Infrasound Rocket Signatures

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1. Abstract

This presentation reviews the work performed by our research group at the Geophysical Institute as we have applied the tools of infrasound research to rocket studies. This report represents one aspect of the effort associated with work done for the National Consortium for MASINT Research (NCMR) program operated by the National MASINT Office (NMO) of the Defense Intelligence Agency (DIA). Infrasound, the study of acoustic signals and their propagation in a frequency band below 15 Hz, enables an investigator to collect and diagnose acoustic signals from distant sources. Absorption of acoustic energy in the atmosphere decreases as the frequency is reduced. In the infrasound band signals can propagate hundreds and thousands of kilometers with little degradation. We will present an overview of signatures from rockets ranging from small sounding rockets such as the Black Brandt and Orion series to larger rockets such as Delta 2,4 and Atlas V. Analysis of the ignition transients provides information that can uniquely identify the motor type. After the rocket ascends infrasound signals can be used to characterize the rocket and identify the various events that take place along a trajectory such as staging and maneuvering. We have also collected information on atmospheric shocks and sonic booms from the passage of supersonic vehicles such as the shuttle. This review is intended to show the richness of the unique signal set that occurs in the low-frequency infrasound band.

2. Introduction

The infrasound band of acoustic signals lies at frequencies below approximately 15 Hz. At these low frequencies the absorption of acoustic energy by the atmosphere is very small and, as a result, infrasound signals can travel great distances carrying information about the source and signal path to distant observers. It is not uncommon to observe signals from natural sources such as volcanic eruptions thousands of kilometers from the source. The low absorption rate combined with a dispersionless medium makes the use of the infrasound band very useful in the detection and characterization of distant sources. Because acoustic propagation speeds are relatively slow the primary use of infrasound signals is best suited to diagnostic evaluations of events or the detection of preparatory activities associated with events of interest.

In this report we will describe the infrasound signatures of a variety of rockets. The data have been collected at two sites. The first site is the Poker Flat Research Range operated by the Geophysical Institute of the University of Alaska Fairbanks where multi-stage sounding rockets are launched to probe the auroral ionosphere. The second site is Cape Canaveral where larger rockets such as the Delta and Atlas series are launched. In addition to the description of the characteristics of the ignition, launch and early flight tracks of rockets we have also collected sonic boom data from the returns of various shuttle missions.

In all instances, infrasound data is collected using an array of specially designed, low frequency microphones. With arrays of four to six microphones collecting data synchronously it is possible to extract the azimuth of arrival of signals as well as their phase velocity across the array. These data can be converted to azimuth/elevation estimates that can be used to follow the rocket during its early stages. Combined with standard signal processing techniques the transient behavior of the spectral content of the signals from the rocket motors allows identification of the motor type, etc.

3. Infrasound Rocket Signatures

Fig. 1 shows the infrasound recording of a two-stage Terrier-Orion sounding rocket that was launched from Poker Flat Rocket Range (PFRR) in Alaska. In this overview several features are of significance. First, note the large initial transient near 6 seconds. This transient is characteristic of solid motors and will be discussed in more detail below. Following the transient is the signal from the main motor burn. Since the rocket is moving away from the infrasound array the signal suffers Doppler shifting as can be seen in the spectrogram. The Terrier motor burns out after approximately 5 seconds and the vehicle enters a coasting phase. Because of the distance to the vehicle it takes the acoustic waves some time to return to the microphone array so the Terrier burn out appears at about 15 seconds into the record. Next, the ignition transient of the Orion motor is witnessed near 38 seconds in the record followed by the Orion burn and the signal ends with the Orion shutdown. In the next section we will inspect the transients more closely.

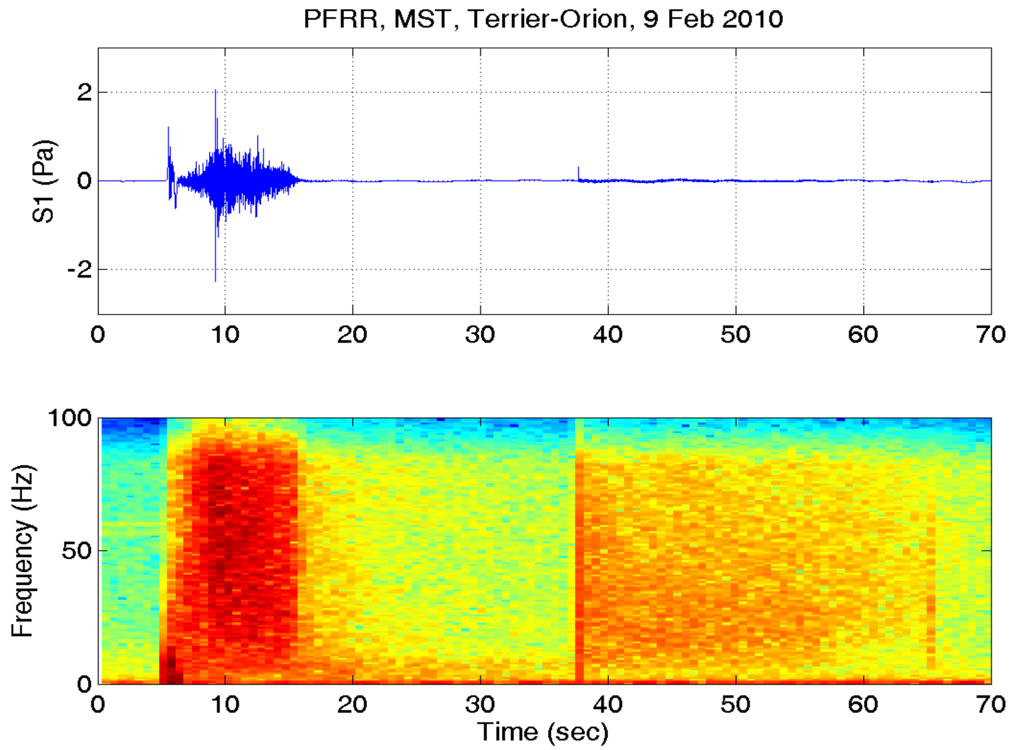

Fig. 1. The acoustic signals from a Terrier-Orion, two-stage sounding rocket

3.1 Solid Motor Transients

In this section we show the similarity in the launch signatures of solid rocket motors compared to liquid fueled motors. There is a characteristic feature in the acoustic signature that identifies solid motors no matter what the size: the large ignition transient when the motor is ignited followed by a few pressure oscillations as the motor comes to full burn. Fig. 2 shows the ignition transients for a Delta II rocket launched from Cape Canaveral Air Force Station (CCAFS). The top panel in the figure shows the first minute of the launch signal that includes the initial transient. The bottom panel shows an expanded waveform of the first 1/3-second. The waveform in the bottom panel clearly shows the start transient that characterizes a solid motor. The initial pulse has a frequency centered near 7 Hz.

Liquid engines do not show and initial transient. The acoustic infrasound data shows a slow increase in signal amplitude leading to the rocket finally leaving the launch pad and ascending into its trajectory. Fig. 3 shows the start sequence for an Atlas V launched on 4 April 2009 from CCAFS. The top panel shows the entire infrasound record for the launch and the bottom panel shows the first six seconds of the record. Note that no start transient is present as the liquid engine is started.

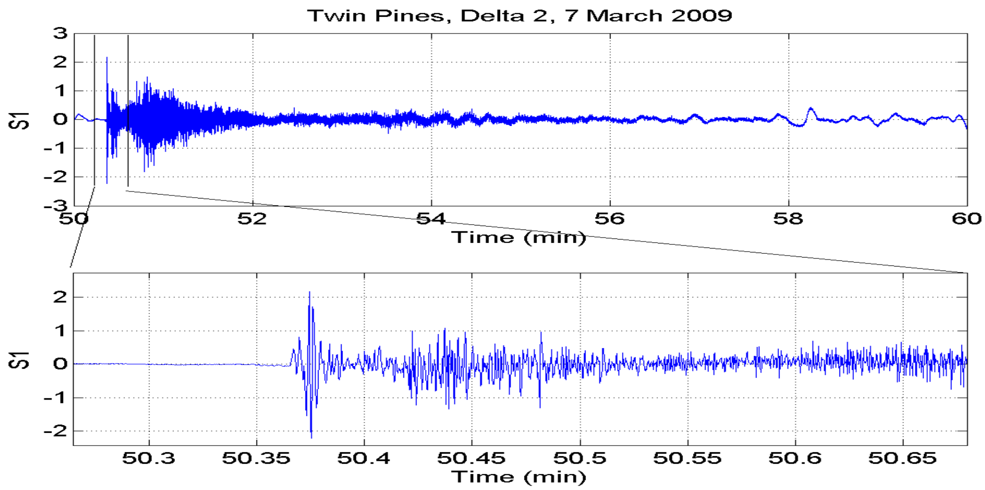

Fig. 2. The top panel shows the first ten seconds of the infrasound signals from a Delta II launch on 7 March 2009. The bottom panel shows the first 1/3-second of the waveform with the start transient.

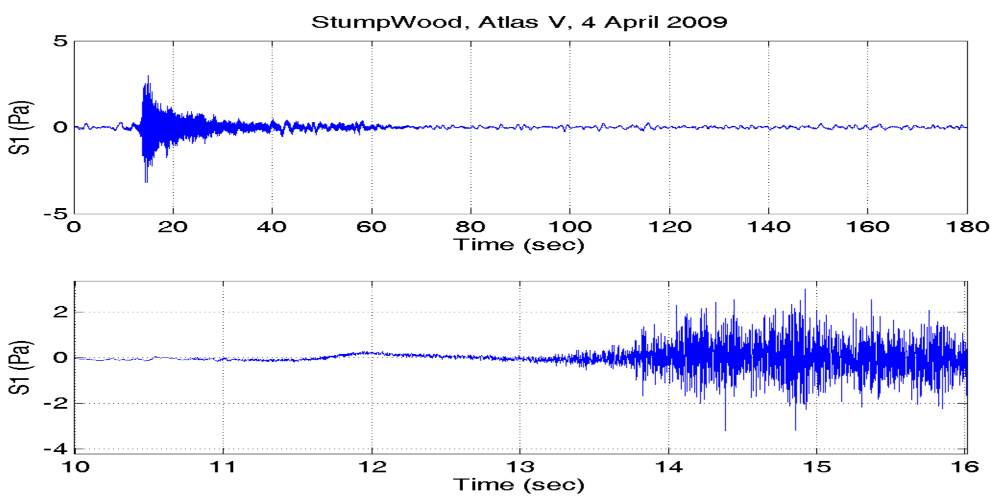

Fig. 3. The top panel shows the complete, single-sensor, infrasound record for an Atlas V launched 4 April 2009. The bottom panel shows the first 6 seconds of the infrasound record. Note the absence of any start transient and the rocket motor is ignited.

3.2 Doppler Shifts

As a rocket ascends and accelerates away from the infrasound array the infrasound spectrum undergoes a Doppler shift to lower frequencies. Fig. 4 shows the waveform and associated spectrogram for the motor signals received during the Terrier motor (1^{st} stage) burn. The red lines superimposed on the spectrogram are estimates of the Doppler shifts based upon the increasing velocity of the rocket as it accelerated upwards. One can see that the peak frequency of the received signal decreases as predicted. Such an analysis enables the reconstruction of the motor spectrum in a stationary frame by correcting for the Doppler shifts.

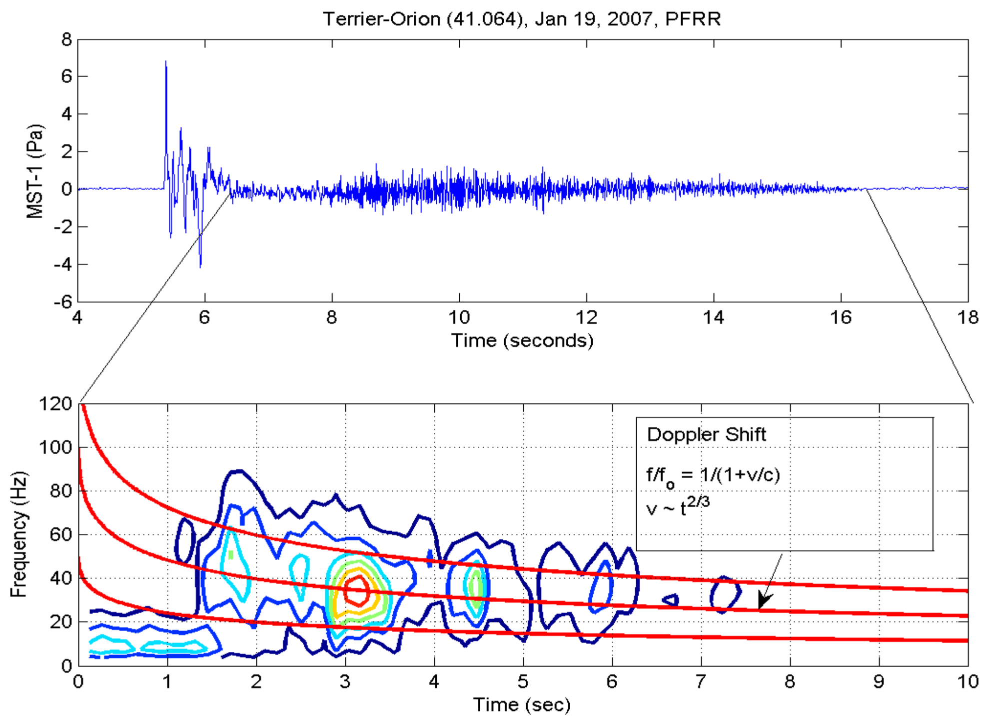

Fig. 4. The top panel shows the waveform during the launch and first-stage motor burn for a Terrier-Orion sounding rocket launched from Poker Flat Research Range. The bottom panel shows the spectrogram of the received signals. The three red curves show the predicted Doppler shift of the spectrum with time.

3.3 Spectral Analysis

For each rocket engine the spectrum of acoustic infrasound evolves as the engine comes to full power and the rocket begins to lift away from the launch pad. In this section we show two examples of the power spectra obtained during the early times just after motor ignition. The first example is that of an Atlas V launch on 10 December 2007 and the second example is that of a Delta II rocket launched on 27 September 2007. The spectra we show represent the first few seconds of the motor burns. For the Atlas V, with a liquid motor, it takes approximately 10 seconds for the rocket to clear the gantry while the Delta II, using solid motors, clears the gantry in a few short seconds.

In Fig. 5 we show the waveform from the infrasound recordings at CCAFS for the Atlas V launch on 10 December 2007. The top panel of the figure shows the extended waveform for the entire launch while the bottom panel shows the expanded waveform for the initial few seconds of the motor burn. Fig. 6 shows three power spectra estimated from the data in Fig. 5. There are several features to notice. First, the dominant signal power lies in the frequency band between 10 and 100 Hz. In that band several prominent spectral peaks occur near 10, 20 and 30 Hz. These emissions are present at varying levels throughout the initial phase of the motor burn. Video images show that the rocket clears the gantry as it lifts off after about 10 seconds so these spectral peaks characterize the engine in full flight.

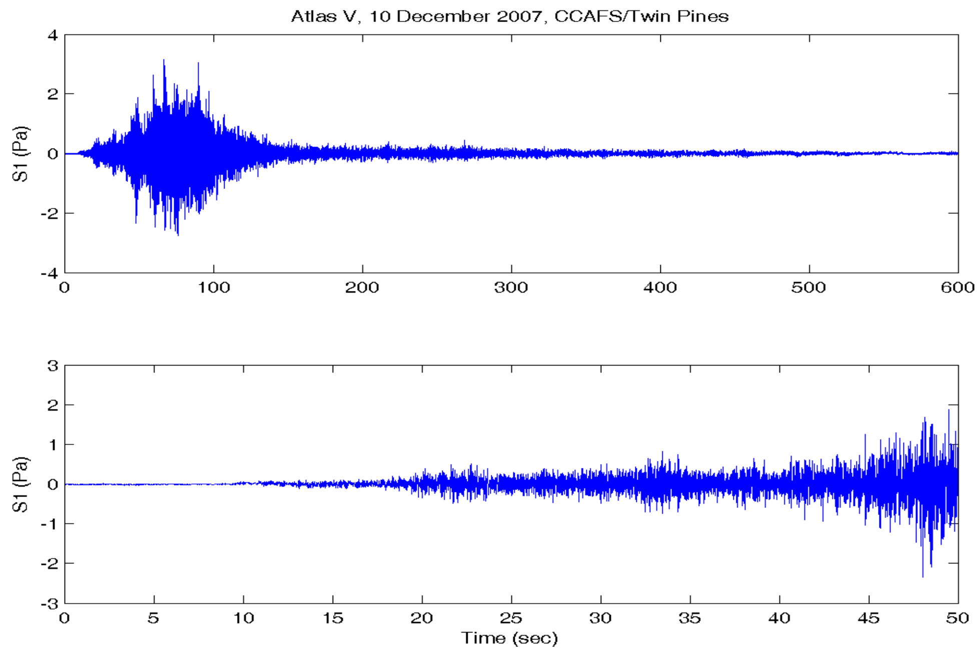

Fig. 5. The top panel shows the infrasound waveform for a ten-minute segment following the launch of an Atlas V rocket at CCAFS on 10 December 2007. The bottom panel shows an expanded waveform for the first 50 seconds of record.

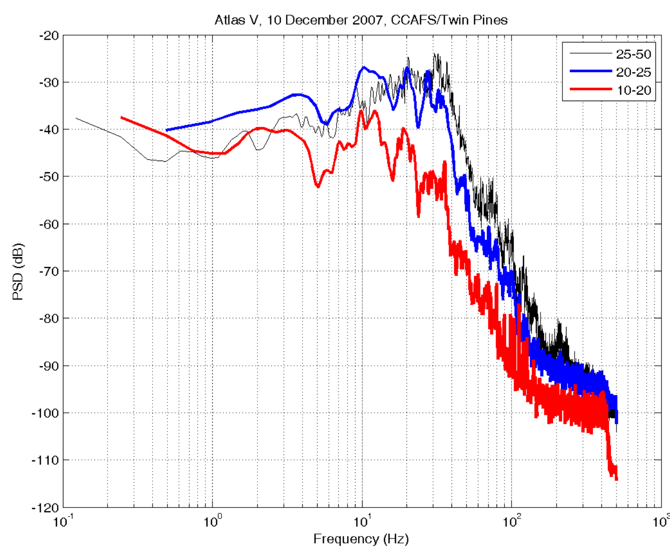

Fig. 6. This figure shows the power spectra obtained from three time slices of the infrasound record taken during the launch of the Atlas V on 10 December 2007. Note that there are significant peaks in the spectrum that characterize the Atlas motors.

Next we show the same analysis for the Delta II launch from CCAFS on 27 September 2007. In Fig. 7 we show the waveforms. The top panel of the figure shows the signals from the complete launch while the lower panel shows the expanded waveform for the first 10 seconds.

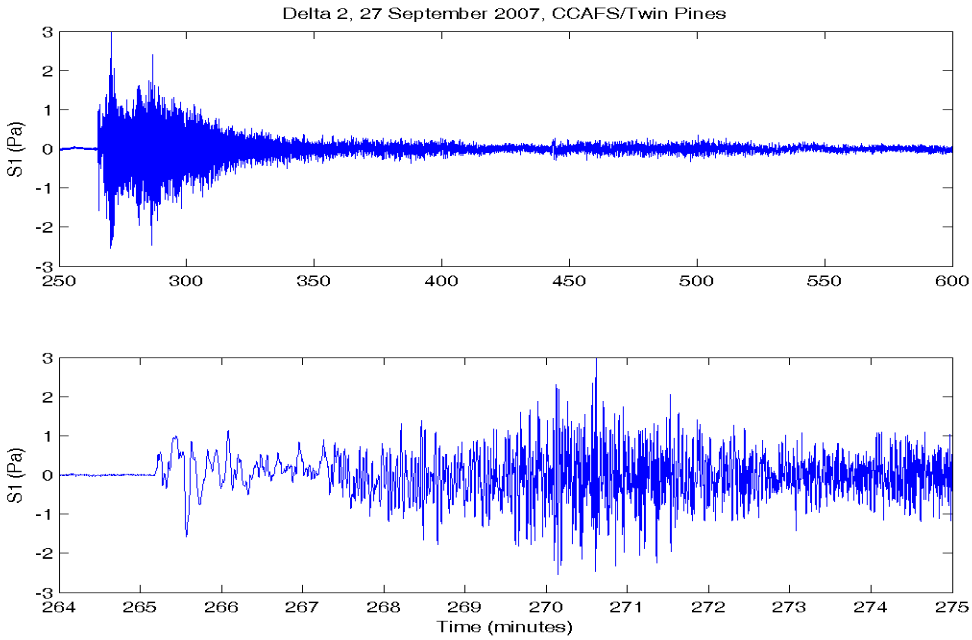

Fig. 7. This figure shows the infrasound signals obtained during the launch of the Delta II rocket on 27 September 2007. The top panel shows the entire launch sequence while the bottom panel shows and expanded wavform for the first 10 seconds after ignition.

Fig. 8 shows the power spectra obtained from segments of the initial sequence. The spectrum from the first few seconds shows prominent peaks at approximately 20, 40 and 60 Hz suggesting a resonant phenomenon. The later spectrum, taken from signals generated after the vehicle has cleared the gantry, shows a broader set of signals with a primary peak near 20 Hz.

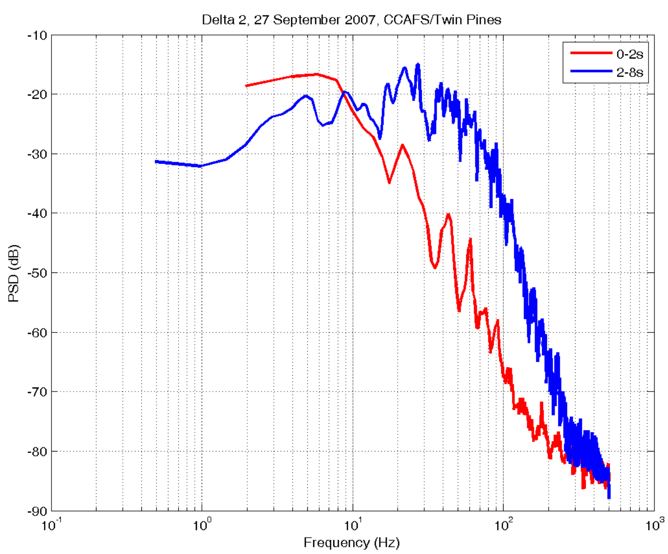

Fig. 8. This figure shows the power spectral density from two intervals in the data received during the Delta II launch from CCAFS on 27 September 2007. The red trace shows the spectrum during the first few seconds after ignition while the blue trace shows the spectrum after the rocket has cleared the gantry.

4. Trajectory Analysis

Using the combined data from a microphone array it is possible to estimate the bearing to a source. If the source is above the ground the wave fronts strike the ground at an angle that is the elevation angle, θ, of the source. This leads to an apparent increase in the phase speed, v, of the acoustic waves given by $v=c/\cos(\theta)$ where c is the ambient speed of sound. Estimates of v and measurements of the ground temperature allow the sound speed and thus the elevation angle to be estimated. Fig. 5 shows the waveform along with estimates of the trace velocity and elevation for the early stages of the Delta 2 rocket launched on 20 December 2007. The top panel shows the waveform and the second panel shows the apparent trace velocity. The bottom panel shows the elevation derived from the trace velocity. Note that the speed appears to rise as the rocket ascends and then levels out as the rocket moves downrange.

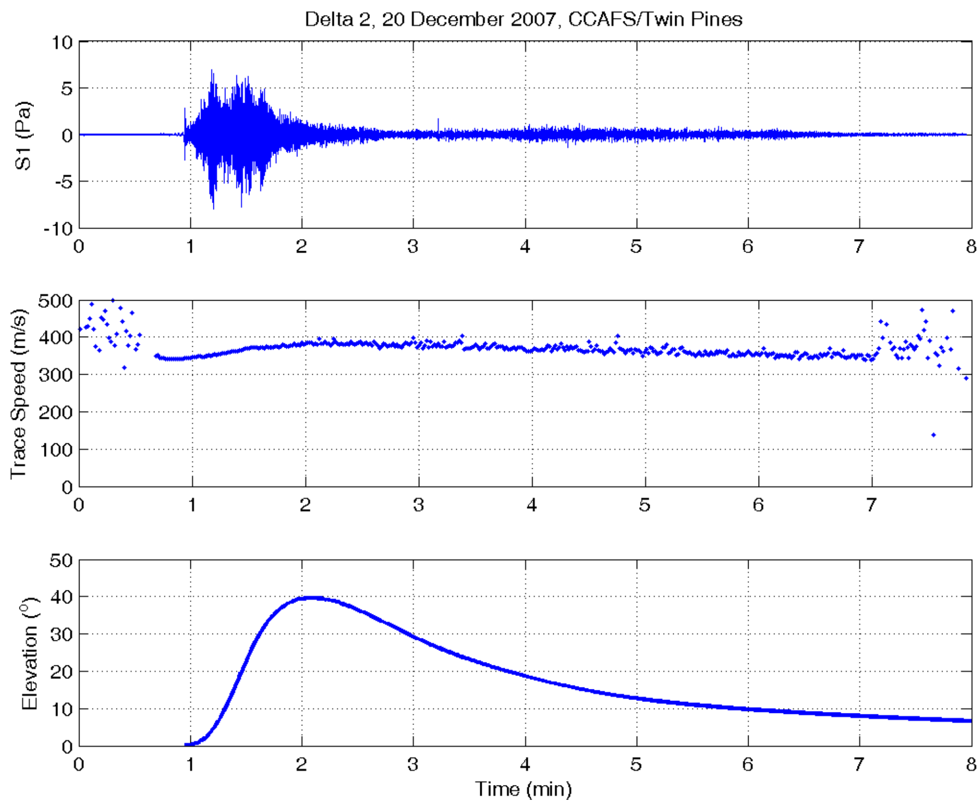

Fig. 5. This plot shows the estimates of trace speed of acoustic waves. The top two panel shows the rocket waveform, the second panel shows the estimates of trace speed and the bottom panel the inferred elevation.

5. Sonic Booms

In addition to the launch observations we have also been able to record the sonic booms associated with the return of shuttle missions as the craft descends over the Florida peninsula. A sonic boom is the result of the coalescence of the leading and trailing shock waves associated with the supersonic flight of an aircraft. The waveform of the sonic boom is typically an ‘N’ wave, so named because the time history resembles the capitol letter N. Generally the amplitude of the N wave is proportional to the size of the object and its speed. The time duration of the N wave is determined by the size of the object and may be affected by the variations in sound speed in the atmosphere. Fig. 6 shows the sonic boom associated with the shuttle STS120 on 7 November 2007. In this case the peak amplitudes were clipped at about 20 Pascal’s as shown in the top panel of the figure. The bottom panel shows a power spectrum of the turbulent wake downstream of the N wave compared to the upstream ambient atmosphere. Several peaks are noticeable in the spectrum beginning at 5 Hz superposed on a broad turbulent background.

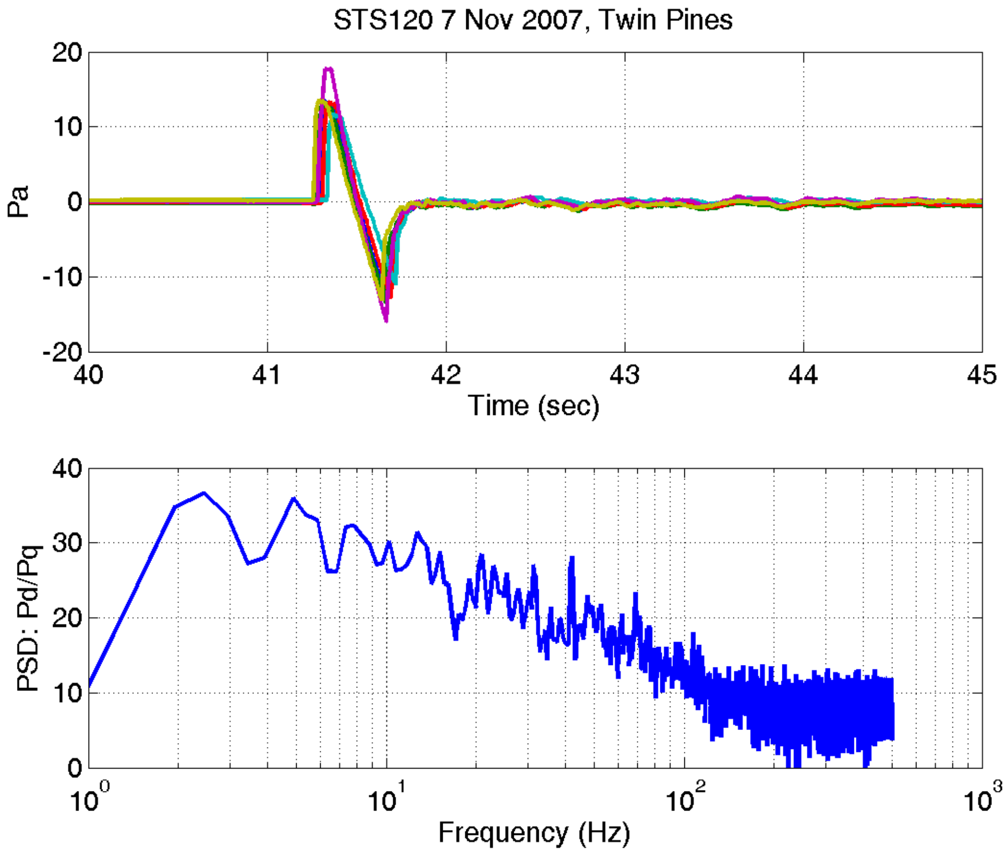

Fig. 7. The top panel shows the sonic boom, or 'N' wave, associated with the over flight of the shuttle STS120 on its return from space on 7 November 2007. The bottom panel shows a power spectrum of the downstream turbulence compared to the upstream data.

6. Summary

During our research we have collected data from over 30 sounding rockets at the Poker Flat Research Range and more than 20 large rockets launched from the Cape Canaveral Air Force Station. From this data base we are able to identify the unique characteristics of the rocket motor ignitions, the spectrum of the primary engine as the rocket moves away from the launch pad, subsequent staging and motor starts and the spectrum of noise associated with those stages. Using array data we have been able to track the vehicles in azimuth and elevation as they move downrange.

The infrasound spectrum is not just the low-frequency extension of the broadband acoustic spectrum but contains a unique set of signals that characterize the rocket motor and subsequent activity and staging.

7. Acknowledgements

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