A Portable Infrasonic Detection System

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ABSTRACT

During last couple of years, NASA Langley has designed and developed a portable infrasonic detection system which can be used to make useful infrasound measurements at a location where it was not possible previously. The system comprises an electret condenser microphone, having a 3-inch membrane diameter, and a small, compact windscreen. Electret-based technology offers the lowest possible background noise, because Johnson noise generated in the supporting electronics (preamplifier) is minimized. The microphone features a high membrane compliance with a large backchamber volume, a prepolarized backplane and a high impedance preamplifier located inside the backchamber. The windscreen, based on the high transmission coefficient of infrasound through matter, is made of a material having a low acoustic impedance and sufficiently thick wall to insure structural stability. Close-cell polyurethane foam has been found to serve the purpose well. In the proposed test, test parameters will be sensitivity, background noise, signal fidelity (harmonic distortion), and temporal stability. The design and results of the compact system, based upon laboratory and field experiments, will be presented.

1.0 Introduction

The infrasonic detection system developed at NASA Langley Research Center comprises a low-frequency/low-noise microphone, a small compact windscreen, and a data acquisition/signal processing system. Its design differs from that of a conventional audio system in that the peculiar features of infrasound are taken into account. First, infrasound propagates over vast distances through the Earth's atmosphere as a result of very low atmospheric absorption and refractive ducting that enables propagation by way of multiple bounces between the Earth's surface and the stratosphere. A second property that has received little attention is the great penetration capability of infrasound through solid matter – a property utilized in the design and fabrication of the system windscreens. Thus the system fulfills several instrumentation requirements advantageous to the application of battlespace acoustics: (1) a low-frequency microphone with especially low background noise, which enables detection of low-level signals within a low-frequency passband; (2) a small, compact windscreen that permits (3) rapid deployment of a microphone array in the field. The system also features a data acquisition system that permits real time detection, bearing, and signature of a low-frequency source.

2.0 Infrasonic detection system

The infrasonic detection system comprises a low-frequency, low-noise microphone, a compact windscreen, and a data acquisition/signal processing system.

2.1 Low-frequency, low-noise microphone

The figure of merit of a diaphragm-based microphone is the sensitivity-bandwidth squared product [1]. For low-frequency applications, bandwidth squared can be traded for sensitivity, which is the basis of the design of the low-frequency microphone. A low bandwidth/high sensitivity design is realized through a high diaphragm compliance (low diaphragm tension) and a large diaphragm radius. However, it is desirable that the series compliance of the diaphragm-air layer (beneath the diaphragm) combination be controlled by the diaphragm, not the air layer. Consequently, the air layer compliance is enhanced by means of a large microphone backchamber. Finally, it can be shown that of all available microphone detection technologies the electret condenser microphone has the lowest background noise floor.

Another limitation to low-frequency detectability, which also has not received much attention, is 1/f noise [2]. It is always present in the background noise spectrum. Because of the lack of a theory of 1/f noise, its minimization cannot be included in a design. However, in conventional condenser microphone (air or electret) the cut-on frequency of 1/f noise has been found to scale inversely with microphone radius. This is another reason why low background noise is favored by a large diaphragm radius.

The prototype microphones are manufactured by PCB Piezotronics under contract to LaRC. The microphone model number is M77306 and the power supply number is 480E09, an off-the-shelf device used for accelerometers and other instrumentation. Nominal performance specifications are:

    Diaphragm diameter: 3"
    Sensitivity: 700 mV/Pa
    Bandwidth: dc to 1200 Hz

The background noise is treated in Section 2.2. Figure 1 shows the microphone and power supply.

2.2 Background noise measurement

The background noise of a measurement system determines the minimum resolvable signal that can be detected by the system [3]. Background noise measurements were performed at LaRC on several low-frequency microphones as well as the B&K laboratory standard 1" microphone type 4160 for comparison. The measurements were performed in the "acoustic isolation vessel" shown in Fig.2 [4]. The test microphone is mounted in an inner vessel, which is suspended inside an outer vessel. The intervening

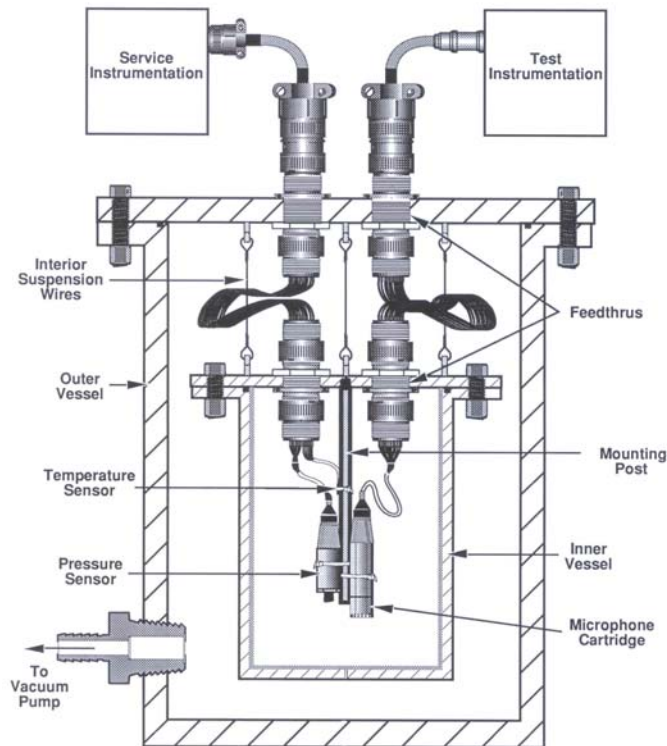**Figure 1.   PCB Model 477306 microphone with Model 480E09 power supply.**

Figure 2.   Vacuum isolation vessel used to measure the background noise of microphones.

space is evacuated to a vacuum not exceeding 10^{-5} Torr, but the microphone remains under ambient conditions at all times. The acoustic isolation afforded by the system was measured to be 155 dB. A temperature sensor and a pressure sensor permit the monitoring of the temperature and pressure inside the inner vessel. Signals are conducted through the walls of the vessels by means of feed-thrus with gold-plated pins and very good vacuum sealing specifications. A photograph of the background noise measurement system is shown in Fig. 3.
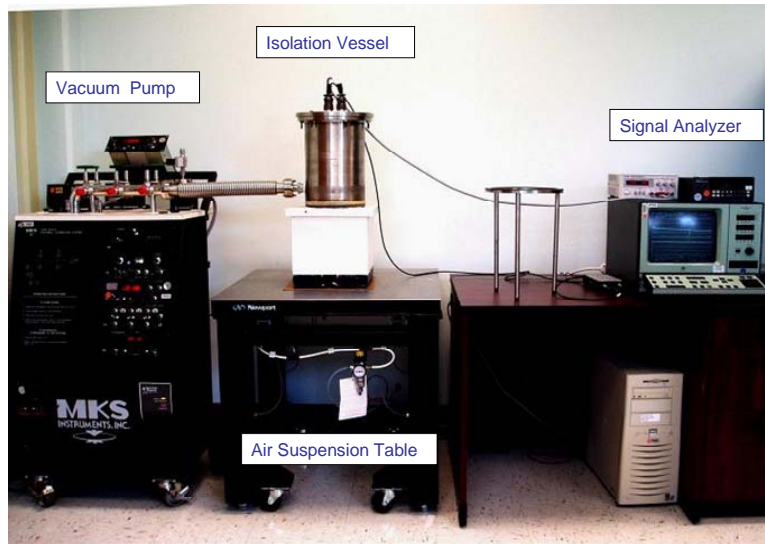

Figure 3.   Background noise measurement system comprising a vacuum pump, acoustic isolation vessel, air suspension table, and signal analyzer. Instruments for the measurement of temperature and pressure lie upon the analyzer.

The results of background noise measurements performed on several microphones, together with data taken from measurements by Sandia Laboratory on the Chaparral Model 5 microphone, are shown in Fig. 4 [5]. The power spectral density PSD is referred to $20\mu Pa/(Hz)^{1/2}$. The B&K 4193 is a ½" pressure
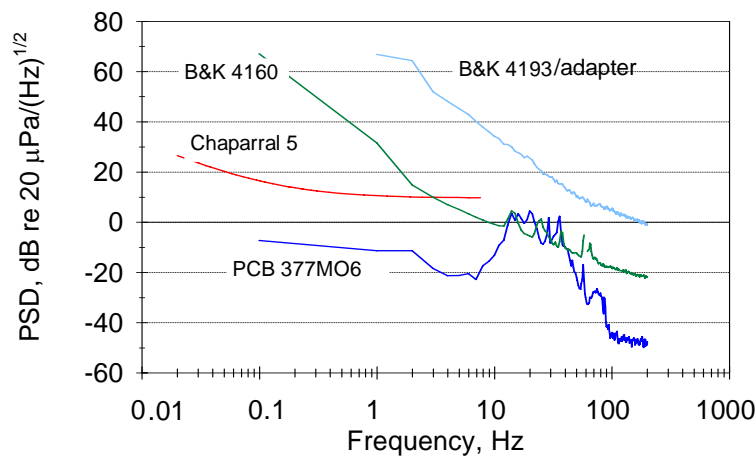

Figure 4.   Background noise measurements on low-frequency microphones and a laboratory standard microphone.

4

microphone fitted with an adapter for low-frequency service. The adapter, however, attenuates the signal by 14 dB and thus increases the background noise. The measurements on the Chaparral Model 5 microphone include the electronic noise only and not the contribution due to the Brownian motion of the diaphragm. The PCB 377MO6 microphone shows a broad peak from 20-70 Hz, believed to be an artifact of the measurement system. Even so, the background noise in the infrasonic range is about 20 dB lower than that of any known microphone. At higher frequencies the noise approaches an asymptotic level of -46 dB. The corresponding diaphragm displacement is 9×10^{-15} m. For reference, the diameter of a proton is 2×10^{-15} m.

3.0 Compact windscreen

The compact windscreen developed at LaRC is based on a different principle than used in the past [6]. Consider the classical problem of sound in air (medium 1) passing through a solid wall of thickness W (medium 2) into air (medium 3) on the other side. See Fig. 5. The transmission coefficient depends
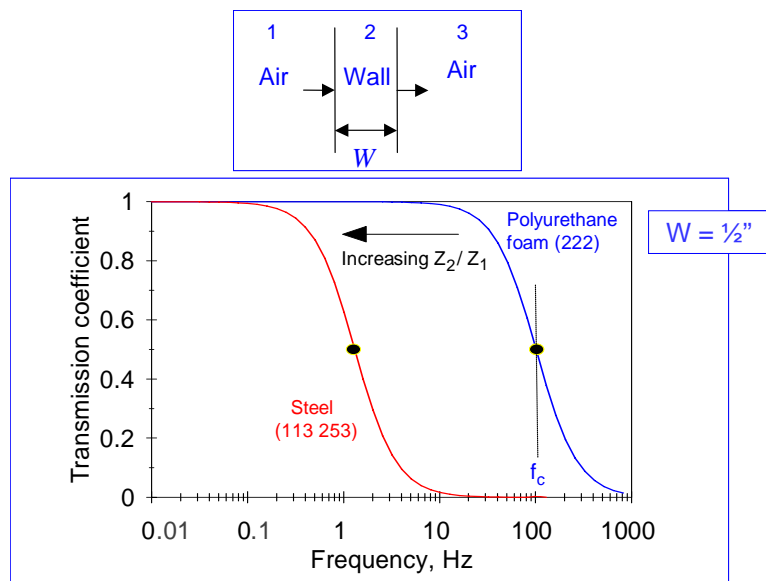

Figure 5. **Penetration of low-frequency sound through a solid wall. Top: Model for calculating the transmission coefficient. Bottom: Transmission coefficient of polyurethane foam and steel for a wall thickness of ½" (0.0127 m). The numbers in parentheses are the acoustic impedance relative to air.**

upon the wall thickness and specific acoustic impedance. For a wall thickness of ½" (0.0127 m) polyurethane foam (closed-cell, "eight pounder"), having an specific acoustic impedance of 222, permits the passage of infrasound with a transmission coefficient close to unity; but a steel wall, having a specific acoustic impedance exceeding 10^5, permits the passage of only the far infrasound – below 0.1 Hz. Thus the polyurethane windscreen will permit infrasonic signals to reach an interior microphone but will block ambient wind.

3.1 Windscreen testing

A variety of windscreens fabricated from closed-cell polyurethane foam at LaRC were tested for four specifications: (1) wind noise reduction, (2) transmission of infrasound, (3) suppression of Aeolian tones, and (4) water retention. The first three were conducted in a wind tunnel generating a maximum

wind speed of 9.3 m/s (21 mph). The wind tunnel was fitted with a subwoofer at one end for transmission testing. A cylindrical windscreen having an internal diameter of 0.0762 m (3"), internal height of 0.2286 m (9"), and wall thickness of 0.0127 m (1/2") was found to give the best performance.   The results are summarized in Figs. 6a and 6b. Figure 6a shows the results of the wind noise reduction test. The

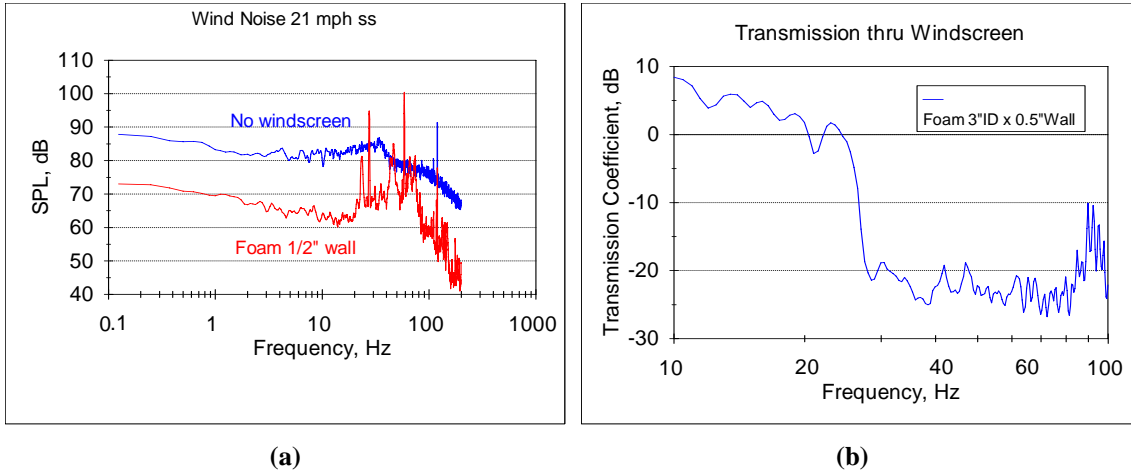(a)   (b)

Figure 6. Results of testing on a closed-cell polyurethane foam windscreen having an internal diameter of 0.0762 m (3"), internal height of 0.2286 m (9"), and wall thickness of 0.0127 m (1/2").   (a) Wind noise reduction test. (b) Sound transmission test.

response of the microphone to a 21 mph wind was measured without and with the windscreen. The tests reveal that the windscreen reduces the wind noise by at least 20 dB over the entire infrasonic frequency range.   Further, the Aeolian tones (spikes) lie beyond the infrasonic range and can be attenuated electronically. Figure 6b shows the response of the microphone to an infrasonic signal generated by a sub-woofer.   The tests reveal good transmission below 20 Hz and 20-25 dB attenuation above this frequency. Interestingly the test even reveals a small gain (~6 dB) at low frequencies. Recalling that a plane wave can be synthesized from a Fourier-Bessel series of cylindrical waves, we attribute the gain to the superposition of ingoing and outgoing cylindrical waves penetrating the windscreen.

A water submersion test revealed that the polyurethane foam absorbs 2.8% water by weight, making it a suitable material for outdoor, all-weather service.

3.2 Windscreen installation for a fixed microphone array

Figure 7 shows the fixed microphone array installation at Langley Research Center.   The objective is to detect infrasonic emissions from clear air turbulence (CAT). The microphone array is arranged as an equilateral triangle with a microphone spacing of 100 ft. (30.48 m). The microphone signals are transmitted to the data acquisition system, located in the control room, through underground cables. The microphone power supplies and a weather station are located in a weather-proof cabinet (not shown). The array area is surrounded by a drainage ditch.

The microphones are placed in a box-shaped, tightly sealed windscreen (12 x 12 x 14 in.), buried in the ground with the top lying flush with the ground surface, as shown in the insert. This arrangement takes advantage of the fact that mean wind speeds tend to vanish near the ground surface.   The windscreen is surrounded by a layer of crushed rock, from which a drain pipe conducts rain water to the surrounding ditch.
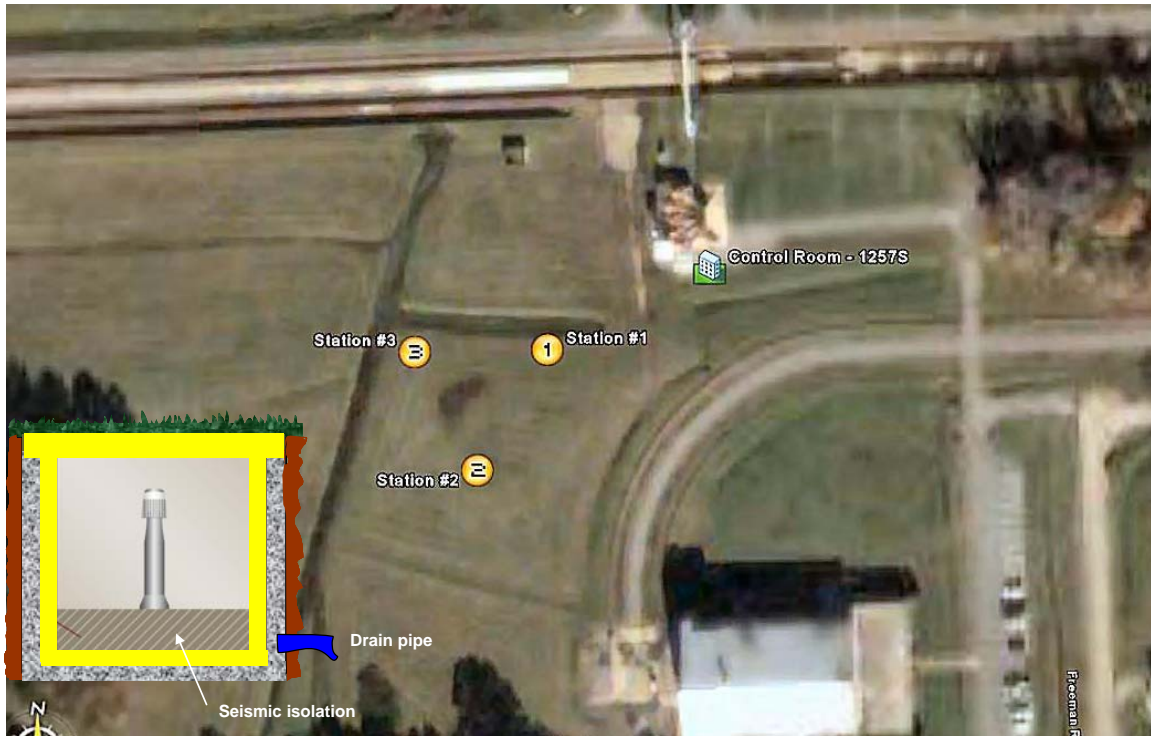
6

Figure 7. Fixed microphone array installation at Langlery Research Center. The satellite picture shows the locations of the three microphones, the drainage ditch, and the control room. The insert (bottom left) shows a microphone station, in which the microphone is seated in a box-shaped windscreen buried in the ground.
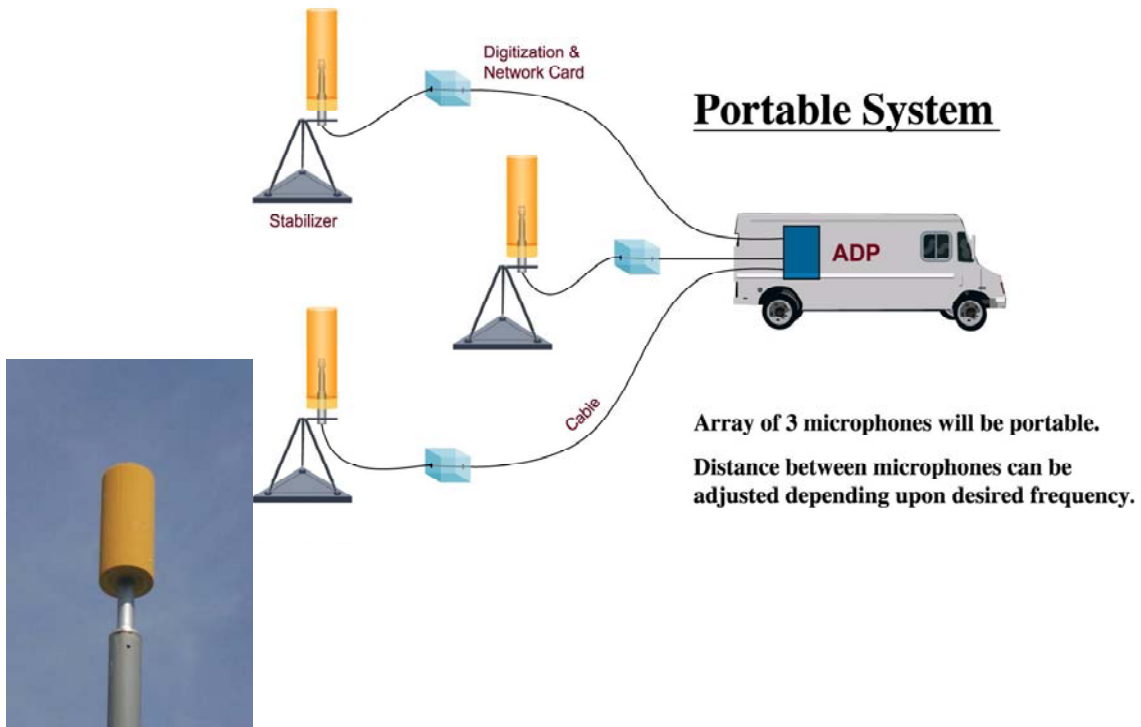

Figure 8. Concept for a portable infrasonic microphone array, suitable for rapid deployment in the field.

3.3 Windscreen installation for a portable microphone array

Figure 8 shows a concept for a portable, rapid-deployable microphone array in the field, as may be suitable for tornado chasing or for military applications. The closed-cell polyurethane windscreen is cylindrical in shape (3 in. internal diameter x 9 in. internal height) with an end cap for sealing tightly around the microphone preamplifier, as shown in the insert. The test results for this configuration, shown in Fig. 6, reveal that this is the optimal windscreen design for maximizing wind noise reduction and infrasonic transmission. The data acquisition system is located in an instrumentation van. The compactness of the windscreen is the key to rapid field installation.

4.0 Data acquisition/signal processing

The data acquisition/signal processing system fulfills three functions: source detection, direction, and identification. Identification of received infrasonic signals with a source must satisfy four criteria:

- (1) Concomitancy. When the source is present, its signals must be received. Conversely, when the source is absent, the signals must disappear. In the case of a transient event of known location, like a Space Shuttle launch, then the time of arrival of the event must conform to the distance between the source and microphones (assuming a known speed of sound).
- (2) Directionality. If the infrasonic signals are received on a multi-element array, then the direction of incidence upon the array must conform to the bearing angle of the source. In the special case of signals originating from CAT, the source bearing can be determined from pilot reports (PIREPS).
- (3) Characteristic signature. The received signals must conform to the known signature of a presumed source. This criterion is the most difficult with which to comply, for it requires a catalog of infrasonic source signatures that are found in the environment.
- (4) Coherence. The signals received on a multi-element array must "look alike" on all microphones in the array. In other words, the coherence between microphone pairs must be high. The metric for coherence in our work is the geometric mean of all microphone pairs.

5.0 Applications

The primary application of the fixed three-element array is to detect and locate clear air turbulence (CAT) in the Earth's atmosphere.   The array operated continuously in the field at LaRC for a period of four years. Infrasonic emissions from CAT are predicted from Meecham's theory of 1971 [7]. In addition to the above primary application, other interesting signals were received and identified.

5.1 Infrasonic detection of clear air turbulence in the Earth's atmosphere

Figure 9 shows an example of infrasonic signals received on the fixed array at LaRC on September 12, 2006. The resolution is too coarse to reveal time delays among the three signals (maximu delay ~ 0.1 s), but the time delays based on cross-correlations yield the bearing angles shown in Fig. 10, which also shows the simultaneous PIREP locations. The excellent coherence among the signal pairs indicates successful wind screening by the arrangement shown in Fig. 7. The high signal coherence and good correspondence with PIREP locations provide a promising case that the signals are indeed received from CAT. Investigation of the characteristic signature of CAT-emitted infrasound is in progress.

A single array can yield only the bearing angle of the source. To locate a source like CAT a second three-element array will be needed.
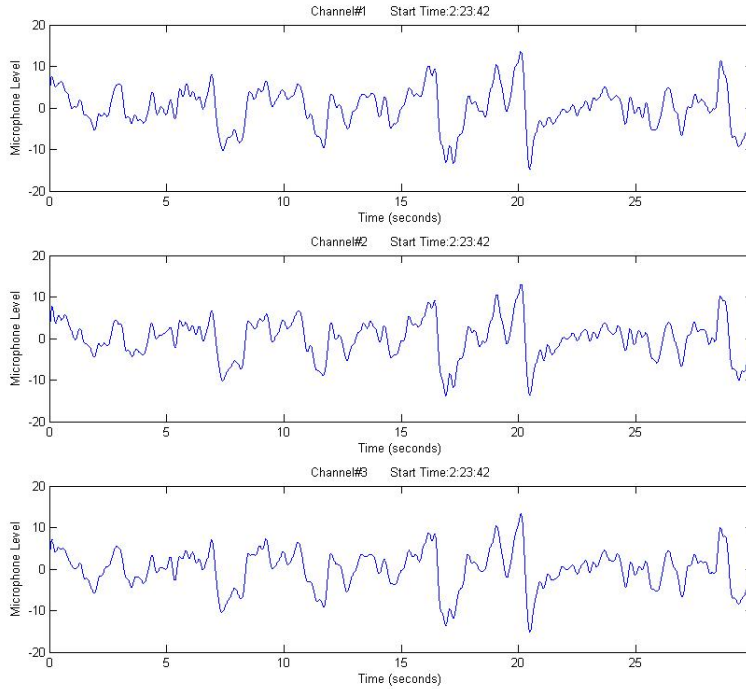
Figure 9. Infrasonic signals received on the fixed array shown in Fig. 7 on September 7, 2006. The time block is 30 s and signal bandwidth is 0.2-4 Hz.
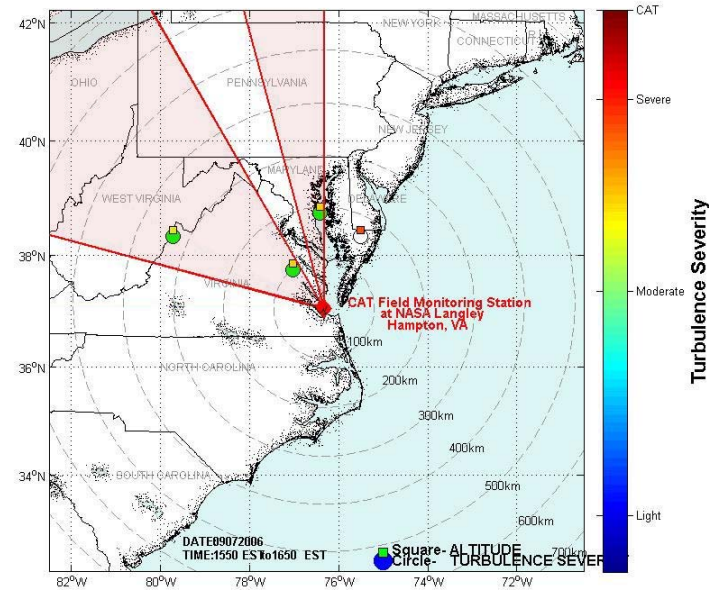

Figure 10. Bearing angles of received infrasound and corresponding PIREPS on September 12, 2006. Three PIREPS are indicated by green circles (moderate turbulence). Pink shaded areas indicate the range of bearing angles of received infrasound over a one hour period.
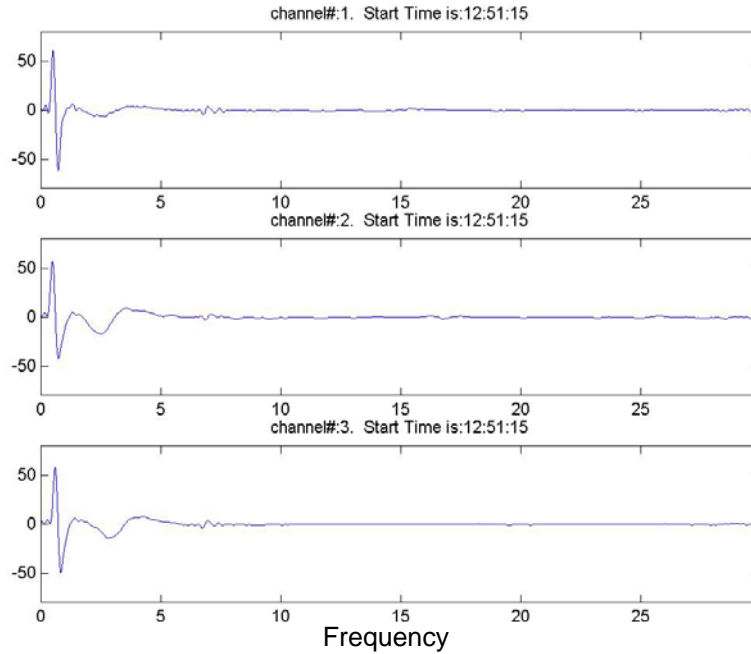
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5.2 Sonic boom

Figure 10. Sonic boom from a jet fighter.

Figure 10 shows a sonic boom on all three microphones from a passing jet fighter.   Following the characteristic N-wave, some trailing reflections can be seen.   The high coherence among microphone pairs again reveals successful wind screening.

5.3 Space Shuttle launch noise

The noise from launches of the Space Shuttle has long served as a benchmark for the reception of infrasound on stations along the east coast and beyond.   Figure 11(a) shows the direct propagation path

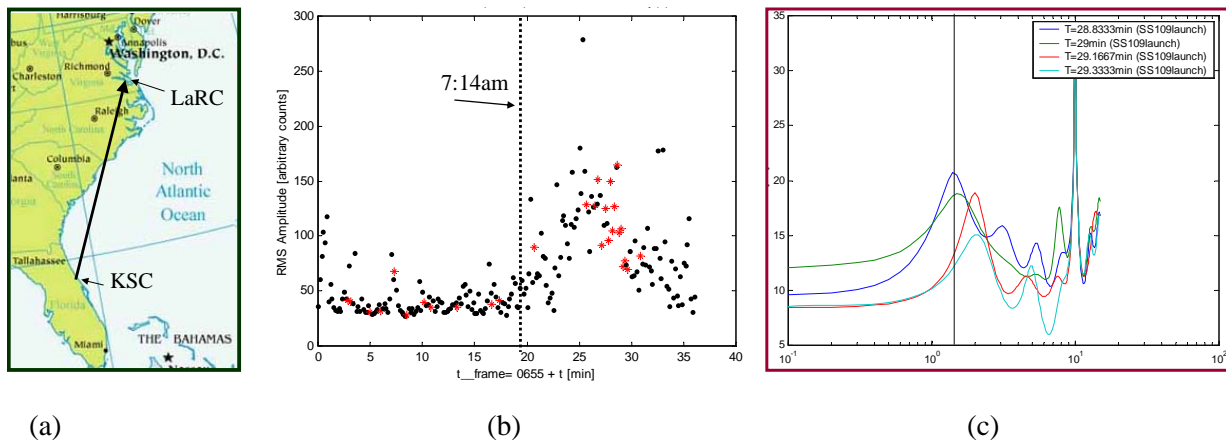(a)   (b)   (c)

Figure 11.   Launch noise of Space Shuttle STS 109 received at LaRC on March 2, 2002, showing (a) the propagation path, (b) the amplitude of received infrasound (in digital counts), and (c) the spectrum of received infrasound.   The Shuttle noise was received at 7:14 am, 52 min. after launch (6:22 am).

10

from Kennedy Space Center to LaRC. The path length is 660 miles long, corresponding to a signal delay of 51 min. based on a sound speed of 767 mi/hr. The bearing angle is 220° with respect to due north. Both the time delay and bearing angle are found to correspond to these figures. Figure 11(b) shows a burst in the amplitude of received sound (in digitized counts) starting at the arrival of the launch noise at 7:14 am. Figure 11(c) shows the spectrum of the received infrasound from STS 109 at various time intervals. There is a primary peak at about 1.5 Hz, followed by subsidiary peaks, which may be due to be reflections. The peak at 10 Hz is due to another source in the environment, since it remained long after the Shuttle noise decayed. Interestingly, data taken in 1984 (on a different array at LaRC) revealed that the primary peak occurred at 0.5 Hz. Thus something changed in the launch conditions in the intervening 18 years.

5.4 Infrasonic emissions from a helicopter in flight
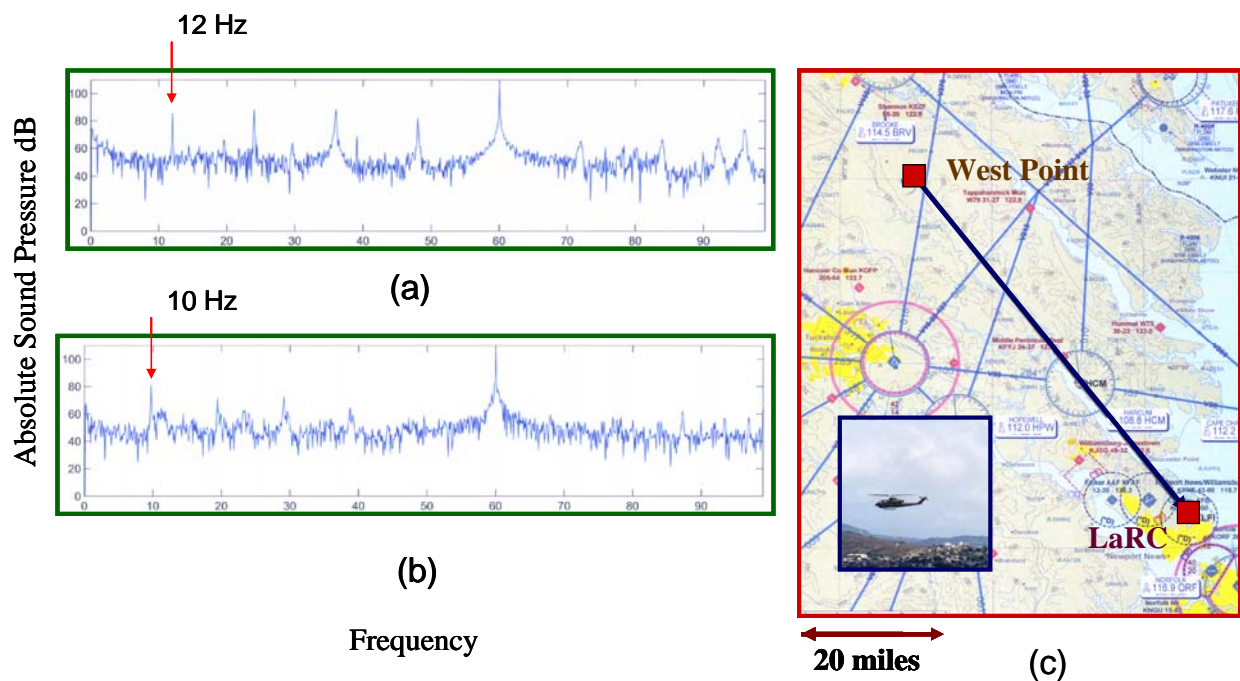

Figure 12. Spectrum of helicopter noise: (a) directly above microphone array, (b) two minutes later flying away from the array; (c) flight path showing Huey UH-1H in insert.

Figure12 shows the results of a helicopter flight test for the purpose of determining the tracking capability of the array. The spectrum of the rotorcraft hovering above the array (a) reveals a fundamental blade slap frequency of 12 Hz. As the rotorcraft flies away from the array (b) the spectrum two minutes later reveals a Doppler shift down to 10 Hz. Figure (c) shows the flight path from LaRC to West Point, Virginia, and return.

5.5 Infrasonic detection of human gait in a room

Infrasound is a powerful tool for detecting human movement. High sensitivity requires that the detection microphone have a very low background noise. Figure 13 shows the spectrum of a human walking in a room, as recorded by Extreme Endeavors, Inc. under Space Act Agreement SAA1-789. The spectrum reveals two pronounced peaks: a stationary high frequency peak and a Doppler-shifted low-frequency peak, both as a result of the gait.
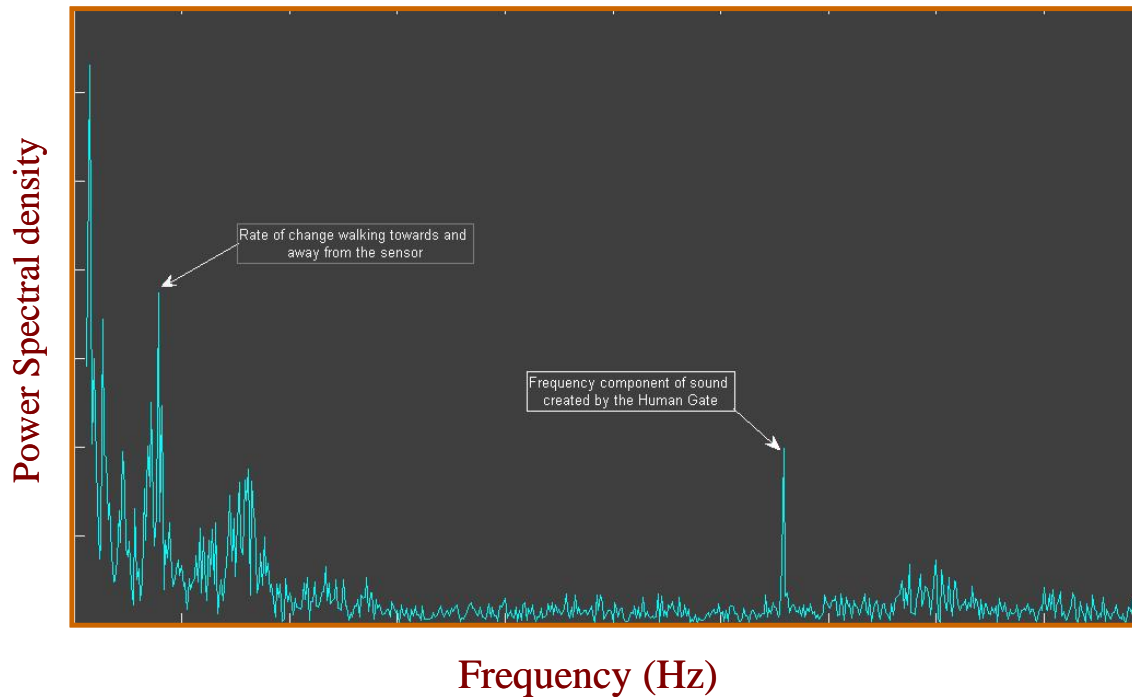
Figure 13. Infrasonic components of human gait in a large room.

6.0 Future needs

More data are needed to characterize CAT and an additional array to locate infrasonic sources.

7.0 Summary

An infrasonic detection system developed at LaRC features a low-noise infrasonic microphone, a compact windscreen, and a data acquisition/signal processing system that detects, locates, and identifies sources of infrasound. If the system is configured as a fixed array, the windscreen is in the shape of a box buried in the ground such that the lid is flush with the ground surface. On the other hand, if it is configured for portability, then the windscreen is cylindrical shaped and fits snugly around the microphone body or preamplifier. The system could be deployed rapidly in the field. The system was designed for the detection of infrasound generated by atmospheric clear air turbulence (CAT). On several occasions coherent signals were received on a three-element array that correspond well to PIREP locations. Other applications included the detection of sonic booms, Space Shuttle launch noise from Kennedy Space Center, helicopter tracking, and footprint signatures in caves.

8.0 Acknowledgement

9.0 References

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