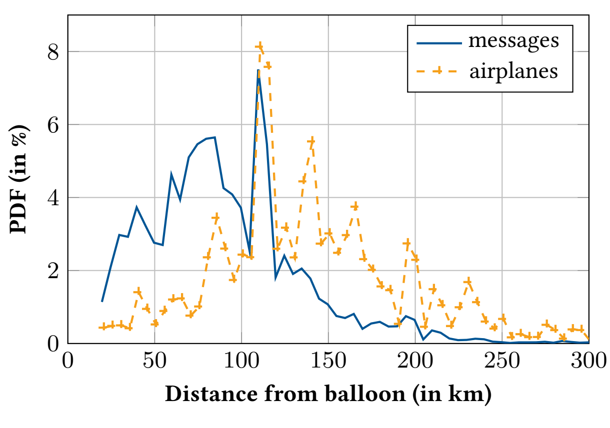


Figure 9: Comparison between the distribution of observed flights and the distribution of received messages.

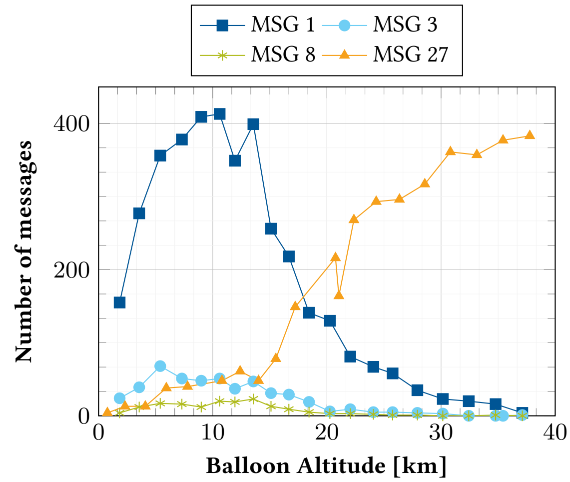


Figure 10: AIS Message Types Occurrence Frequency.

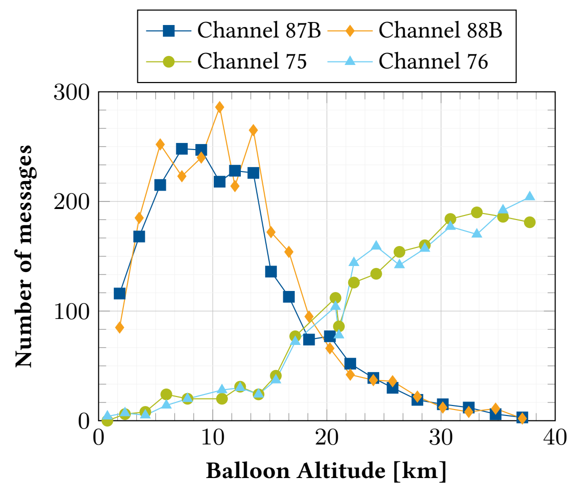


Figure 11: Number of AIS Messages per channel.

We can clearly see that the different bands should be measured at different altitudes. For channel 87B and 88B, we need to measure at altitudes up to 15 km, while for Channel 75 and 76, the rule 'higher is better' applies.

5.3 LTE

5.3.1 Measurement setup. For LTE measurements, the setup with the balloons was the following:

- **SKY-BULL**: We collected 5 s of I/Q samples every 60 m up to an altitude 10 km. The measured frequencies were 796, 806 and 816 MHz with an antenna gain of 20 dB and a sampling rate of 1.92 MHz.
- **SKY-DATA**: I/Q samples were gathered using the same parameters except for the maximum altitude and antenna gain, which were set to 4 km and 15 dB respectively for this run.

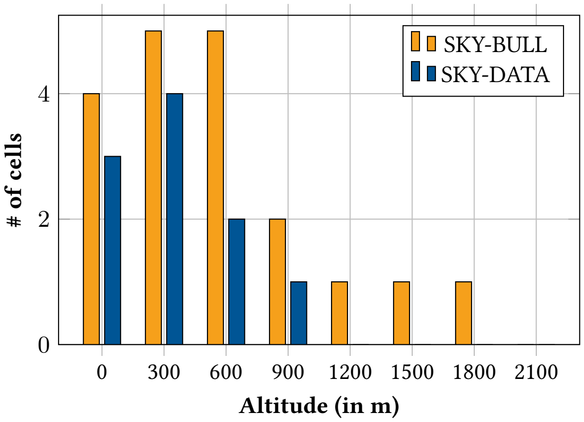


Figure 12: Number of LTE cells detected at different altitudes.

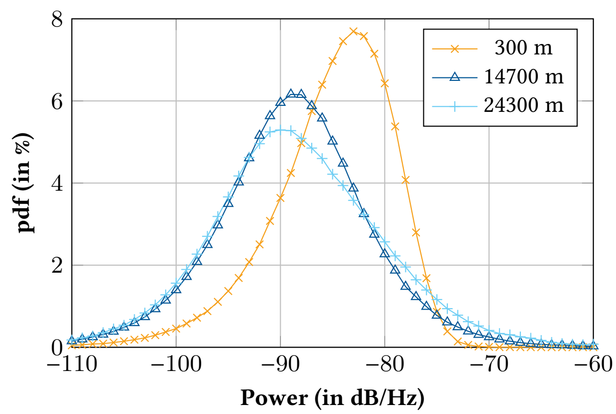


Figure 13: Probability density function of combined noise and signal PSD values for three different altitudes.

5.3.2 Measurement results. We measured the number of LTE cells, employing the open-source package *LTE-Cell-Scanner*[4]. As it can be seen in Figure 12, the amount of LTE cells starts increasing up to 600 m altitude and then gradually decreases until no cell is visible at 2000 m of altitude. The results at the lower altitudes are perfectly in line with the measurements obtained in [24]. However, here we can clearly see that these results cannot be extrapolated to higher altitudes. We could not even observe any cell higher than 2100 m in any of the launches. It is clear that from this altitude the neighbouring cells start to interfere each other and prevent receptions of messages from the base stations.

When monitoring these bands with balloons, it is clear that the measurements need to be performed at low altitudes.

5.4 Telemetry

5.4.1 Measurement setup. 434 MHz is a popular band for broadcasting telemetry information of balloons. Our balloons used this band, but as can be seen on the tracker of *habhub*, many other balloons make use of this frequency as well. We were hoping to also spot these in the sky.

- **SKY-KING**: We collected I/Q samples every 4800 m for 200 seconds. The RF-gain of the RTL-SDR was set to 30 dB and the center frequency was set to 434.5 MHz. This allowed us to oversee a part of the ISM band and a part of the band where high-altitude balloons are transmitting.

5.4.2 Measurement results. We ran the raw IQ signal through the MATLAB Periodogram command to get the PSD data out. These results were averaged to smooth the curve and then put in dB. The results are visualized in Fig. 13 and Fig. 14.

The first thing we observe in the measurement campaign is the noise floor of the signal. The noise floor goes down with higher altitude. This could be explained in 2 ways:

- The thermal noise goes down thanks to the lower temperature at these altitudes.
- The voltage of the balloon goes down, limiting the power to the amplifier and decreasing the amplification.

This lower noise floor can be seen in Fig. 13. The maximal peek shifts to the left towards the lower end of the power distribution. Notice as well that we can observe more signals at higher altitudes, this is visible in the measurements in the region from -75 dB/Hz to -65 dB/Hz. Therefore, these curves have a longer tail. We can see the same in the PSD in Fig. 14. Notice the low noise floor on the right of the figure and the many peaks on the left. Given the higher signals appearing, we assume that it is actually the thermal noise going down.

A lot more signals can be seen when going higher. Some of these signals are broadcastgin chatting radio amateurs. The highest peaks on all altitudes are radio amateur broadcasters. The high peak on the right side of the curve of 24300 m is a data channel from a balloon, transmitting a long preamble and a small packet of data. And another balloon transmitting the RTTY protocol was found as well, but its SNR was too low to decode.

The variety of signals appearing in the ISM band made this IQ data set ideal to check for signals and to do a signal count. This is shown in Fig. 15. The figure shows clearly that when flying higher, it is possible to observe up to 14 times more signals compared to an altitude of 300 m. This proves that our balloon platform is actually a good idea to cover the blind spots as it allows to extend the coverage of the existing network.

To count the amount of signals, we did an 4096-sized FFT on the incoming IQ signals and averaged all the frequency bins with an IIR filter. Then, we made a dynamic threshold with a 0.4-median filter taking into account 40 frequency bins to distinguish signals from noise. All FFT bins with a value 6 dB higher than the threshold were seen as signals. Post-processing was done to merge different detections together to get the final count.

6 DISCUSSION

6.1 Spectrum monitoring with SkySense

[4]https://github.com/Evrytania/LTE-Cell-Scanner

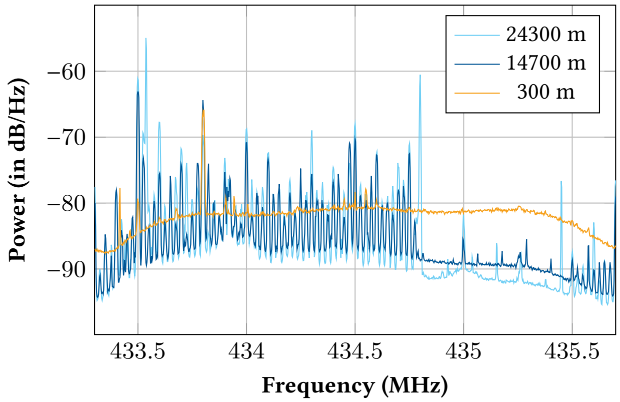


Figure 14: PSD for three different altitudes.

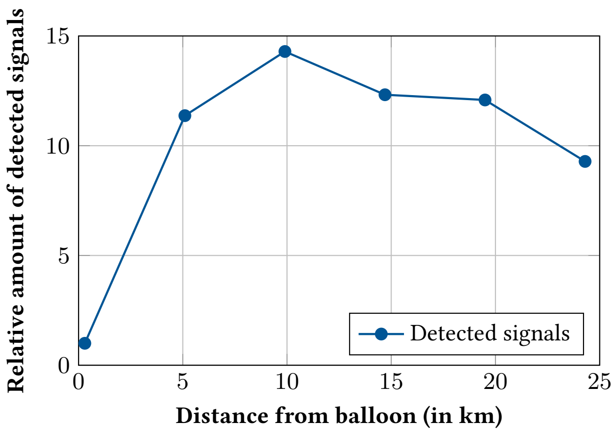


Figure 15: Relative amount of detected signals in the 434.5 MHz band.

Our initial analysis results confirm that spectrum sensing with low cost and lightweight hardware at higher altitudes is possible and an interesting idea as proven by Figure 15.

However, there are some fundamental limitations to high altitude sensing. Balloon receivers at higher altitudes perform badly for ground-based services due to increased ambient interference levels. This is shown in Section 5.3. As the balloon goes higher, it becomes impossible to decode the transmission of ground-based transmitters. However, if we are only interested in channel occupancy, this might be sufficient.

For air-based services, the balloon setup is well adjusted. However, due to the congestion on the 1090 MHz ADS-B band, collisions limit the system performance and reduce the amount of visible flights. However, we still believe that balloons form a good way of measuring the interference and noise on the ADS-B band for future research. The optimal altitude for measuring ADS-B in congested region such as the region around Frankfurt is between 5 and 12 km, which gives a trade-off between stability and collisions.

Altogether, we believe that balloons can form a reliable mean for measuring wireless spectrum as an *extension* to the Electrosense platform or a collaborative spectrum sensing platform. For increasing the reliability and usability, there is a need for compressing the obtained spectral information and getting that information to ground infrastructure more reliably, as balloons might get lost. One way of doing this compression, is doing the analysis locally and sending only key features to the ground. Ideally, the whole measurement campaign is still stored on a memory device to be recovered later. This data can be uploaded after recovery to the Electrosense server. And finally, it would be really interesting if the altitude and the position can be controlled. Interesting work towards internet-providing balloons has been done in [25].

Additionally, few balloons will not cover the complete area under investigation. It might be interesting to combine the sensors with the meteorological balloons of the Belgian and German weather services to cover the full German time-frequency-area space. In this way, around 30 balloons can be deployed daily to monitor this surface. Note that the launch platforms of these balloons are at a proper distance from any airport. This part is left as future work.

The ideal use case of this platform would be 3D interference maps that can be queried for accessing a 3D channel dynamically. A prime example would be a flying base station, the installer could query the database to verify if the drone will interfere with the current cell planning or not.

6.2 Things we learned and limitations of the system

The first important thing we learned is to reduce the amplification during the flight. Line-of-Sight signals are strong enough to be received over long distances, and therefore, the amplification is not required. Notice that this also depends on what signals are measured: For GPS signals, this amplification is essential. However, for many clear signals in the data set, such as ADS-B and LTE, amplification easily clipped these signals. This setting seems trivial but was underestimated during the initial measurements. This is also visible in Fig. 16. The yellow line shows a clipped signal, although the transmitter was several tens of kilometers away.

While parsing the measurements, we noticed that some measurement showed an initial power loss of 17 dB. The reason of this power loss is a strong transmitter nearby, namely the telemetry unit. Occasionally, the telemetry was still transmitting while the measurements started, which resulted in this power loss. This power loss turned out to be a good thing in the case of Fig. 16. This figure shows ATC communication. During the time that the amplifier is off, more planes talking to the tower in Frankfurt can be observed.

Another observation we did when parsing the data was the leakage of DVB-T2 signals. DVB-T2 signals are designed for penetrating walls and entering basements. For this reason, they are very strong, especially in Line-of-Sight. Many signals in our data set contain DVB-T2 signals due to harmonics. It is therefore important next time to add additional filters to decrease these strong transmitters and amplifier stages with high IP3.

Long battery lifetime is also crucial as it might take hours to recover the balloon, especially when it lands in a tall tree in a German forest. Moreover, the payload needs to have a high tolerance to crashes for when it lands on solid surfaces like roofs. These roofs

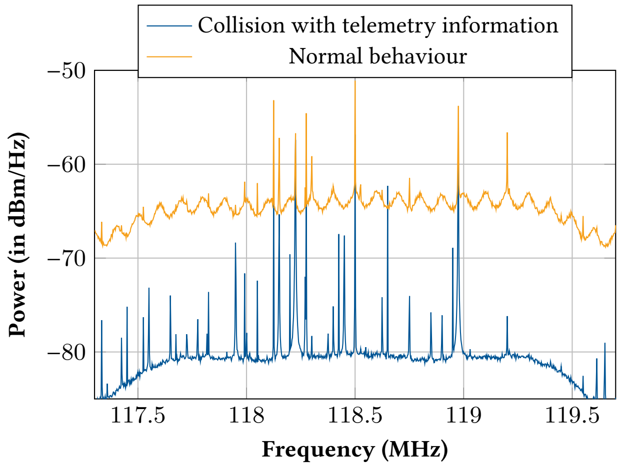


Figure 16: Power loss in the received signal for ATC traffic.

damage the payload significantly and need to be taken into account at design time.

In the measurements we performed, we used monopole antennas. The radiation pattern of these antennas is parallel to the surface of the earth. This pattern is interesting when measuring signals coming from planes, but for measuring signals on the ground, a patch antenna with a radiation pattern towards the ground is more interesting. Although this effect will not tremendously change the results.

Finally, as previously mentioned, the FCRU manages the measurements and stops them each time telemetry data has to be sent. Therefore, a continuous measurement can only last 7 minutes. This restriction is because measuring the wireless spectrum while sending telemetry data would lead to high interference, as mentioned before. This restriction could be circumvented with a band pass filter on that frequency, enabling continuous measurements.

7 CONCLUSION

In this work, we presented an extension of the Electrosense framework to go up in the sky. We designed a high-altitude balloon that could measure signals at high altitudes up to 40 kilometers. With this balloon, we collected data during 3 consecutive days, 6 flights in different bands. The results show that it is feasible to measure signals at altitudes up to 40 kilometer and that it is possible to make a powerful scanning platform in the sky.

Analyzing the data that we acquired, we demonstrated a lower noise floor at higher altitudes, resulting in further transmission ranges and more visible planes. However, due to these long transmission ranges, congestion happens more easily in some bands. It is therefore important to measure signals at the proper altitudes. For ground based services, altitudes up to 2 kilometer are ideally suited. From 5 to 15 kilometer, it is better to scan the ADS-B and S-AIS bands. When going higher, it is interesting to scan T-AIS bands and scan for DVB-T2 signals.

Finally, we discussed the hardware platform and highlighted the lesson learnt and some future directions to make the platform more powerful and standalone, such as additional signal filters and more intelligence on the sensor itself, and ideas to allow continuous sensing with multiple balloons.

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