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**Key Points:**
- Balloon-borne infrasound sensors in the stratosphere detected the ocean microbarom
- The microbarom was present in the stratosphere but not on nearby ground stations
- Ground-based microbarom studies underestimate the occurrence of the phenomenon

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# A Comparison of the Ocean Microbarom Recorded on the Ground and in the Stratosphere

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**Abstract** The, ocean microbarom is an acoustic signal generated via nonlinear interaction of ocean surface waves. It can propagate for thousands of kilometers and represent a significant infrasonic noise source for ground infrasound stations across the globe. However, wind noise often compromises detections at ground stations. Furthermore, the microbarom may travel in elevated acoustic ducts that do not transmit enough energy for detections on ground stations. Here the presence of the ocean microbarom on two high-altitude balloon flights is investigated. A spectral peak consistent with the microbarom was observed on sensors in the stratosphere but not on those deployed on the ground near the flight path of the balloon. This is probably due to an elevated acoustic duct and/or a superior signal-to-noise ratio in the stratosphere. Thus, microbarom activity quantified solely with ground-based sensors may underestimate the occurrence of the phenomenon. However, high levels of interference from flight system electronics and/other other payloads may have obscured other microbarom episodes during the balloon deployments.

**Plain Language Summary** Low-frequency sound from colliding ocean waves, called the ocean microbarom, can travel for thousands of kilometers and is detected throughout the world. However, interference from wind often swamps the signal on ground microphones. We show that microphones on high-altitude balloons are effective means of capturing this signal, and that these particular sound waves are easier to detect using airborne sensors. It is possible that ground-based studies fail to capture the full extent of ocean microbarom activity.

## 1. Introduction

The temperature and wind structure of the lower layers of Earth's atmosphere often combine to form a directional acoustic wave guide known as the "stratospheric duct." This structure permits acoustic signals to be detected by ground stations much farther away compared to a ductless atmosphere. However, ground stations also suffer from persistent wind noise and contamination from other signals such as ground vibrations. The stratospheric duct does not always reach the Earth's surface, limiting its utility in some atmospheric conditions.

An alternate strategy is to place the acoustic sensors in the stratosphere, where they may benefit from the previously mentioned wave guide (when present) as well as increased range for direct wave arrivals compared with ground stations. While this was recognized as early as the late 1940s (Weaver & McAndrew, 1995), attempts to directly measure acoustic waves in this region have been rare. Wescott (1964) found acoustic signals consistent with atmospheric turbulence and aircraft. Other unknown signals were briefly discussed, and spectral lines persisting for 0.5–1 h are present below about 25 Hz on spectrograms.

More recently, acoustic sensors on two balloon flights in the middle stratosphere (35–37 km above sea level) detected a variety of signals, most of which were of unknown origin (Bowman & Lees, 2015, 2016). However, spectral peaks consistent with the ocean microbarom were tentatively identified. The ocean microbarom (hereafter referred to as "microbarom") is a signal recorded on infrasound stations throughout the world (Bowman et al., 2005). It is the acoustic equivalent of the ocean microseism. An extensive discussion of the origin of microseismic noise can be found in Kedar et al. (2008), which follows the theory of Longuet-Higgins (1950). It suggests a common ocean surface wave source mechanism that generates acoustic waves in the atmosphere and seismic waves in the Earth. Microbarom signals are commonly generated in the north Atlantic, south of Greenland, and in the central Pacific ocean. These infrasound waves can travel for thousands of kilometers. They occupy a frequency band from 0.13 to 0.35 Hz and have

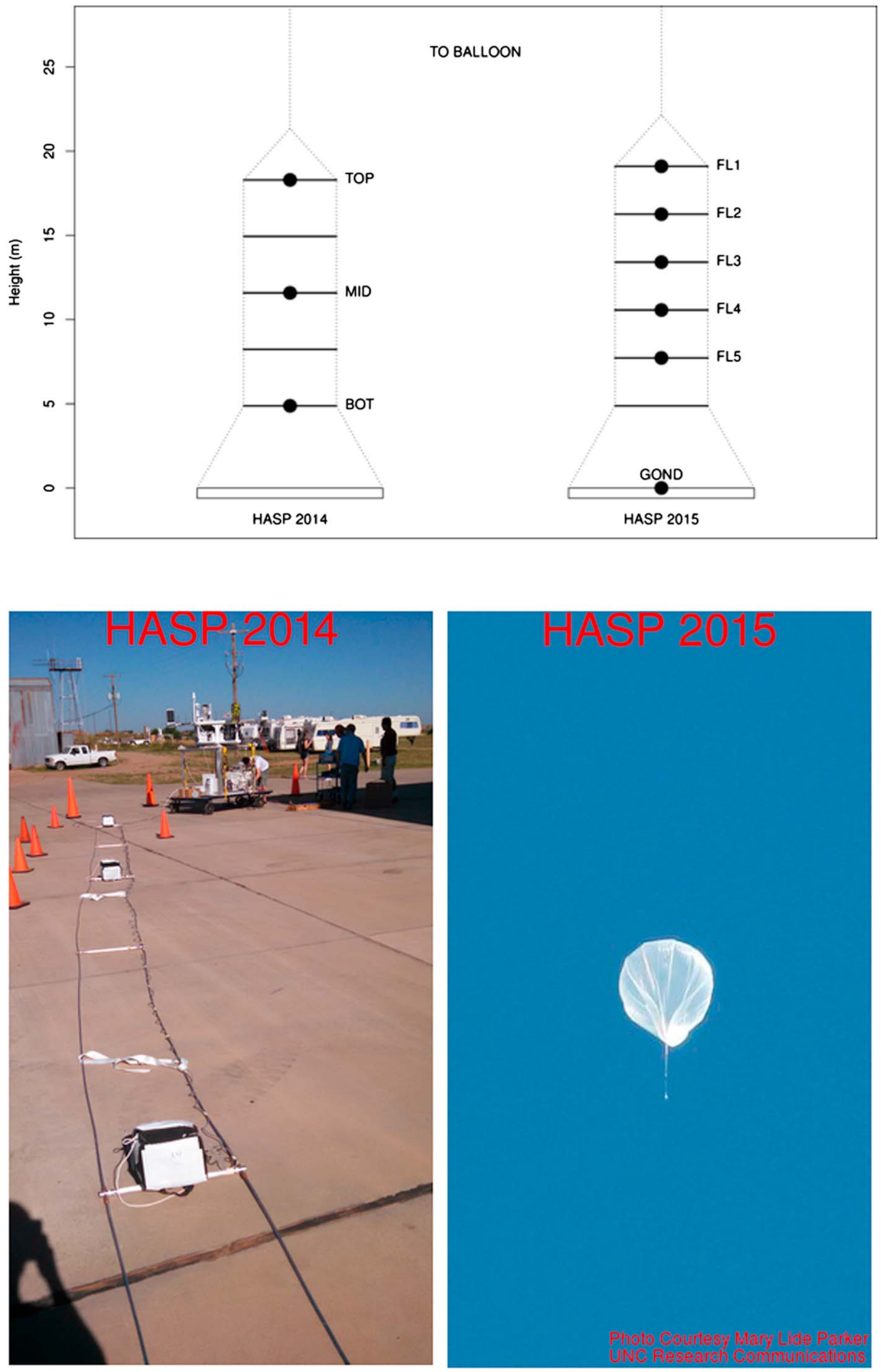


**Figure 1.** Infrasound microphone layout on the (top) HASP 2014 and 2015, (bottom left) the HASP 2014 flight ladder microphone array during a ground test, and (bottom right) the HASP 2015 balloon at neutral buoyancy in the stratosphere. Note that station GOND on the HASP 2015 was located on the instrumented gondola below the flight ladder.

characteristic amplitude modulations in the time domain (Campus & Christie, 2010). While the microbarom interferes with the ability to detect other signals in this band, it can be useful for determining whether an infrasound array is operating correctly. This is because the presence of a microbarom spectral peak indicates that the array is not overly affected by wind or instrumentation noise. The converse is not true; however, detections of the microbarom strongly depend on atmospheric conditions along the propagation path

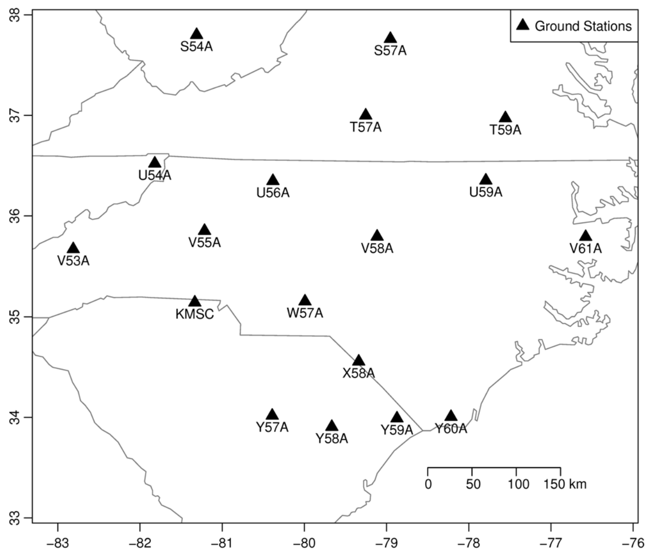


**Figure 2.** Ground stations used in determining microbarom activity on the East Coast during the HASP flights.

(Landès et al., 2012). Also, the peak is most evident during the night hours as there is a well-documented, strong diurnal wind noise variation (Brachet et al., 2010).

Here, the reported microbarom peak on the two balloon flights described in Bowman and Lees (2015, 2016) are investigated. The signals are compared with records from ground acoustic stations both near the balloons' flight path as well as on the American East Coast and Southwest. A microbarom episode detected by the 2015 balloon infrasound detectors during a ground test is discussed as well. Ground stations did not record the microbarom during the 2014 flight, indicating spectral peaks recorded sporadically in the stratosphere are either due to chance or a very weak signal. In contrast, microbarom activity was detected on the East Coast and the Southwest during the 2015 flight. Acoustic stations on the balloon recorded a peak in the microbarom range during this time period as well, although the signal appears contaminated with a local noise source. The lack of detection on nearby temporary ground stations in 2015 suggests that the balloon may have been located in an elevated acoustic duct. Alternatively, the lack of wind noise on the free flying sensors may have contributed to the successful detection. These lower noise levels are due to a combination of the sensor moving at the mean wind speed, diminished turbulence in the stratosphere, and a fluid density drop of 2 orders of magnitude with respect to the Earth's surface.

## 2. Methods

The stratospheric acoustic array was launched to 32–37 km above sea level on a zero pressure balloon as part of the High Altitude Student Platform (HASP) (Guzik et al., 2008). The launch location was Ft. Sumner, New Mexico, with landing points in northeast Arizona (2014) and central New Mexico (2015). Sensors were arranged on the "flight ladder" that attaches the instrumented gondola to the balloon envelope, creating a vertically oriented linear array (see Figure 1). The array consisted of InfraBSU infrasound microphones (Marcillo et al., 2012) digitized using Omnirecs Datacube recorders at a sample rate of 400 Hz. Three sensors were used in 2014, and six in 2015.

Infrasound time series from ground stations was acquired from open data available on the Incorporated Research Institutions for Seismology Data Management Center. Eighteen stations on the East Coast (Figure 2) and 12 in the Southwest (Figure 3) were used to constrain regional microbarom detections. Three stations within 0.5° of the flight path of the HASP 2014 balloon (ANMO, W18A, and Y22D) were investigated to determine the local microbarom wave field in that year. In 2015, two three-element infrasound sensor arrays were deployed within 10 km of the balloon launch site. Data from the less noisy of the two (a temporary three-element infrasound array named CATL) are used here.

Spectra in the microbarom range were calculated by applying the multitaper method as described in Lees and Park (1995) and then smoothed with a Gaussian filter. Variations in the microbarom on a subhourly time

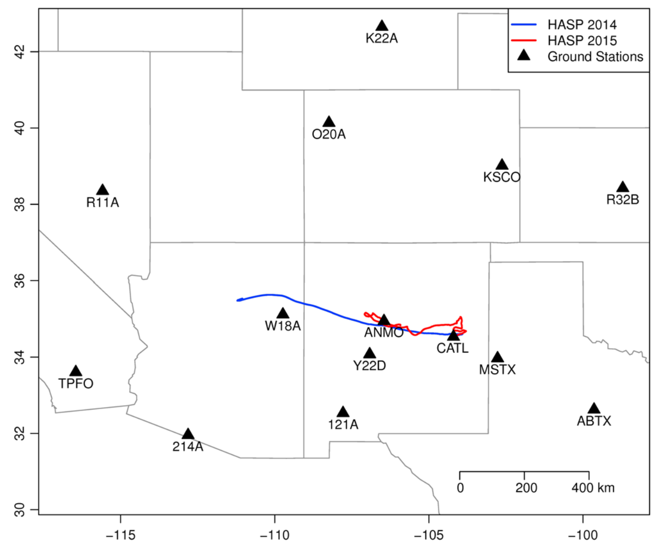


**Figure 3.** Trajectory of the HASP balloons and ground stations used in determining the microbarom signal levels in the American Southwest during the flights.

scale was analyzed using acoustic data from the HASP 2014 flight, the HASP 2015 flight, and a ground test of the HASP 2015 array in North Carolina. Spectra of overlapping 10 min segments of data were taken using the multitaper method without smoothing. Each spectral curve between 0.05 and 1.5 Hz was modeled using a weighted quadratic curve in log-log space; removing this trend thus flattens the spectrum (see Figure 4). Finding a peak in the microbarom range is accomplished by testing if the mean of the flattened spectrum in the 0.13 to 0.35 Hz range is significantly greater than the mean of the flattened spectrum in the 0.05 to 1.5 Hz range. This is determined by applying the Wilcox Test at a 95% confidence level. A measure of the relative magnitude of the peak is accomplished by integrating over the microbarom range in the detrended spectrum.

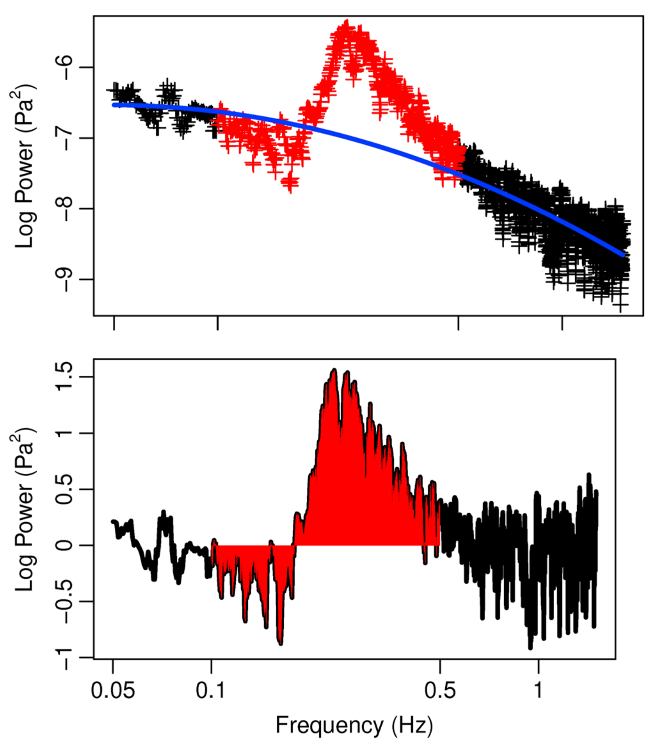


**Figure 4.** Determining the existence and relative strength of the microbarom peak via fitting the spectrum of a 10 min segment of data with a quadratic model (top) and detrending it (bottom).

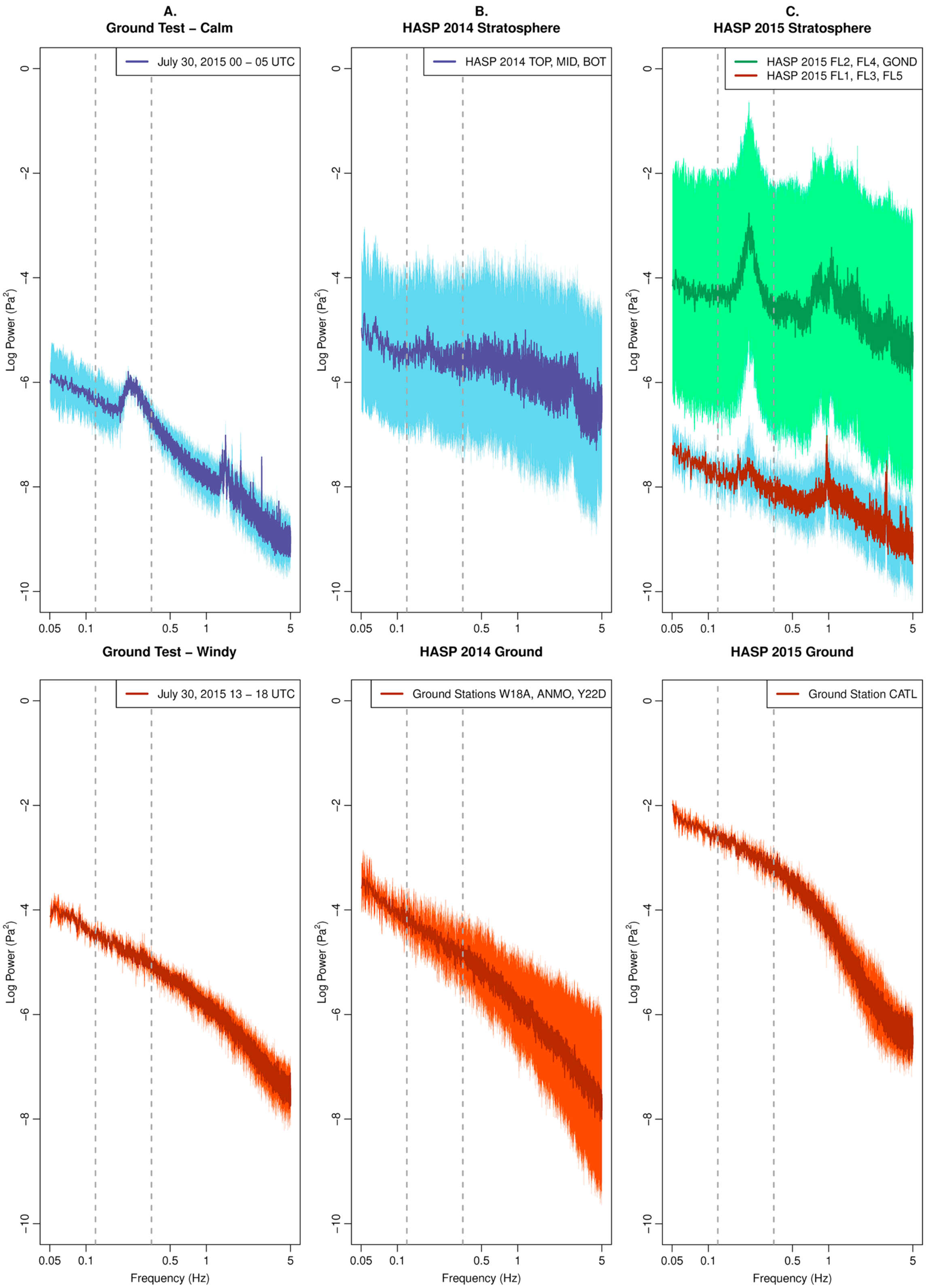


**Figure 5.** Spectra recorded on three of six microphones during a ground test of the (a) HASP 2015 array, all three microphones on the (b) HASP 2014 flight compared with nearby ground based sensors, and (c) three lower noise microphones on the HASP 2015 flight compared with a three-element temporary microphone array deployed near the launch site. Center lines represent the average of the three sensors; shaded regions are their standard deviation. Dashed gray lines indicate the frequency range of the microbarom per Campus and Christie (2010).

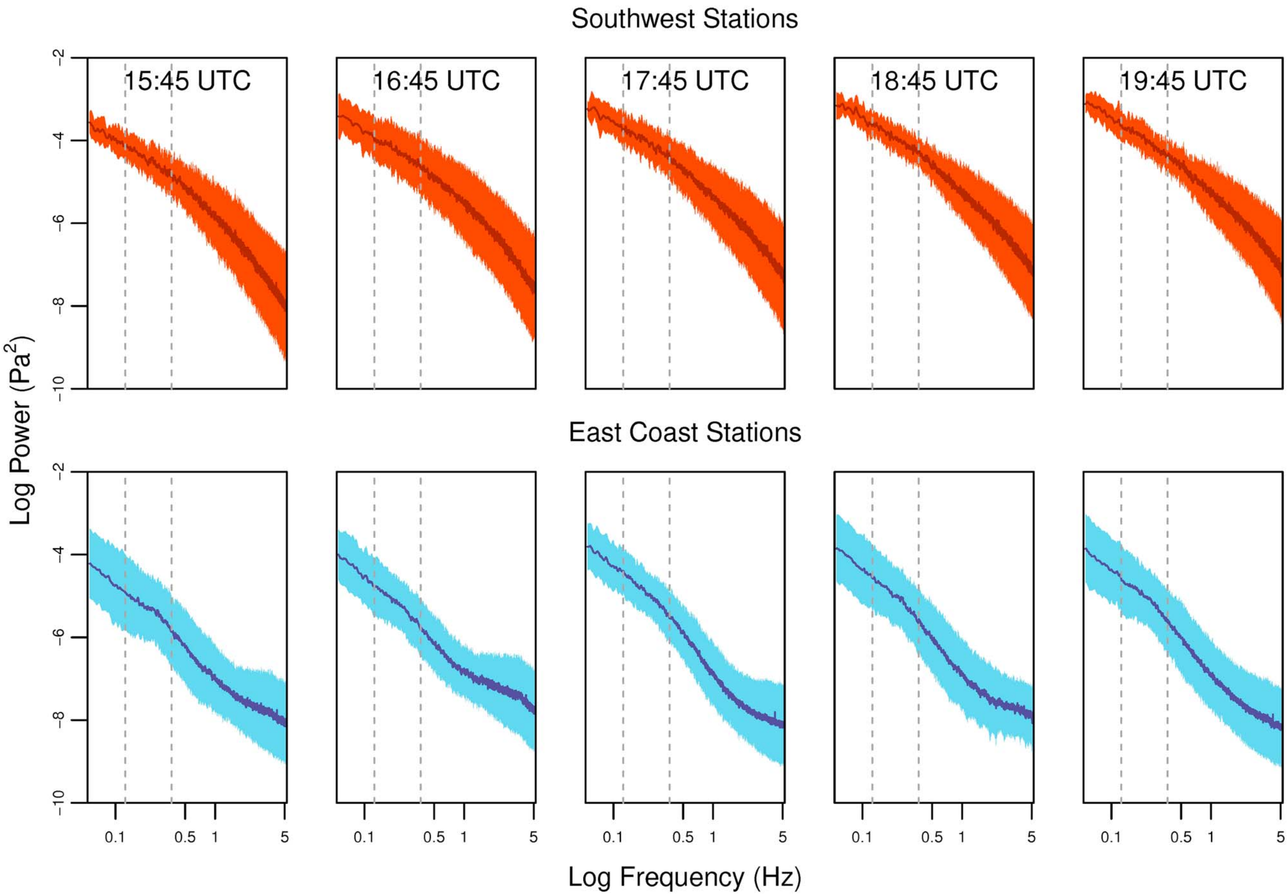


**Figure 6.** Spectra from ground stations in the American Southwest (top row) and the East Coast (bottom row) during the first 5 h of the HASP 2014 flight. Center lines represent the average of all the sensors; shaded regions are their standard deviation. Dashed gray lines indicate the frequency range of the microbarom per Campus and Christie (2010).

## 3. Results

A microbarom episode occurred during an overnight ground test of the HASP 2015 infrasound array in Chapel Hill, North Carolina. Power spectra of a 5 h section of data during local night (01:00 to 05:00 UTC, 20:00 to 01:00 local time) reveal a prominent peak in the microbarom range (see Figure 5a, top). A 5 h section of data from the same deployment 13 h later reveals no peak (Figure 5a, bottom). A colocated hot wire anemometer detected low wind levels during local night, with an increase after dawn. Spectral signatures consistent with wind noise also appear on the microphones during the day.

Infrasound stations on the East Coast do not indicate that the microbarom was propagating from the Atlantic Ocean during the HASP 2014 flight. A peak in the microbarom range is not evident on ground stations in the Southwest either (see Figure 6).

A small increase in spectral power in the lower portion of the microbarom range is observed during a 5 h section of the lowest signal amplitude during the HASP 2014 flight, but this increase is not evident on ground sensors within 0.5° (Figure 5b).

A prominent spectral peak in the microbarom range is present during the 5 h of lowest signal amplitude on the HASP 2015 flight, but the increase is not consistent between two groups of microphones on that flight (Figure 5c). The higher-amplitude microphone set exhibited polarity reversals indicative of electronic interference, which may account for the elevated power of these three. Ground arrays at the launch site did not observe a peak in the microbarom range during this time. However, ground infrasound stations on the East Coast recorded a peak in the microbarom range, which grew more distinct with each hour (see Figure 7). Stations in the Southwest acquired the peak about 3 h into the 5 h period, but it was less distinct.

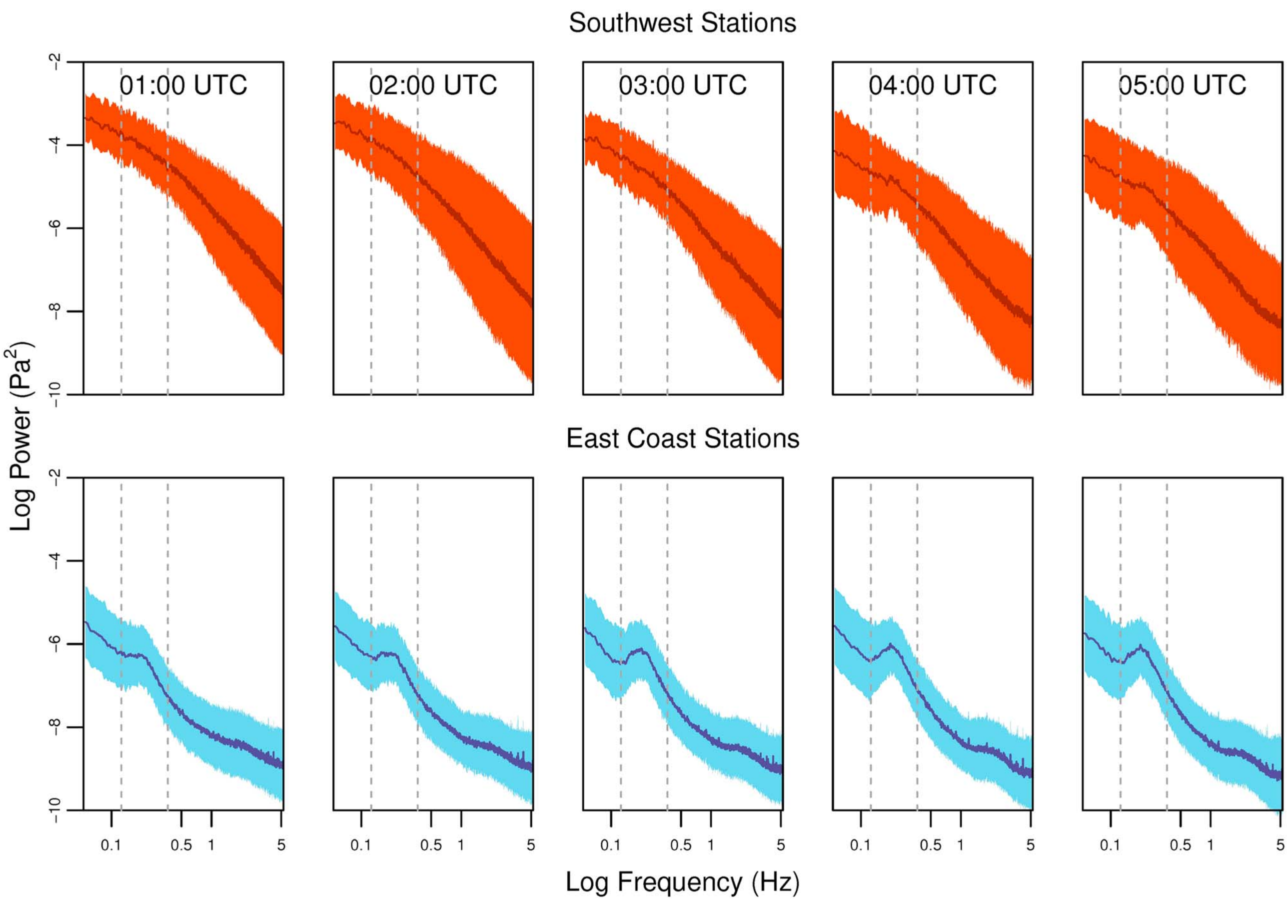


**Figure 7.** Spectra from ground stations in the (top row) American Southwest and the (bottom row) East Coast during the first 5 h of the HASP 2015 flight. Center lines represent the average of all the sensors; shaded regions are their standard deviation. Dashed gray lines indicate the frequency range of the microbarom per Campus and Christie (2010).

Further insight into the nature of spectral peaks in the microbarom range is obtained by examining the standard deviation of the HASP infrasound spectra. Low standard deviations indicate a signal being recorded across all microphones equally. Conversely, a signal localized to one or two microphones will cause an increase in standard deviation. Figure 8 shows that standard deviation indeed drops across the 0.13–0.35 Hz range during strong microbarom activity. A similar drop is not apparent on the HASP 2014 flight. However, a set of three microphones on the HASP 2015 showed an increase in standard deviation in the microbarom range. This indicates that some of these microphones were detecting a signal in this frequency band, and some were not. A set of "noisy" microphones on the HASP 2015 did not show the same pattern; in fact, standard deviation dropped slightly in the microbarom band. Thus, the noise was well correlated between these microphones.

Figures 9a–9d show the power in the microbarom range relative to the rest of the spectrum (top row) and the root-mean-square amplitude of the microbarom band (bottom row). The ground test (Figure 9a) shows a strong microbarom peak (large relative power) during the night, when wind noise was low. After dawn, the microbarom peak becomes statistically indistinguishable from the spectrum around it. The root-mean-square amplitude in the microbarom band is low and steady during the night portion of the ground test, increasing dramatically after sunrise (Figure 9a, bottom).

There were a few episodes in which a statistically significant peak was present in the microbarom range during the HASP 2014 flight. Each episode lasted less than half an hour. The HASP 2014 has large amplitude variations throughout the flight, and there were periods when amplitudes were very different between individual elements of the infrasound array. Interelement variation is captured in the standard deviation shown in Figures 9a–9d, (bottom row). Standard deviation is relatively low during ascent (15:00 to 15:30 UTC), indicating that all three microphones experienced similar amounts of wind noise. From 15:30 to 16:30 UTC,

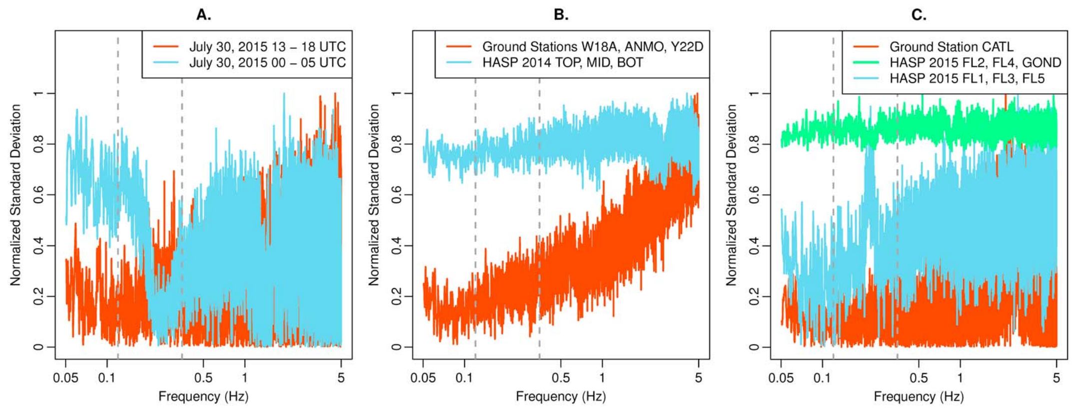


**Figure 8.** Normalized standard deviation of spectra recorded on a series of three microphone sets: a ground test of (a) the HASP 2015 array, (b) the HASP 2014 flight compared with nearby ground based sensors, and (c) the HASP 2015 flight compared with nearby ground based sensors. Dashed gray lines indicate the frequency range of the microbarom per Campus and Christie (2010).

amplitudes were low and standard deviations were low; several short periods of significant peaks in the microbarom peak were present as well. After 16:30 UTC, standard deviation of the RMS amplitude increases greatly for about an hour and remains at an elevated state for the remainder of the flight. A significant peak in the microbarom band occurs for 10 to 20 min after 17:00 UTC and sporadically thereafter.

Three of the six microphones on the HASP 2015 flight recorded RMS amplitudes comparable to that detected on the ground during preflight tests. The remaining three microphones on the flight had much higher amplitudes and polarity reversals consistent with nonacoustic interference. There were two periods of relatively low standard deviation for RMS on the three higher quality channels. The first occurred from approximately 14:00 to 20:00 UTC. There were several episodes of significant peaks in the microbarom range during this time.

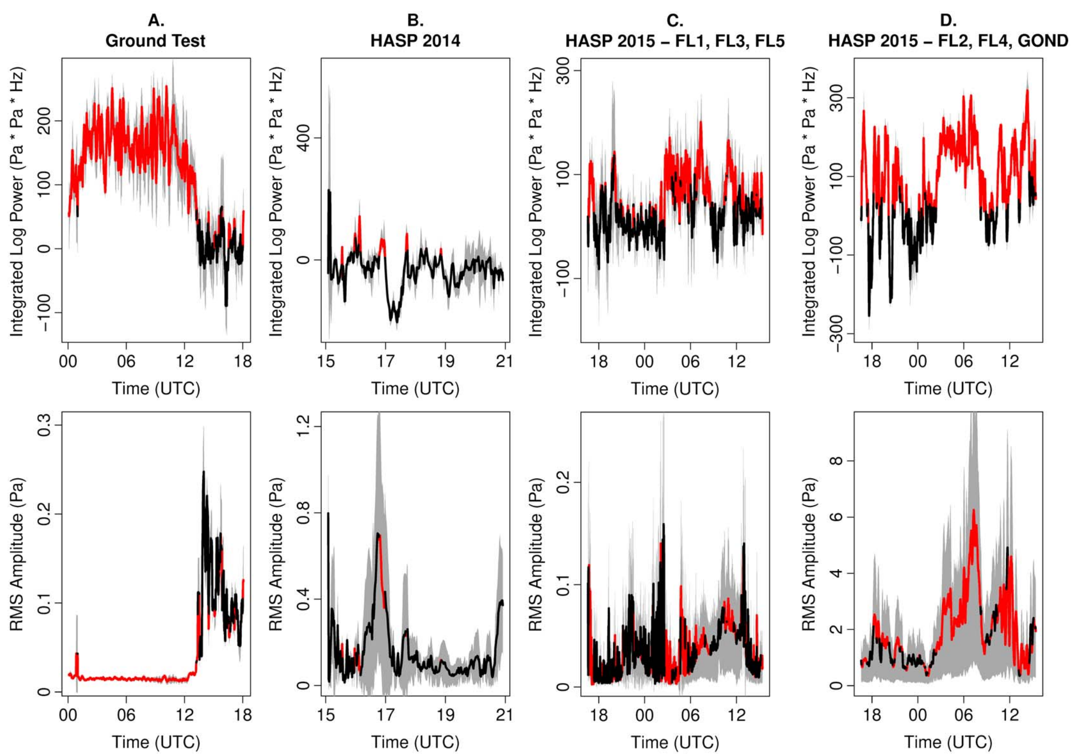


**Figure 9.** (a–d) Integrated log power across the microbarom range (top row) and root-mean-square amplitude in the microbarom range (bottom row). Red indicates a statistically significant spectral peak in the microbarom range. Gray is standard deviation. Note the differences in *y* axis scale between panels.

The second period of low standard deviation between the three higher-quality channels occurred from approximately 03:00 to 05:00 UTC on the following day, during local night. A significant peak in the microbarom range is detected through most of this time period. The three noisy channels have elevated standard deviation throughout the flight compared to the three quieter channels, and RMS amplitude is higher by an order of magnitude.

## 4. Discussion

The microbarom is a relatively faint acoustic signal that arrives from the far field. Thus, an infrasound array that detects the microbarom will show the following: (1) low amplitude, (2) elevated power in the microbarom range, and (3) decreased standard deviation in the microbarom range

The ground test of the HASP 2015 array exemplifies these characteristics. When ground winds are low, the microbarom peak is distinct (Figure 5), and the standard deviation of spectra decreases in the frequency range of interest (Figure 8). Integrated log power is high, and RMS amplitude is low (Figure 9). The peak becomes statistically indistinguishable after dawn, and there is no change in standard deviation across the microbarom range. Integrated log power is low, and RMS amplitude is high. The lack of a microbarom peak during the day is consistent both with previous literature (e.g., Bowman et al., 2005) and the observed increase in wind speed. Since the digitizers and microphones are the same for this test and both HASP flights, the ground detection confirms that the data acquisition system is capable of recording the microbarom.

The HASP 2014 flight had brief episodes of statistically significant spectral peaks in the microbarom frequency range. However, Figure 9 shows high standard deviations between microphones for all peaks after about 17:00 UTC, casting doubt on their reliability. Thus, the only candidates for a true microbarom detection are several short (tens of minutes) episodes between 15:30 and 16:30 UTC 15:00 and 17:00 UTC. No microbarom activity was detected on the East Coast or the Southwest during this time (see Figure 6). This means either the microbarom was traveling in an elevated duct across the continental USA or the peaks were caused by a different phenomenon. Given that the episodes occurred during daylight hours when the microbarom is seldom observed, it is more likely that the detections represent a different phenomenon entirely. Even under the null hypothesis, 1 out of every 20 points in Figure 9 will have a positive detection due to random chance. Since the analysis uses overlapping windows this may create the illusion of a brief, persistent signal.

The HASP 2015 flight lasted a full day/night cycle, a portion of which coincided with a strong microbarom on the East Coast. The peak emerges on ground stations in the Southwest beginning at approximately 0400 UTC (see Figure 7). Fortunately, three of the six microphones on the HASP 2015 flight experienced very low noise levels from about 0100 to 0500 UTC. A statistically significant peak in the microbarom range was present throughout most of this time period, and the three microphones had low standard deviation. The combination of quiet background conditions, a persistent peak in the microbarom range, and low standard deviation between microphones resembles the confirmed microbarom episode detected during the ground test of the same sensors as described above. Given that ground detections were occurring at the same time, this appears to be a bona fide microbarom episode in the stratosphere.

A spectral peak generated by local interference also appears in the microbarom range during the HASP 2015 flight. The power of this peak is inconsistent between microphones as evidenced by the increase in standard deviation on sensors FL1, FL3, and FL5 (see Figure 8). This may obscure the true microbarom and/or provide false detections throughout the majority of the flight. The varying strength of this signal between microphones probably accounts for the high standard deviations seen in the integrated log power and RMS amplitude in the microbarom range for a majority of the flight (recall Figure 9). Fortunately, the interference peak reaches a minimum during the time that the microbarom is present on the ground.

The HASP flights collected approximately 31 h of infrasound data in the middle stratosphere using sensors that had successfully recorded the microbarom during ground tests. Since the HASP 2014 flight took place solely during daylight hours, the lack of microbarom is consistent with previous literature on microbarom trends on ground sensors. Indeed, ground stations showed no evidence of microbarom activity that day. The nighttime portion of the HASP 2015 flight did detect a signal consistent with the microbarom for several hours. Detections on regional ground stations as well as on the East Coast lend credence to the positive signal recorded in the stratosphere. The current limiting factor on the free flying microphones' sensitivity is their susceptibility to interference from other sources. Thus far, we have demonstrated consistency with existing ground stations: the microbarom on the balloon is recorded when the microbarom is present on the surface. The existence of elevated acoustic ducts in the stratosphere suggests that the reverse is feasible in principle (microbarom recorded in the stratosphere when none is detected on the ground). This may explain the lack of microbarom peak detected on temporary ground stations deployed close to the flight path of the HASP 2015 balloon. Improved noise mitigation techniques will clarify the relationship between the microbarom signal on the ground and in the stratosphere on future balloon flights.

The HASP 2014 and 2015 experiments represent the first infrasound microphones deployed in the stratosphere in half a century. Our results indicate that balloon-borne sensor platforms may be more sensitive to far-field acoustic waves than ground-based stations. However, the contribution of wind noise reduction versus an improved signal propagation regime (e.g., the stratospheric duct) has not been quantified yet. An experiment that includes wind measurements on a balloon and a ground station with simultaneous infrasound acquisition on each could shed light on this question. A major limitation of free-flying infrasound sensors is the inability to determine direction of arrival: an array with subwavelength spacing would quickly drift apart. Work must be done to determine if a loose network of isolated stations is sufficient (see de Groot-Hedlin & Hedlin, 2015) or if nontraditional sensors such as gradiometers or air velocimeters are warranted. Despite these challenges, balloon-borne infrasound sensors are able to traverse regions with no ground coverage (the open ocean) and may open the door to seismic exploration of Venus (Cutts et al., 2016) or the gas giants.

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