Seismic signatures of the sonic boom during the launch of Chandrayaan-1

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We present the seismic signatures generated by the sonic boom during the launch of Chandrayaan-1 from the Satish Dhawan Space Centre, Sriharikota on 22 October 2008. A network of six digital broadband seismographs spread over a distance of 35 km recorded the air coupled seismic waves due to the sonic boom. These are recorded as first arriving waves on the seismogram with a velocity of about 338 m/s and frequency of ~ 5 Hz. Also, the amplitudes of the waveforms indicate a high attenuation of the order of 10 in the marshy Pulicat Lake area. The lake area experienced a significant pressure of about 55 microbar due to the impact of the sonic boom.

Keywords: Air-coupled waves, Chandrayaan-1, seismic waves, sonic boom.

WHEN an aircraft moves through the air at supersonic speed, shock waves are formed and coalesce into a cone, known as the Mach cone, with the aircraft at its apex. The shock wave superimposed on the atmospheric pressure has the pattern of an *N*-wave. The *N*-shaped time variation of pressure is derived from a compression from the bow wave, a decompression and final recompression from the tail of the aircraft. The Mach cones emanating from the front and rear of the aircraft intersect a flat surface in hyperbolas (Figure 1 *a*)[1]. At the point of intersection of each positive pressure wave with the surface, a force is directed onto the surface with an angle to the vertical equal to α, where 2α is the angle of the Mach cone (Figure 1 *b*)[2]. When the apparent velocity of the shock front intersecting the surface is comparable to the velocity of seismic waves, these latter waves are excited. When the surface is rough, the horizontal component will transfer energy to the surface. The vertical component of the force creates a hyperbolic elastic depression in the surface which moves forward at the speed of the aircraft following the *N*-wave. In addition, irregularities in the ground properties and acoustic coupling with geographical features become local sources which radiate additional seismic waves. At large distances the geometrical attenuation of the body waves is greater than that of the surface waves, so that the surface waves or 'Rayleigh waves' are larger in amplitude at great distances from ground zero[3]. The seismic effects of sonic boom and its physical interpretation have been discussed in detail by McDonald and Goforth[2], and Goforth and McDonald[4].

Several studies have been carried out to explain the nature of infrasound rays (air-coupled waves) from the high-altitude sources such as missiles, and Apollo rocket launching and reentry phases[5–9]. Benioff et al.[10] gave the first analysed case of sound waves due to air-coupled waveforms from a natural earthquake. Seismic waves excited by the motion of high-rise buildings due to the shock waves caused by the space shuttle Columbia on its return to the base was also reported[11].

Donn et al.[12] presented the results of the launching of Apollo 13 and Apollo 14 from Cape Kennedy and recorded at Skidaway Island, 374 km to the south, and compared the characteristics of the seismic signal with acoustic signal. They observed simultaneous recording of acoustic and seismic signals at times appropriate to the arrival of acoustic waves from source. The seismic signals show a frequency nearly constant at about 4 Hz, whereas the acoustic frequency band is fairly broad from 4 to 0.17 Hz. The strong increase in seismic wave amplitudes corresponds well with the increase in atmospheric pressure amplitude, indicating air-coupling of ground waves at the recording site of Apollo 13 and Apollo 14.
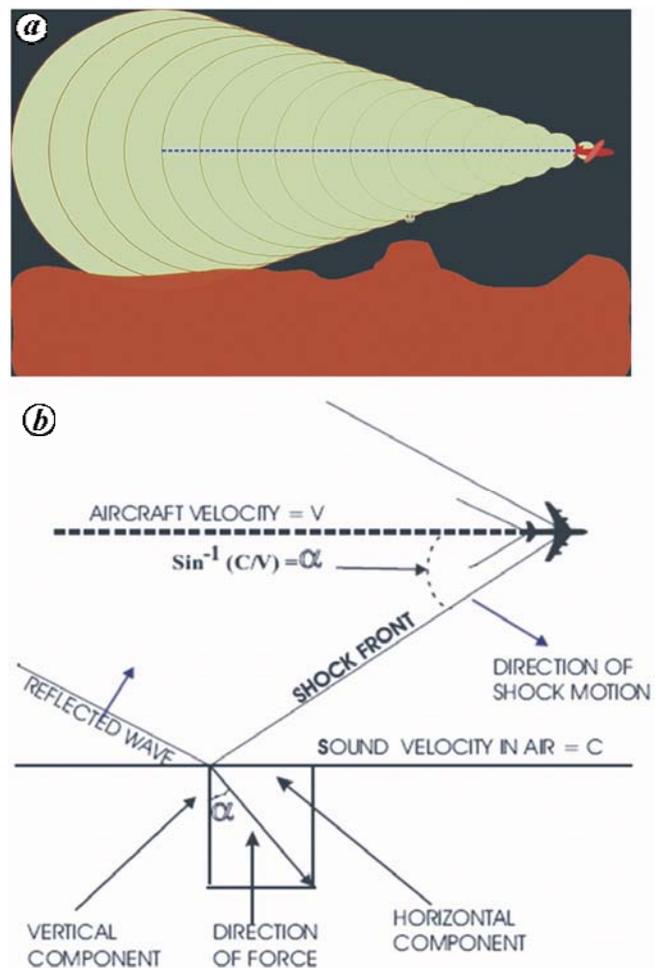

Figure 1. Schematic diagram of the sonic boom[1,2].

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Figure 2. Digital broadband network. Red triangles (MPD, PTA, NNR, PND, KTR and AKT) represent the broadband seismic stations. The white circle represents SHAR, Sriharikota, the point of lift-off of PSLV.

Table 1. Details of the seismic stations in the network

| Station code | Latitude (N) | Longitude (E) | Distance to SHAR (km) | Arrival time UTC | Ground motion (nm) | |
					First motion	Maximum
KTR	13.764	80.124	9.6	00:52:28.86	460	910
PND	13.786	80.153	11.1	00:52:32.43	556	1184
AKT	13.721	80.124	11.5	00:52:33.08	447	1014
NNR	13.814	80.082	19.1	00:52:55.10	133	670
PTA	13.830	80.011	26.6	00:53:16.29	14	70
MPD	13.902	79.993	32.6	00:53:33.62	2	120

We present here the evidence for air-coupled seismic waves generated due to possible sonic boom during the launch of Chandrayaan-1. Chandrayaan-1 is a moon mission programme of the Indian Space Research Organization launched through PSLV_C11 on 22 October 2008 at 06:22 IST (00:52 GMT) from the Satish Dhawan Space Centre (SHAR), Sriharikota, Andhra Pradesh, India. Sriharikota is a spindle-shaped island, with its eastern and western boundaries as the Bay of Bengal and Pulicat Lake respectively. The objective of Chandrayaan-1 was aimed at the preparation of a 3D image atlas of the lunar surface and chemical mapping of the entire lunar surface through high-resolution remote sensing of the moon in the visible, near infrared, microwave and X-ray regions of the electromagnetic spectrum[13,14].

To study the seismological signatures of the sonic boom from Chandrayaan-1, we installed a network of six digital broadband seismographs spread over a distance of about 35 km from the launch site (Figure 2). Each station is equipped with a CMG-3T sensor, a broadband three-component seismometer (Guralp-make) with flat response from 0.003 to 50 Hz, and a 24 bit digital recorder (Reftek-

make). These stations were operated at a sampling frequency of 200 s/s, capable of recording high-frequency signals of about 100 Hz and time tagging was carried out by GPS with an accuracy of microseconds. The stations KTR, PND and AKT are located in the Pulicat Lake area, whereas NNR is situated in its western edge. The westernmost stations PTA and MPD are located in relatively hard soil. The station details are given in Table 1.

The PSLV lifted-off from SHAR with the trajectory away from the line of the seismograph network. Hence we could record the boom carpet that hit the Pulicat Lake and produced the air-coupled seismic waves. The sonic boom at the Pulicat Lake was experienced about 15–20 s after the zero time and continued till about 35–40 s (pers. obs. by the authors).

The three-component seismograms recorded at two stations, KTR and MPD, the nearest and the farthest, show the well-developed body waves and surface waves due the sonic boom with T5 as the zero time, i.e. lift-off time of PSLV (Figure 3). Figure 4 shows the vertical components of the displacement seismograms from the network of six stations. The seismograms were filtered at different frequency bandwidths and the range of 1–10 Hz exhibits maximum displacement. The lift-off time (zero time) of PSLV, the distance of the recording stations from SHAR, the arrival times of the P-waves and the ground displacement due to the impact of the sonic boom as recorded by the first arrival of P-waves and the maximum are given in Table 1. The differential travel times of the P-waves and the distances along a profile from AKT–MPD, PND–MPD and KTR–MPD are shown in Table 2. In the absence of the exact location of the impact of the sonic boom, we derived the velocity of the P-wave using the differential travel time and differential distance between the reference station and the stations along the profiles. The plot of differential distance and arrival time of the above profiles (Figure 5) indicates the P-wave velocity to be 344, 315 and 354 m/s for the three stations respectively with an average velocity of 338 m/s, close to the speed of sound wave in air (330–340 m/s), as reported by an earlier work[11].

The period of the P-waves, the first signature in the seismogram, at stations AKT, PND and KTR obtained from their frequency–amplitude curves (Figure 6) shows
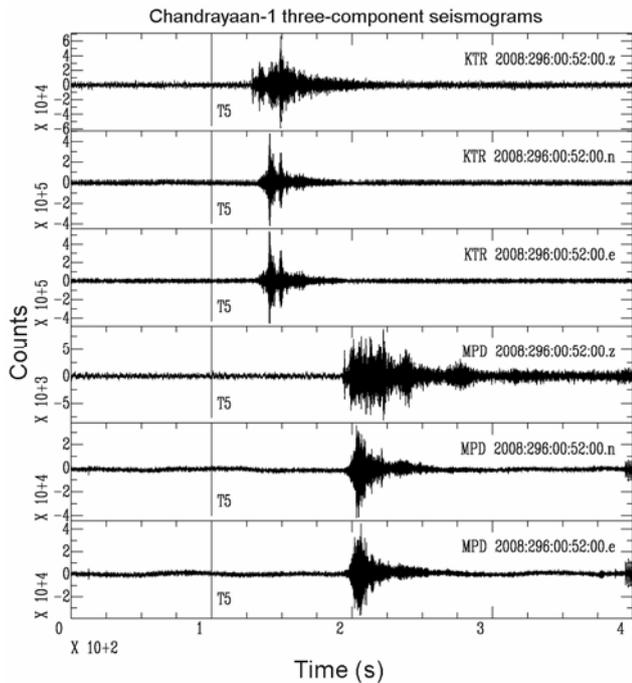
Figure 3. Three-component seismograms of KTR and MPD, the nearest and the farthest stations. T5 is the lift-off time (2008:296:00:52:00.000).
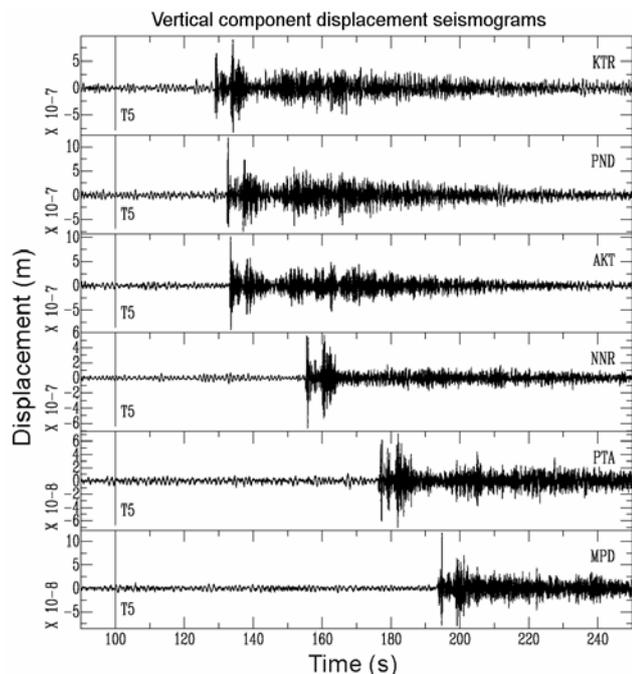
Figure 4. Vertical component displacement seismograms of the seismic stations in the network with increasing distance from SHAR.

Table 2. Differential travel times and differential distance between station pairs with AKT, PND and KTR as the reference

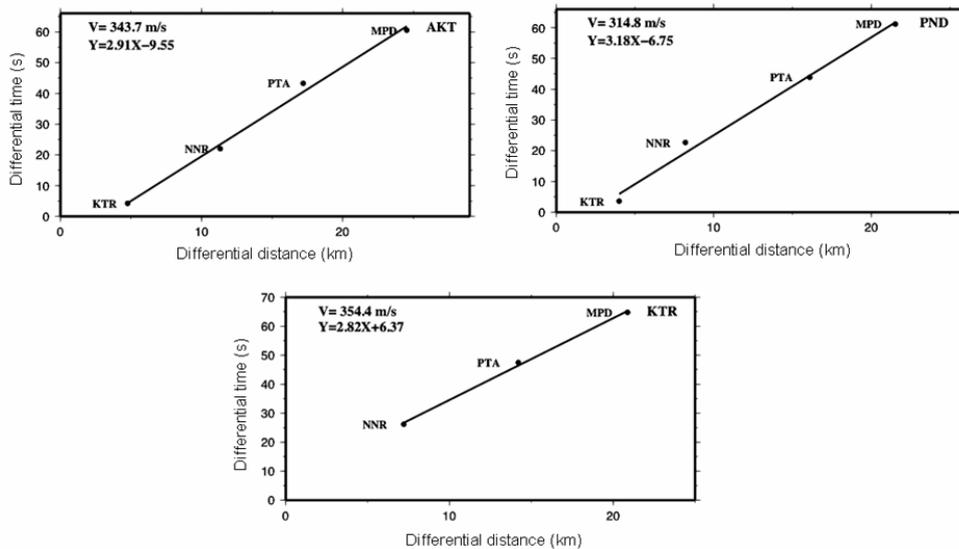| Station pair	Differential distance (km)	Differential time (s)
AKT–KTR	04.77	04.22
AKT–NNR	11.32	22.02
AKT–PTA	17.20	43.27
AKT–MPD	24.53	60.54
PND–KTR	04.00	03.57
PND–NNR	08.21	22.67
PND–PTA	16.09	43.86
PND–MPD	21.53	61.19
KTR–NNR	07.21	26.24
KTR–PTA	14.21	47.43
KTR–MPD	20.87	64.76

Figure 5. Plot of differential distance versus differential arrival time for AKT, PND and KTR as reference stations.
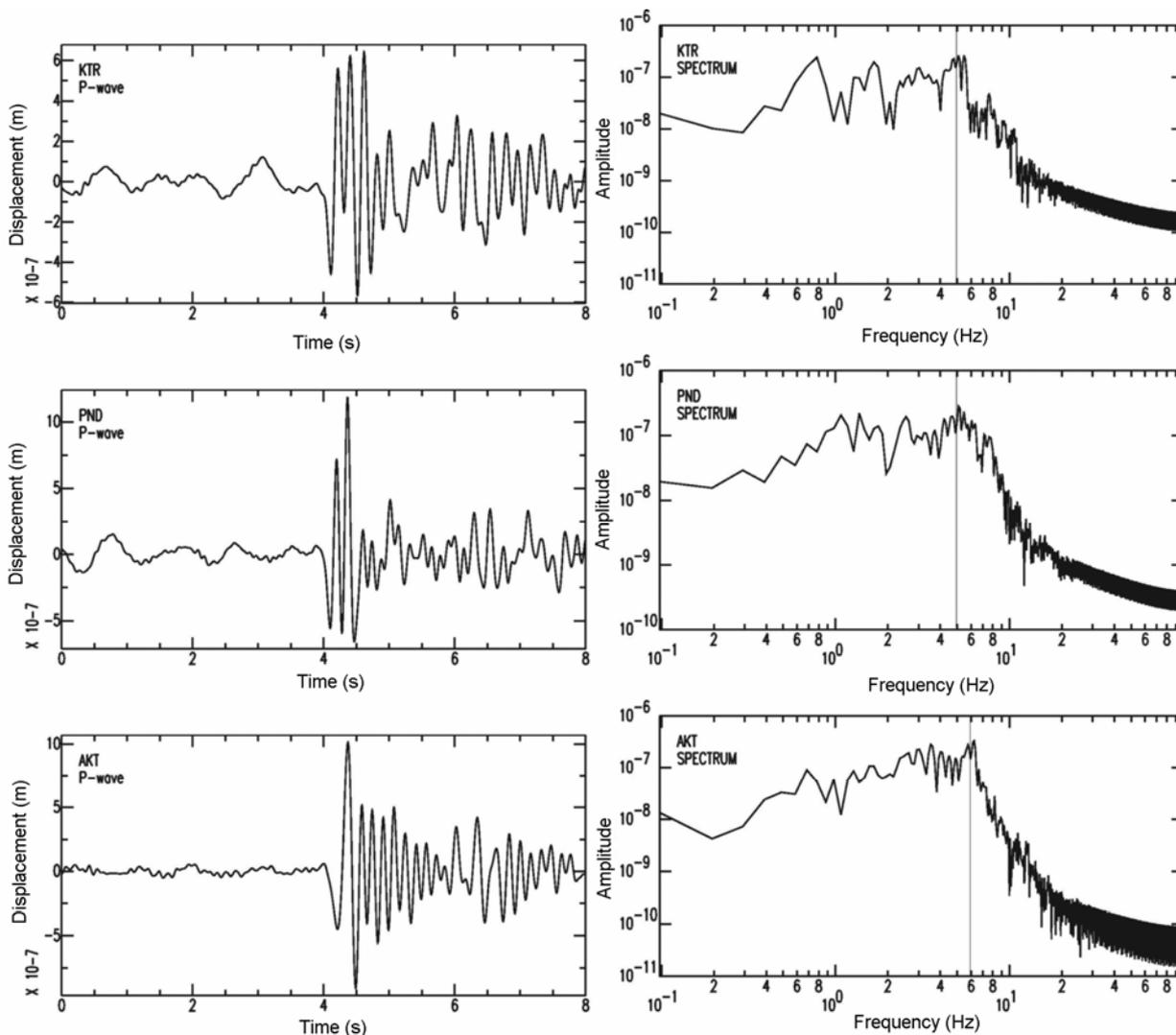

Figure 6. Vertical component displacement seismograms of the *P*-waves and the corresponding spectrum for the stations KTR, PND and AKT showing peak frequency ~5 Hz.

the dominant frequency of about 5 Hz, which is in close proximity of 4 Hz reported[10] for the air-coupled seismic waves by sonic boom during the launch of Apollo 13 and Apollo 14. The ground displacement at the last two farther stations, which are on hard soil (Table 1), is less by an order of 10 compared to the nearby four stations which are on unconsolidated sediments. This could be due to the significant attenuation in the marshy soil of the Pulicat Lake area.

The displacement response of a homogeneous and isotropic elastic half space due to plane pressure wave was theoretically modelled by Sorrel and Der[15]. When a pressure pulse of amplitude p is imposed upon the surface of the half space, the vertical component of ground displacement w generated by the disturbance is approximated to:

$$w = [C_0 p(\lambda + \mu)/2\mu \ (\lambda + \mu)]/(1/2\pi f), \tag{1}$$

where C_0 is the phase velocity in air (propagation speed) and is about 340 m/s; p the amplitude of the air pressure in microbar; f the frequency; λ the Lame's parameter, equal to $\rho(\alpha^2 - 2\beta)$, where α is the compressional velocity and β the shear velocity in the unconsolidated sediments, and μ is the rigidity equal to $\rho\beta^2$.

Since the pressure is a normal force experienced in a unit area, the ground displacement due to the vertical component of the P-waves is considered to obtain the pressure exerted by the sonic boom. The present study shows that the average velocity of the P-waves is 338 m/s, and the corresponding shear wave about 203 m/s. The density of the unconsolidated sediments for this area is taken as 1700 kg/m^3. Equation (1) was solved for the air pressure at selected stations KTR, PND and AKT in the Pulicat Lake region and found to be about 49, 59 and 57 microbar respectively, resulting in an average pressure of about 55 microbar experienced in the region due to the sonic boom.

The seismic waves produced due to the sonic boom of Chandrayaan-1 were recorded till a distance of 35 km. The amplitude of the signals in the unconsolidated sediments is ten times more than that recorded in the farther stations located on the hard soil. The frequency of the P-waves is about 5 Hz, as reported for the rocket launchings of Apollo 13 and Apollo 14. The Pulicat Lake area experienced a pressure of about 55 microbar due to the impact of the sonic boom during the take-off. Verification of these results, however, requires micro-barometric data at these sites. Also, it would be important to have the accurate location of PSLV during the boom. Since ISRO is making great efforts towards the moon mission programme and is launching satellites for various scientific and socio-economic purposes, a semi-permanent network of seismic stations along with micro-barometers and inputs from ISRO may provide significant information on the subsurface structure and the earth–atmosphere interaction during rocket launching.

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