Carolina Infrasound Final Flight Report

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1 Introduction

Infrasound is considered to be acoustic waves 20Hz and below (below the audible range of human hearing). The corresponding wavefield provides crucial information on processes occurring at the solid surface and atmospheric interface, as well as within the atmosphere. Infrasound is of particular interest as low frequency waves have a tendency to attenuate less than higher frequency, thus allowing for the conservation of signals over longer range distances. Because of this, infrasound can be used to monitor both natural (earthquakes, volcanoes, etc) and anthropogenic (nuclear blasts, ventilation systems) activities [Bowman and Lees, 2015].

The first known attempts to observe the infrasonic wavefield in the atmosphere were over 50 years ago [Weaver and McAndrew, 1995] [Wescott, 1961b, a, 1964] [Meecham and Wescott, 1965]. Until Carolina Infrasound's HASP 2014 experiment, no other documented attempt was made to record infrasound in the stratosphere. Though data from the 2014 flight lead to the initial conclusion that the wavefield in the stratosphere is much more complex than the wavefield at the surface [Bowman and Lees, 2015], a HASP 2015 experiment was proposed to improve some of the short comings of the 2014 experiment. During 2015, the effects of rapid pressure changes during ascent and descent were reduced, but the microphones still encountered issues with temperature response during the evening. Results from the HASP 2015 indicated that the complex signals seen on both flights were likely not acoustic in nature, but rather due to electronic interference. However, the design of the HASP 2014 and 2015 experiments were not optimized to distinguish between such interference and true pressure waves.

The HASP 2016 experiment was designed to quantify the presence of spurious signals on stratospheric infrasound arrays, identify and mitigate the source of amplitude discrepancies during flight, and acquire additional observations of low frequency sounds. The variability of infrasound in the atmosphere was explored, and the additional 15 hours of atmospheric acoustic data represented the highest quality infrasound recording in the stratosphere in the last half century.

We succeeded in confirming that long period signals between mechanically reversed filtered microphones represent true pressure fluctuations. We also detected the ocean microbarom, a well characterized infrasound signal that propagates thousands of kilometers. In addition, we confirmed these signals were comparable across two independent stations. As in the HASP 2015 data set, the 15 hours of flight this year again allowed us to observe the temporal variability in stratospheric infrasound. From HASP flights, we now have over 50 hours of atmospheric infrasound observation, with two day to night transitions. Furthermore, the HASP 2016 conclusively demonstrated the efficacy of free flying infrasound stations in the stratosphere.

2 Instrumentation and Flight Configuration

2.1 Location of Sensors and Loggers

The flight system consisted of a Winzen 335 000 m^3 zero pressure balloon. The gondola weighed 907kg with ballast (661kg without). The flight ladder was constructed from two 95mm thick steel cables, and each rung of the ladder consisted of 22mm thick round aluminum stock. There were a total of six rungs, each separated by approximately 2.8m.

The Carolina Infrasound payload had two components:

1. sensors and logger on the gondola (payload slot 8)

2. sensors and logger on the flight ladder

Payload slot 8 contained an Omnirecs 3-channel Data Cube digitizing acoustic data at 400 Hz at a gain of 64 and continuous GPS (Figure 1) attached to payload plate. It also had three InfraBSU infrasound microphones attached to second plate. All instrumentation was covered in aluminum foil prior to launch.

Attached to the fifth rung of the flight ladder was a PTQ-11080 Bud Industries 641.40mm by 530.00mm by 255.00mm plastic box. The box contained a 6-channel Trimble RefTek 130S-01 digitizing acoustic data at 100 Hz at a gain of 32, accelerometer data and continuous GPS (Figure 2). It also had three InfraBSU infrasound microphones directly attached to the sides of the box and a ADXL analog accelerometer chip mounted to one of the sides. The station was independently powered by Ultimate Lithium AA batteries.

2.2 Instrumentation

2.2.1 InfraBSU Infrasound Microphones

As in 2014 and 2015, InfraBSU infrasound microphones, designed by Dr. Jeffery Johnson, were flown on both the gondola payload and the flight ladder payload. A diaphragm nestled between two ports registers pressure differences created as acoustic waves travel through the air. The vibration of this diaphragm results in a fluctuation of voltage, which is then transmitted to the logger. Each station contained three of these sensors, two of which were mechanically filtered on one port. These low-pass filters allow for more timely temperature and pressure equilibration response and reject pressure fluctuations above the band of interest. Previous studies further explain the sensors [Marcillo et al, 2012] and physical properties [Mutschlecner and Whitaker, 1997] of the microphone design.

In order to observe acoustic signals, a total of six microphones were launched. Three of these were located on the gondola; the other three were located on the fifth rung of the flight ladder. Like several microphones in 2014, all six were InfraBSU microphones constructed in 2014. The three microphones on the gondola were logged using a Data Cube. The three microphones on the flight ladder were logged to channels 1-3 of the six channel RefTek 130S-01 data logger. All microphones were powered using individual Energizer Ultimate 9V lithium batteries, a power source proven on the 2014 and 2015 flights, and now the 2016 flight.

In 2014, the team learned that the corner frequency created by the mechanical filters caused the sensors to go out of the data logging range during the ascent and descent of the balloon. As a result, the corner frequency was raised for the 2015 flight, allowing for the voltage to remain within the limit of the data logger. Microphones flown in 2016 remained at corner frequencies comparable to those of 2015. The three microphones on each payload component were specifically configured to distinguish between pressure fluctuations and electronic noise based on the placement of the mechanical filter. Two microphones had filters on opposite ports, creating a polarity reversal for pressure signals but not for electronic interference. The third microphone was left unfiltered, or mechanically disabled. Any signal recorded on this microphone was likely not a pressure fluctuation. Real signals were identified when waveforms from the two filtered sensors had opposite polarization and were not present from the unfiltered sensor.

2.2.2 Accelerometer

HASP acceleration data was collected on the flight ladder using a 5V ADXL335 triple-axis accelerometer. The accelerometer was wired to a battery pack powered by two Energizer Ultimate AA lithium batteries wired in series. Using the output pin, the accelerometer was set to regulate power at the 3V provided by the battery pack. The three channels were wired to a RefTek channel cable, allowing the signals to be digitized on channels 4-6 of the 6-channel data logger.

2.2.3 Data Cube Infrasound Loggers

The three InfraBSU microphones on the gondola were digitized using an Omnirecs Data Cube3 logger. The Cubes were originally designed to digitize seismic data, but because acoustic and seismic waves have similar frequency ranges, these lightweight loggers digitize infrasound signals well. This was confirmed by successful logging during the flights in both 2014 and 2015, and now 2016. The acoustic data was recorded on high resolution mode at a gain of 64 and a sampling rate of 400Hz. The internal GPS was configured to collect continuous GPS data, and the power was supplied from payload slot 8 using individual DC-DC converters with an output of 16V. All data were stored locally in the Cube.

2.2.4 RefTek Infrasound Loggers

The three InfraBSU microphones and the accelerometer on the flight ladder were digitized using a Trimble RefTek130S-01 logger. Like the cubes, these loggers were designed to digitize seismic data on the surface. The HASP 2016 was the first attempt to digitize atmospheric infrasound signals with a RefTek. The acoustic data was recorded at a gain of 32 and a sampling rate of 100Hz. Continuous GPS and time data were collected using an internal TCXO and an external GPS Receiver/Clock. The GPS collects time, frequency and position, and is connected to the RefTek by a cable.

Data was written asynchronously to one of two SD cards housed in the Well Enclosure. Data was written to disk at each hour to conserve battery power. The pressure valve located at the top was released in order to allow the plastic encasing to equilibrate to pressure and temperature changes associated with the atmosphere. Logger controls were set and confirmed using the RefTek iFSC App for iPhones and/or iPods through a WiFi Serial Adapter.

2.2.5 RefTek Power Supply

Because the flight ladder payload was completely independent from the gondola, an external power system was designed. 16 Energizer Ultimate lithium batteries were wired in series using two 12V AA cell battery clip holder box cases for a 24V output. A 24V power supply was necessary because the RefTek will shut down once voltage drops below about 9.8V. The 24V ensured the RefTek would remain powered for the duration of the flight. Due to the RefTek being unable to accept more than 12V, a RioRand LM2596 DC-DC Buck Converter was used to step down the 24V to the desired 12V. The output was wired to a RefTek power cable, which connected to the RefTek to provide power.

2.3 Mechanical Specifications

2.3.1 Flight Ladder Payload

The flight ladder payload was contained within a hard shell PTQ-11080 Bud Industries 641.40mm by 530.00mm by 255.00mm plastic box, securely attached to the fifth rung of the flight ladder. This orientation was chosen to maximize array aperture whilst minimizing the chance of striking the flight vehicle upon launch. The attachment system consisted of two 1500lb test aluminum eye bolts secured to the flight ladder payload via nuts and washers affixed to 2in by 6in wooden backing places. Backing plates were located on the inside and outside of both widths of the box. The top eye bolts were attached to steel cables, which then attached to heavy duty hooks on the fifth rung. The bottom eye bolts were attached in the same way to a temporary rung below the box. PVC pipe was placed around the steel cable of the flight ladder in order to prevent the ladder from crushing the box upon launch. Four steel cable loops, two on each side, were used to attach the lengths of the box to the steel cable of the flight ladder. Four adjustable nylon straps were added and reinforced by white tape to better secure the enclose. This configuration can be seen in Figure 3.

Acoustic sensors, the external RefTek GPS, the power supply, and the digitizer were located inside of the hard shell box, mounted to an internal backing plate. This reduced the opportunity for movement during flight. This was imperative because the box rotated 90 degrees as the flight ladder shifted from a horizontal to vertical orientation during launch. A layer of foam insulation lined the sides, top and bottom of the boxes interior. The exterior was enveloped in a layer of white tape. The microphones were exposed to the outside atmosphere through tubes of the same length connected to each microphone port mounted through drilled holes on the sides of the box. Though there were pressure releases from other holes drilled in the box to mount the internal backing plate, two small additional holes were drilled through one face in order to ensure the successful pressure equilibration of the payload. In contrast to previous Carolina Infrasound flights, no cables ran between the gondola and the flight ladder. This configuration can be seen in Figure 2.

2.3.2 Gondola Payload

The gondola payload was attached to a small payload plate. It was bolted to the plate using nuts, washers and four threaded metal dowels. Two horizontal plates acted as attachment points for the digitizer and the infrasound microphones. A non-rigid outer envelope consisting of an inner layer of aluminum foil and an outer layer of white tape provided thermal control. This envelope also acted as a shield to reduce the effect of electronic interference from other payloads on the gondola.

3 Engineering and Scientific Results

The HASP 2016 flight recorded 15 hours of acoustic data, floating at an average altitude of about 37km. This allowed for the observation of another day to night transition. This is particularly important because the microbarom is typically obscured during the day on the ground due to surface winds and in the atmosphere due to atmospheric tides. However, stations on the HASP 2016 detected the microbarom through part of the flight, most likely as a result of low wind noise and a favorable atmospheric acoustic duct. It is important to note the HASP 2016 launched unusually late in the morning due to abnormally calm surface winds.

The acoustic network on HASP 2016 performed better than those of previous HASP flights. The voltage output from the infrasound sensors remained within the data loggers' limits. Unlike previous years, microphones attached to the Data Cube and the RefTek appear to have had similar amplitude responses between them during the flight (Figure 4); acoustic amplitudes across all four active microphones were consistent. The absence of amplitude discrepancies during the 2016 flight suggests there was either no electronic interference this year, or the mismatch from previous years was not due to electronic interference from other HASP payloads or interactions with the flight ladder.

In addition to amplitude agreement, signals across the array seemed to correlate. The separation of the payloads was specifically designed to confirm signals observed on the gondola are comparable to signals observed on the flight ladder. The similarity of the waveforms between stations (Figure 5) indicates that even though the stations were separated by 14m, they recorded similar signals. To ensure real acoustic signals were being recorded, two microphones on each payload were filtered mechanically opposite of each other in order to reverse the polarity of one of the sensors. The agreement between sensors both across the network and within a payload matched with consistent amplitude responses increases the confidence that real acoustic signals are being recorded. This confidence is furthered by a known signal, the ocean microbarom, being clearly visible (Figure 4).

As expected, acceleration data correlated to the recorded responses of the disabled microphone on the flight ladder payload. Because filters enable the sensors to differentiate between pressure, temperature and ambient movement, the correlation between an unfiltered microphone and the accelerometer was expected. This correlation will help differentiate signal from hardware responses. Another improvement from previous years is GPS and timing. In 2015, three types of data loggers were flown. Of these loggers, only the Data Cube recorded continuous location and timing data, and thus only data logged by the Data Cube was able to be analyzed. This year, GPS and timing was successfully maintained by both the Data Cube and the RefTek. Concerns about RefTek temperature and pressure responses were raised close to thermal-vacuum testing, but testing in the lab suggested data could still be logged at extreme temperatures. This was confirmed during thermal-vacuum testing and during the flight.

Overall, the gondola payload performed well. Though configured differently, the instrumentation of this payload was similar to the previous two years. With three years of successful data collection, we are confident in the InfraBSU infrasound microphone and Data Cube logger coupling.

In contrast, the coupling of the InfraBSU infrasound microphones and the RefTek was problematic. While the cube can be set to a gain of 64, the highest to which the RefTek can be set is 32. This is thought to result in higher electronic noise in signal recorded by the RefTek. This ultimately obscures the lowest amplitude acoustic signals for which we are looking. If a similar experiment is attempted, data loggers should be consistent across the network. Though the RefTek is considered to be a better seismic logger on the surface, there was no observable advantage to logging with it during flight.

Data collected on the flight ladder resulted in invaluable confirmation of acoustic signals in the atmosphere. However, the flight ladder payload experienced severe damages upon impact with the ground after termination. A corner of the box was also ripped away, leading to the loss of one microphone and the accelerometer. In addition, the casing of the RefTek was shattered, requiring that it be sent to Trimble for repair. The casing was replaced, but the RefTek has not performed properly since. Cables connecting instrumentation to the RefTek were stripped, most likely due to forces experienced at impact.

4 Figures

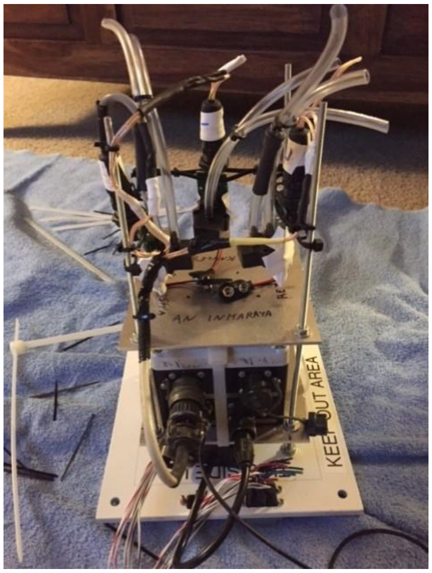

Figure 1. The internal workings of the gondola payload. Three InfraBSU infrasound microphones are attached to the top plate. The Omnirecs Data Cube3 logger sits directly below, on the payload plate. The outer shell has not yet been added.

Figure 2. The internal workings of the flight ladder payload. Three InfraBSU infrasound microphones are enclosed in cases with a white PVC body and a securely fit black top. The ADXL accelerometer is mounted to the side of the box. The Trimble RefTek130S-01 logger sits in the middle, with its GPS in the bottom left corner. The power system sites to the left of the RefTek.

Figure 3. The flight ladder payload attachment system. Two steel cables secure the payload to the fifth rung (left) and two steel cables secure the payload to a temporary rung (right). PVC reinforces the steel cables of the flight ladder where four steel cable loops attach the sides of the box.

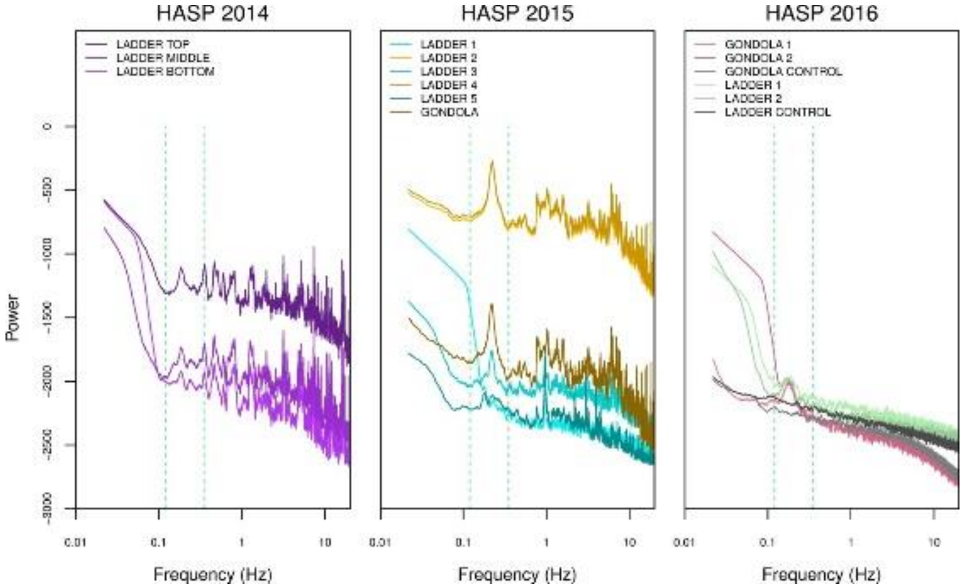

Figure 4. Power spectrum of signals recorded during a portion of float on the HASP flights during 2014 (left), 2015 (middle) and 2016 (right). Amplitude discrepancies can be seen in the 2014 and 2015 data sets, while amplitudes in the 2016 data set are consistent. Dashed vertical lines represent the frequency limits of the microbarom peak [Campus and Christie, 2010]. All spectra were calculated using one hour of float and the same smoothing parameters.

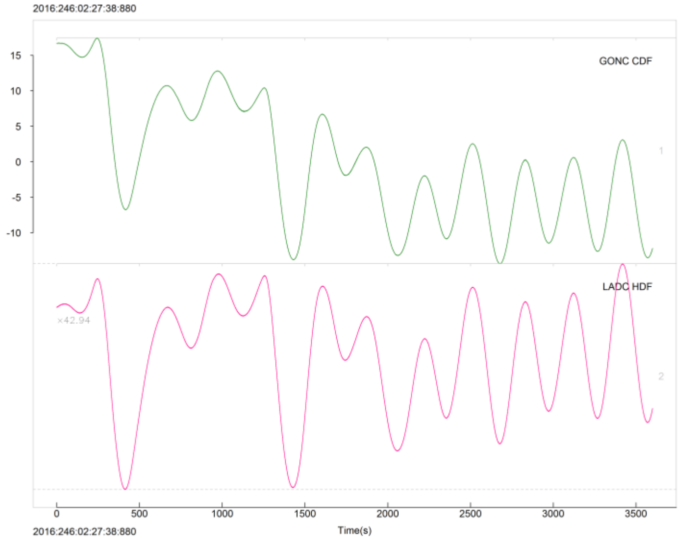

Figure 5. Raw signal agreement between waveforms recorded on the gondola (top) and the flight ladder (bottom) during a portion of float on the HASP 2016 flight

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5 Publications and Presentations

Bowman, D.C. and Lees, J.M. (2015). Infrasound in the middle stratosphere measured with a free flying acoustic array. *Geophysical Research Letters* DOI: 10.1002/2015GL066570

Bowman, D.C. and Lees, J.M. (2015). Infrasound in the stratosphere measured with a free flying acoustic array. *Seismological Society of America Annual Meeting*

Bowman, D.C., Johnson, C.S., Gupta, R. A., Anderson, J.F., Lees, J.M., Drob, D.P., and Phillips, D. (2015). High altitude infrasound measurements using balloon-borne arrays. *American Geophysical Union Fall Meeting*, Abstract S54B-06.

Bowman, D.C. (2016) Infrasound from Ground to Space. Ph. D. Dissertation, The University of North Carolina at Chapel Hill, Chapel Hill, North Carolina

Bowman, D. C. and Lees, J. M. (2016) Capturing acoustic energy input into the upper atmosphere using free flying sensor arrays. *2016 Joint CEDAR/GEM Workshop*, Santa Fe, New Mexico, USA.

Bowman, D. C. and Arrowsmith, S. J. (2016) Infrasound event detection via free flying stations in the stratosphere. *Infrasound Technology Worshop*, Quito, Ecuador

Bowman, D.C. and Lees, J.M. (2016). Direct measurement of the acoustic wave field in the stratosphere. In *Proceedings of the 2016 IEEE Aerospace Conference.*

Bowman, D.C., and Lees, J.M. (2016), Direct Measurement of the Acoustic Wave Field in the Stratosphere.

Cutts, J. A., Jackson, J. M., Mimoun, D. and Bowman, D. C. (2016) Venus exploration with infrasound techniques. 3rd *International Workshop on Instrumentation for Planetary Missions*, Pasadena, California, USA.

Seiffert, K.T, Bowman, D.C., and Lees, J.M. (2016) S11C-2476: Separating Noise from the Infrasonic Wave Field in the Lower Atmosphere Using Free Flying Arrays. *American Geophysical Union Fall Meeting*, Abstract S11C-2476.

6 Team Demographics

Name	Gender	Ethnicity	Race	Role	Student Status	Affiliation	Disability
Anderson, Jacob F.	M	Non-Hispanic	Caucasian	Student Member	Graduate	Boise State University	None
Bishop, Jordan W.	M	Non-Hispanic	Caucasian	Student Member	Undergrad	UNC-Chapel Hill	None
Bowman, Daniel C.	M	Non-Hispanic	Caucasian	Outside Advisor	Graduate	UNC/Sandia Labs	None
Dinwiddie*, Ethan C.	M	Non-Hispanic	Caucasian	Student Member	Undergrad	UNC-Chapel Hill	None
Lees, Jonathan M.	M	Non-Hispanic	Caucasian	Faculty Advisor	Professor	UNC-Chapel Hill	None
Rodd, Rebecca L.	F	Non-Hispanic	Caucasian	Team Member	Graduate	UNC-Chapel Hill	None
Ronan*, Timothy J.	M	Non-Hispanic	Caucasian	Student Member	Graduate	UNC-Chapel Hill	None
Seiffert*, Kayla T.	F	Non-Hispanic	Caucasian	Student Leader	Undergrad	UNC-Chapel Hill	None

*Graduating in 2017

Graduates:

Jordan W. Bishop graduated from the University of North Carolina at Chapel Hill in August 2016 with a Bachelor's of Science in Geological Sciences (Geophysics). He currently works as a Lab Assistant for the University of North Carolina at Chapel Hill Geological Sciences Department, and is in the process of applying to graduate schools. He was involved in the HASP flight of 2016.

Daniel C. Bowman graduated from the University of North Carolina at Chapel Hill in May 2016 with a Doctorate in Geophysics. He now works as a Geosciences Engineer at Sandia National Laboratories in Albuquerque, New Mexico where he continues his work with atmospheric acoustics. He was involved in the HASP flights of 2014, 2015 and 2016.

Rebecca L. Rodd graduated from the University of North Carolina at Chapel Hill in May 2016 with a Masters in Geophysics. She now works as a Seismic Analyst at the Scripps Institution of Oceanography at University of California at San Diego. She was involved in the HASP flight of 2016.

C. Scott Johnson graduated from North Carolina State University in May 2016 with a Masters in Electrical and Computer Engineering. He is now working at IBM. He was involved in the HASP flight of 2015.

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