DETECTION OF EARTHQUAKE FROM THE STRATOSPHERE USING INFRASOUND SENSORS, DESTINY, BEXUS 28

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Abstract

Investigating Venus, a planet with strong similarities to Earth, is key to understanding our solar system history. However, harsh surface conditions (460°C and 92 atm) prevent the use of long-lasting landers. An alternative is to measure ground seismic events from a high altitude (∼55 km) where Venus presents earthly conditions, via stratospheric infrasound measurements using balloons. Conservation of energy and decrease in air density allow infrasound signals to be amplified making their detection easier at high altitude.

DESTINY - Detection of Earthquakes through a STratospheric InfrasoundstudY - flew on the BEXUS 28 balloon in October 2019. Its aim was to use stratospheric infrasound measurements to locate ground seismic events, as a proof of a concept to study the seismic activity of Venus. This paper briefly describes the design of the experiment needed to achieve this objective. It highlights the success of the experiment in detecting a generated ground seismic event, and concludes on the prospects of conducting this experiment on Venus.

Introduction

Venus, the second closest planet to the sun in the solar system, is similar to Earth in many aspects. Of the terrestrial planets, it is the one who has the closest radius and mass to those of Earth. Moreover, radar images of Venus (as shown in figure 1, from [1]) reveal a very large diversity of terrain profiles, with signatures of important possibly still active geological activity. Therefore, an investigation into the internal structure of Venus is key to deepening our understanding of our planet and our solar system.

However, this investigation is deterred due to the harsh conditions found at the surface of Venus. Indeed, the average surface temperature on Venus is close to 460°C, and the surface pressure is close to 92 atm. These extreme conditions prevent the use of long-lasting landers, which are the favorite science platform needed to investigate seismic activity. As of today, the longest-lasting lander is the Soviet Venera 13, which managed to operate on the surface of Venus for a record-breaking duration of 127 minutes. However, this is nowhere near the weeks needed to investigate the internal structure of Venus.

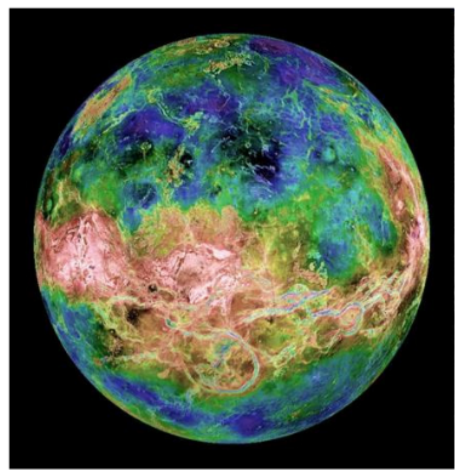

Figure 1: Global radar imaging of Venus, indicating large terrain diversity, and elements of the 40,000-km-long Venusian rift system, from [1]

One possible solution suggested by the Venus Seismology Study Team from Keck Institute for Space Studies [1] consists in investigating, from the atmosphere of Venus, the infrasounds produced by seismic activity on the surface of Venus, thanks to balloon-borne pressure measurements. Indeed, two main arguments supports the use of ballon-borne pressure measurements.

The first argument in favor of this solution is that Venus presents favorable conditions at high altitude.

Indeed, at about 55 km of altitude, The atmosphere of Venus presents earthly conditions, with a temperature of about 27°C and an atmospheric pressure of about 0.5 atm. These conditions make the use of long-lasting balloons possible. In the past, scientific balloons have already been deployed successfully on Venus (Vega 1 and Vega 2 missions, Soviet Union, 1985), demonstrating that balloons could be used for longer duration missions on Venus.

The second argument in favor of this solution is that ground seismic events generate infrasound pressure waves that are amplified as they propagate towards the upper layers of the atmosphere. Indeed, the effects of the conservation of the energy of the acoustic wave assuming dissipationless propagation are coupled to the effects of the decrease in air density along the propagation towards higher altitudes. In these conditions, it has been shown by [2] that the amplitude p of the acoustic wave propagating in an inhomogeneous medium of variable density ρ_0 satisfies the following relation

$$\frac{p}{p_0} \quad \alpha \quad \frac{1}{\sqrt{\rho_0}} \tag{1}$$

Hence, an infrasound wave propagating towards higher altitudes will be amplified, thus making its detection easier and possible for ballon-borne pressure measurement devices.

DESTINY - Detection of Earthquakes through a STratospheric InfrasoundstudY - was part of the BEXUS 28/29 project of the REXUS/BEXUS programme. It was conducted by a team of French students from Ecole polytechnique in collaboration with the SSPA/DEOS research team at ISAE-SUPAERO, and flew on the BEXUS 28 balloon in October 2019. DESTINY stands as a proof of concept for this method, by demonstrating the possibility of studying the seismic activity of Venus from its atmosphere using balloon-borne infrasound sensors.

The DESTINY experiment aims at testing this method on the Earth's stratosphere. To this end, a ground explosion was used as a mock seismic event. This paper briefly describes the design of the experiment needed to achieve this objective. It focuses mainly on the results of the analysis of the data gathered during the 3-hour long flight. This paper highlights the success of the experiment in detecting the ground explosion, and concludes on the prospects of conducting this experiment in Venus.

1 Mission design

DESTINY aimed at designing an appropriate experiment to detect from the stratosphere the infrasounds generated by earthquakes. This section describes the design of the DESTINY mission that got to fly in the BEXUS 28 balloon in October 2019.

1.1 Mission statement

In order to fully demonstrate the possibility of studying the seismic activity of Earth from its stratosphere, we needed for the DESTINY experiment to first be able to the measure infrasound signals in the stratosphere. These measurements done during the whole duration of the BEXUS 28 mission would allow us to characterize the infrasound background in the stratosphere. From these measurements, we needed to be able to extract signals related to geophysical process and to identify their nature. Then, we needed to be able to locate the origin of these identified signals associated to geophysical processes. This allows us to state to three objectives to be fulfilled by the DESTINY experiment. DESTINY needs to:

1. Characterize the infrasonic background noise during the stratospheric flight.

2. Extract signals related to geophysical processes from infrasound measurements and identify them.

3. Locate the identified infrasound sources.

The mission was thus designed to be able to detect the occurrence of earthquakes at the time of the flight. However, the BEXUS 28 balloon was planned to fly for a few hours. The chances were very high that no earthquakes would occur during the flight, so, in order to have at least a geological event to be detected by the experiment, a 800kg TNT equivalent ground explosion was used as a mock earthquake near the launch site of the balloon (Kiruna, Sweden). The explosion was performed by the Swedish mining company LKAB.

In accordance with the experiment objectives, the mission was thus designed and tested in order to be able to detect this explosion from the stratosphere.

1.2 Mission concept

The experiment was designed in order to allow for the analysis and the localization of the sources of infrasound waves. In order to be able to locate the origin of the infrasound signal, an experiment made up of multiple detection devices mounted on a constellation of balloons flying at the same time would have been the ideal scenario. In the present case, only one balloon was available. Hence, the design chosen for the DESTINY experiment consisted in two separates boxes, each equipped with the adequate detection devices (barometer for the measure of the infrasound waves and its acquisition hardware) distributed in the balloon as depicted in figure 2. The first box (in red in the figure) was located in the gondola of the balloon, and will thus be referred to as Gondola Box (GB), and the second box was attached to the flight train of the balloon, 33 meters above the GB, and will thus be referred to as Flight Train Box (FTB).

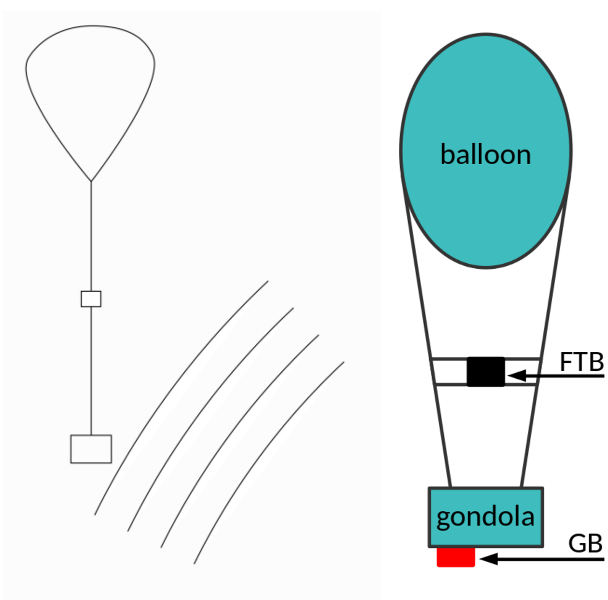

Figure 2: Disposition of the boxes on the balloon.

In principle, each box had to measure the arrival time of the infrasound wave associated to the explosion, and the arrival time difference between the two boxes would have allowed us to retrieve the inclination of the incoming wave. This would have allowed us, after backward propagation simulation, to locate the source of these infrasound signals.

The amplitude of the infrasound signal associated to the explosion was estimated to be close to 0.3 Pa at the location of the detection. Hence, in order to be able to fully detect this signal, we used for each box a Paroscientific 2000 Barometer with acquisition frequency of 180 Hz and pressure measurements resolution of 0.014 Pa, allowing for very precise measurements of the wave.

1.3 Mechanical design

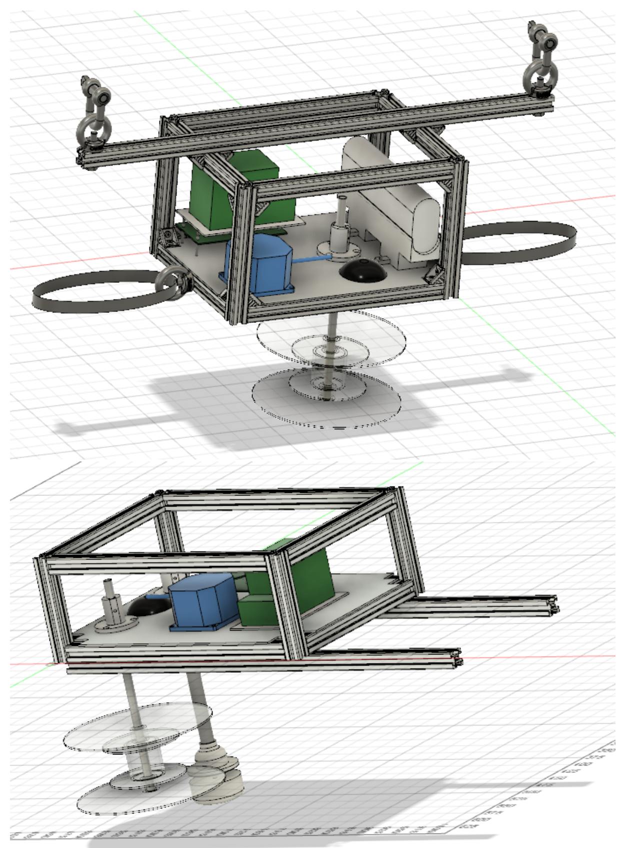

Figure 3: (Above) Flight train box inner disposition. (Below) Gondola Box. These two figures describe the final design adopted for the two boxes, containing each the acquisition hardware in green, the barometer in blue, the inertial measurement unit in black, as well as the the inlet in transparent below each box, which is a passive filter used to reduce the noise in the barometer signal. The FTB (above) contains a battery in gray, and the GB was equipped with an anemometer in white. The outer structure of the boxes was made of aluminium profile bars.

The two boxes were designed to run in the same way, independently of each others. Each box was equipped with a barometer, shown in blue in figure 3, which is the main instrument of the experiment. Figure 3 describes the final designs of the boxes that were adopted for the flight. In addition to the barometer, each box was equipped with an inertial measurement unit (IMU) shown in black, with thermometers, and with the acquisition hardware used for data processing and data storage of all the sensors of the box. The gondola box was designed to use the gondola power supply, while the flight train box, located 33 meters above on the flight train, was equipped with a battery for power supply. The gondola box was also equipped with an anemometer. The external structure of the boxes were made of aluminium profile bars.

The boxes were also equipped with an inlet, shown in transparent in the figure below each box. The inlet is a passive filter used to reduce the noise in the signal measured by the barometers. They were designed specially for the needs of the DESTINY experiment out of light and resistant materials. The complete design was chosen so as to satisfy the requirements of the experiment in terms of weight, size, thermal dissipation and mechanical resistance.

1.4 Launch campaign

The DESTINY experiment was tested using the facilities of CNES at Aire-sur-Adour, in the South of France, where the experiment was run under the harsh conditions of the stratosphere. We were allowed to use the cold and vacuum chamber of the CNES to simulate different scenarios the system could have encountered during the real flight. These tests aimed at characterizing the thermal response of the experiment, and to ensure that the experiment would not crash and would still be running under the harsh conditions of the stratosphere. These tests also aimed at calibrating the thermal regulation system implemented in the boxes, by preventing the hardware from reaching extreme cold or hot temperatures.

The preparation of the mission for the launch campaign was done according to the following schedule:

- Selection of DESTINY for BEXUS 28: 27-29 NOV 2018
- Preliminary Design Review: 11-15 FEB 2019
- Critical Design Review: 14-16 MAY 2019
- Integration Process Review: 17-18 JUL 2019
- Test campaign - CNES: 16-20 SEP 2019
- Experiment Acceptance Review: 30 SEP 2019
- Launch campaign - Esrange: 18-28 OCT 2019

At the Experiment Acceptance Review, the experiment was functioning and fully integrated, and was accepted to fly on the BEXUS 28 mission. The launch campaign was planned from the 18th to the 28th of October 2019, at Esrange Space Center near the city of Kiruna in Sweden. The flight occurred on Friday the 25th of October 2019, and lasted a little more that 3 hours, during which the 800kg TNT equivalent explosion was successfully done at the LKAB Mertainen mine close to the city of Kiruna in Sweden. Our experiment went mostly according to plan and we collected the data we expected.

2 Results

We discuss in this section the results of the analysis of the data collected by the experiment. We first recall the three objectives of the experiment:

1. To characterize the infrasonic background in the stratosphere.
2. To detect the explosion.
3. To locate its origin.

The aim of the analysis of the data will thus be to complete these three objectives.

2.1 General results

The first step towards the analysis of our data collected during the flight was to make preliminary analysis in order to check the consistency of the data. We first inspected the trajectory of the flight, as well as the altitude profile. These are shown respectively in figure 4 and figure 5. Figure 4 shows the trajectory of the balloon as measured by Inertial Measurement Units which is consistent with the trajectory measured by other experiments. Figure 5 shows the altitude versus longitude profile of the flight, showing that the balloon drifted eastward during the whole duration of the flight. The floating phase was reached after about 1.5 hours of ascent at an altitude of 27 km, and the balloon cutoff was done nearly 1.5 hours after reaching the floating phase.

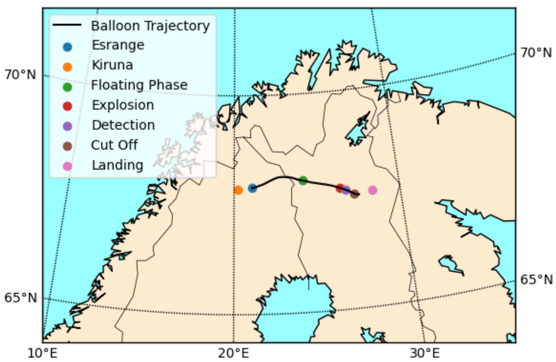

Figure 4: Trajectory of the flight reported on a map, showing that the balloon was launched from Esrange Space Center and flew towards the East indicating strong eastward winds in the atmosphere. The floating phase was reached a little bit after crossing the Swedish/Finnish border, and the landing occurred close to the Finnish/Russian border.

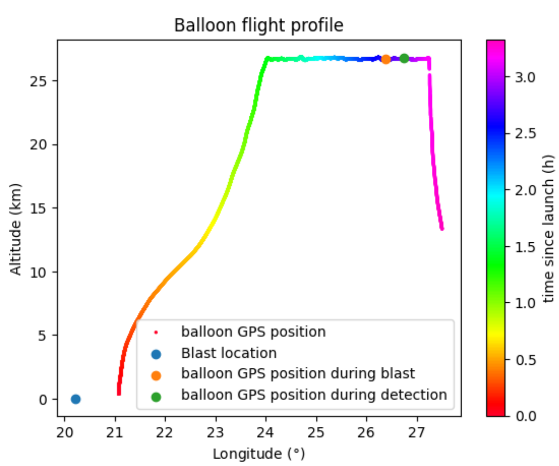

Figure 5: Profile of the flight of the BEXUS 28 balloon measured by the Inertial Measurement Unit of the DESTINY experiment shown in altitude vs longitude, showing that the balloon drifted eastward during the whole duration of the flight. In this figure are shown the position of the balloon at the time of the explosion, and the position at the time of the detection.

Since we also measured the atmospheric temperature and the atmospheric pressure from the ground up to an altitude of 27 km through the captors on board, we also investigated our data to confirm that our data matched the atmospheric theoretical models that already exist.

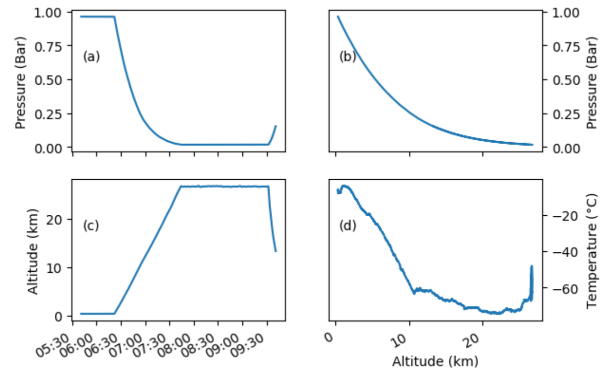

Figure 6: (a) Measured atmospheric pressure vs time. (b) Altitude vs time. (c) Measured atmospheric pressure profile (exponential law). (d) Measured atmospheric temperature profile.

Figure 6 shows in panel (a) the measured atmospheric pressure as a function of time and in panel (c) the measured altitude of the gondola versus time, both showing the four phases of the mission (before launch, ascent, floating phase, descent). These two profiles are collected into a single profile shown in panel (b), which gives an almost exact decreasing exponential behavior of the atmospheric pressure as a function altitude as predicted theoretically using the following theoretical relation

$$P(z) = P_0 \exp\left(-\frac{7gz}{2C_pT_0}\right) \tag{2}$$

where P denotes the atmospheric pressure, z denotes the altitude, T_0 is the ground temperature, g the gravity of Earth, P_0 the ground atmospheric pressure and C_p the ground specific heat of the air. Panel (d) shows in turn the atmospheric temperature profile as a function of altitude, showing that the overall behavior is consistent with the International Standard Atmosphere model for the temperature. Indeed, we can observe from panel (d) that the atmosphere is decomposed into several layers into which the temperature evolves linearly as a function of altitude, with a strong negative gradient in the 0 - 10 km altitude region.

This preliminary analysis allows us to check the consistency of the data gathered during the flight, and allows us to ensure that no major anomaly occurred with the instruments. We now turn into the analysis of the stratospheric infrasound background.

2.2 Stratospheric infrasound background

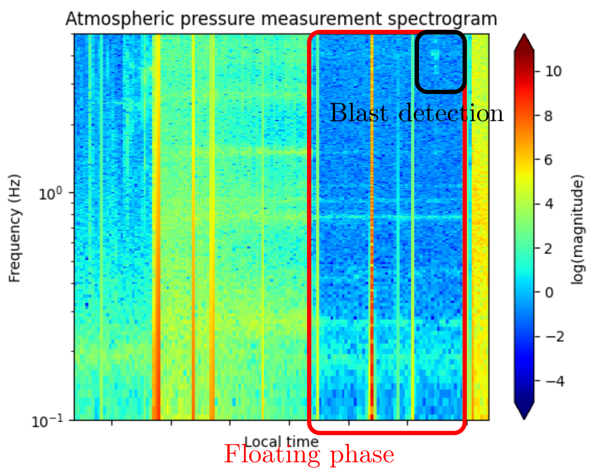

Figure 7: Spectrogram of measured atmospheric pressure vs time (x axis) and frequency (y axis) showing the properties of the infrasonic background in the stratosphere for the Flight Train Box.

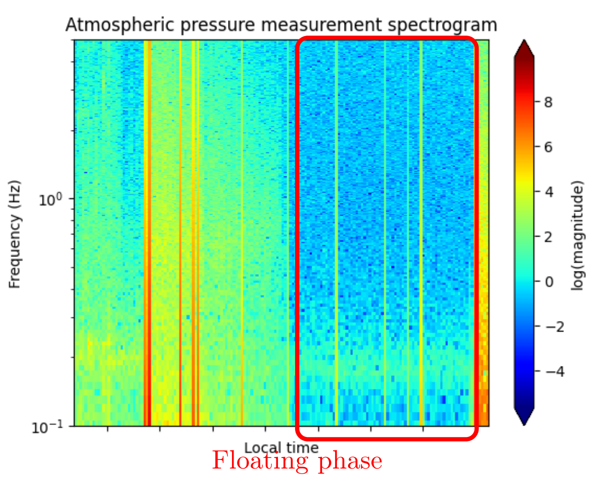

Figure 8: Spectrogram of measured atmospheric pressure vs time (x axis) and frequency (y axis) showing the properties of the infrasonic background in the stratosphere for the Gondola Box.

The solution investigated here to study the stratospheric infrasound background was to convert the time series of the amplitude of the pressure as a function of time into spectrogram showing the spectral distribution of the signal as a function of time. These spectrograms are shown in figure 7 for the Flight Train Box, and in figure 8 for the Gondola Box. The regions of the spectrograms associated to the Floating phase have been indicated in red in each figure. Comparison of these two spectrograms shows that the pressure signal detected by the Flight Train Box presents much contributions from much more frequencies than the signal detected by the Gondola Box. These dominant frequencies are identified in the form of horizontal lines spanning the entire spectrogram.

The fact that most of these frequencies are observed from only the barometer of the flight train box indicates that the barometer of the flight train box was sensitive to sources of pressure waves from which the barometer of the gondola box was shielded. It was thus assumed that these contributions do not come from the infrasound background. This comparative analysis of the two spectrograms allows us to identify one major contribution coming from the stratospheric infrasound background. This contribution was identified in both spectrograms as a consistent excitation at 0.2 Hz with an amplitude close to 0.1 Pa. This contribution have been identified as coming from the microbaroms. Microbaroms are pulses of atmospheric infrasound emitted by ocean surface waves, and evidence of observation of these microbaroms have already been identified in the literature [3] and documented. Hence, our main conclusion is that using the data registered by the DESTINY experiment, we identified the microbaroms as the only contribution to the infrasound background.

2.3 Blast detection

Another main observation that can be done from the spectrogram of the barometer of the flight train box is the existence of a one-time excitation in the signal observed close to the end of the floating phase at 4 Hz. The associated signal collected by a few of the sensors of the DESTINY mission have been shown in figure 9. From this figure, we observe that the barometer (first panel) registers the incidence of at least three infrasound wave at 09:13 and between 09:14 and 09:15.The detonation occurred at 09:00 local time, at the LKAB Mertainen mine which is located 24km South West of the launching area in Esrange. Considering the delay due to the propagation of the signal in the atmosphere, we expected to detect the explosion between 9:12 am and 9:15 am approximately, which is exactly the time at which the arrivals ave been registered by the sensors. This allows to identify these arrivals to the infrasound wave coming from the explosion.

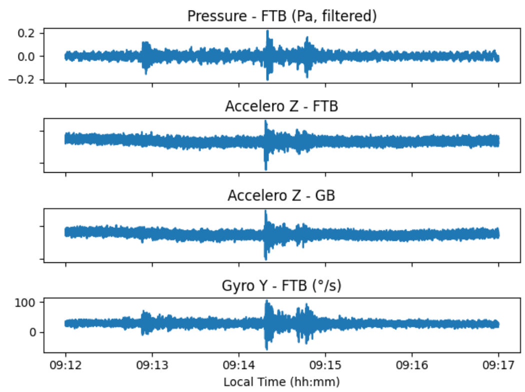

Figure 9: Measurements of the signal associated to the blast from the FTB barometer (no detection from the GB barometer), but also from inertial sensors (accelerometers and Gyroscope).

It has been demonstrated in the literature [4] that for a given event (ground explosion in our case), the stratospheric returns come in pairs consisting of a fast and slow arrival. The pair is created through competition between path length and propagation speed when the impulse is propagating in the stratosphere. Thus, we were expecting to detect two arrivals for our explosion, and the measurements are showing two or three arrivals depending on the instrument. However, one major drawback is that the barometer of the gondola box did not detect these arrivals, as can be seen from the spectrogram shown in figure 8. It was understood later from numerical simulations that the shock wave arrived at the balloon from above, after having been reflected by the upper layers of the atmosphere. Hence, given the incidence of the incoming shock wave, the gondola might have absorbed the wave and prevented the barometer from detecting it, which is not the case for the Flight Train Box.

We thus managed to detect the explosion using the infrasound sensors, and this detection was unexpectedly supported by the measurements coming from the inertial measurements units indicating that the balloon responded mechanically to this wave.

2.4 Localization of the source

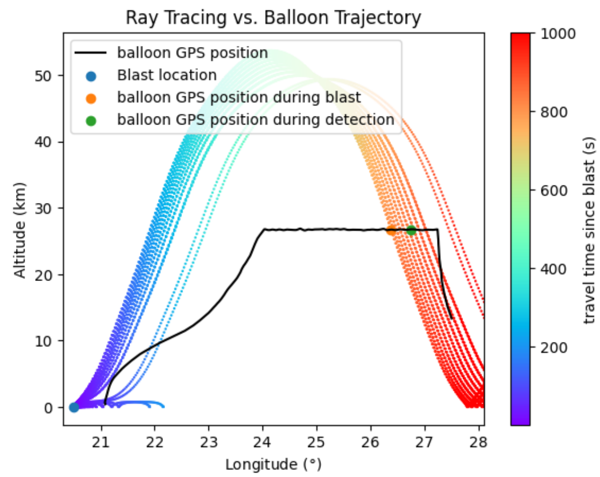

Figure 10: Simulated infrasound propagation from blast location vs Balloon trajectory as an alternate method for identifying the blast's location from the knowledge of the atmospheric profiles.

The first solution that was considered in order to locate the source of the infrasound wave was to compute the incidence angle of the shock wave by comparing the phase shift between the detection of the barometer of the flight train box and the detection of the barometer of the gondola box. This solution have been rendered impossible due to the fact that no detection have been observed in the signal registered by the gondola box.

The solution investigated here is to use our partial knowledge of the direction and the strength of the atmospheric winds in order to numerically simulate a possible trajectory that could have been followed by the detected infrasound wave. This method does not aim at locating precisely the origin of the signal, but may be used to guess more or less precisely the region where the source could have come from. Figure 10 shows that an indicative model for the atmospheric winds may give relevant results. This figure shows that given the atmospheric conditions of the flight, the infrasound waves were more likely to have arrived to the balloon from above after having been reflected by the upper layers of the atmosphere. Fortunately, other methods have been investigated in the literature [5] demonstrating that infrasound sources could be located using balloon-borne infrasound sensors, using several balloons detecting the same event.

Conclusion

The set up as we designed it allowed us to accomplish two of our three objectives. We were indeed able to use it to characterize the stratospheric infrasound background by identifying the microbaroms as the main source of noise. We were also able to detect the occurrence of an infrasound event, which was our blast in this experiment. However, we were confronted to technical difficulties to accomplish the third objective, consisting in locating the source of the detected infrasound event. It was initially planned to rely mainly on linear geometry in order to localize the sources of the infrasound events detected with the two barometers. The fact that the data was missing in the Gondola Box was not the only issue. The propagation of infrasound in the stratosphere is a physical phenomenon which involves nontrivial nonlinear equations. The use of numerical tools [6] proved to be essential to carry this task. Fortunately, other experiments have demonstrated the possibility of achieving our third objective, allowing us to state that DESTINY, together with other experiments, successfully proved the concept to be used for the investigation of the structure of Venus.

Acknowledgements

This project is the result of a huge collaboration between students of different courses, and laboratories of the Ecole Polytechnique and Isae-Supaéro. We would like to thank all the people and organisations which have taken part in this project. We thank David Mimoun, researcher at ISAE-Supaéro, as well as Marti Bassas-Portus for having followed us and helped us during the entire project. We thank Jean-Claude Rubio and his team for having enabled us to test our experiment at the CNES center. We thank Léo Martire, who was a PhD student in applied maths at ISAE-Supaero, as well as Daniel Bowman, for their help in the data analysis of the experience. We thank the mining company LKAB for performing the blast during the flight. We thank the Student Spatial Center of the Ecole Polytechnique, and all the researchers and other members of the university who permitted us to complete successfully our project. We finally thank Maria Snäll, Stefan Krämer, and more generally all the members of the REXUS/BEXUS programme and Esrange, for having permitted us to conduct this wonderful project. The REXUS/BEXUS programme is realised under a bilateral Agency Agreement between the German Aerospace Center (DLR) and the Swedish National Space Agency (SNSA). The Swedish share of the payload has been made available to students from other European countries through the collaboration with the European Space Agency (ESA). Experts from DLR, SSC, ZARM and ESA provide technical support to the student teams throughout the project. EuroLaunch, a cooperation between the Swedish Space Corporation (SSC) and the Mobile Rocket Base (MORABA) of DLR, is responsible for the campaign management and operations of the launch vehicles.

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