Cross Wind Effect on Sound Propagation

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1. Introduction

Under certain atmospheric conditions, blast waves from an explosion may be propagated over unusually long distances. This can occur if there is an increase with altitude in the velocity of sound due to an increase with altitude in the temperature or the wind speed or the combination of the two. The observation of sound beyond intermediate surface zones of silence is generally due to the refraction of sound in the upper stratosphere. It has been shown that sound can propagate over long horizontal distances through the natural waveguides that generally exist in the atmosphere (Schrödinger, 1917; Brekhovskikh, 1960; Gutenberg, 1951). The propagation of sound through the atmosphere is considerably influenced by atmospheric winds both in the velocity of the sound wave and the path that it follows. The standard practice in analysis of sound propagation utilizing ray-tracing techniques is to include the component of wind speed in the plane of travel of the sound in computing the speed and the refractive characteristics of the path (Cox, Plagge and Reed, 1954; Rayleigh, 1945). The wind component normal to the plane of propagation between the source and receiver (cross wind) is usually neglected; however, earlier investigators have described methods which, in essence, treat the cross wind as a translating mechanism (Duckert, 1951; Richardson and Kennedy, 1952). The purpose of this paper is to describe the effects of cross wind on the propagation of sound resulting from two high-altitude explosions over the White Sands Missile Range.

2. Theory

For atmospheres having only horizontal winds, the local speed of sound is a function of both temperature and wind speed and may be determined approximately from

$$c = c_0 + u\cos\theta$$

where $c_0 = 20.1\sqrt{T}$ (T is absolute temperature in deg K), u = wind speed (m sec^{-1}), θ = angle between direction of propagation and direction of wind. The effect of the wind component normal to the direction of propagation is discussed below.

Consider the wave front of sound being emitted in a motionless medium from a point source S as shown in Fig. 1. If R is the receiver, the travel time t from S to R along a ray normal to the wave front is:

$$t = RS/c, \tag{1}$$

where c is the speed of sound.

Now let the medium move at right angles to the line RS (from right to left as shown in Fig. 2) at a uniform speed u, with respect to the fixed points R and S. Let x be the distance from S to S', y the distance from R to S, and z be the distance from R to S'. Let t_1 be the new time required for the wave front to travel from S to R. During the time t_1, the origin of the wave front will appear to have moved to S' and

$$x = ut_1. \tag{2}$$

Let Δt be the difference in time required for the wave front to travel from S to R with and without the effect of the moving medium, that is:

$$\Delta t = t_1 - t \tag{3}$$

$$y = ct \tag{4}$$

$$x = u(t + \Delta t). \tag{5}$$

If we now consider the right triangle RSS' in Fig. 2,

$$\tan\theta = x/y = u(t + \Delta t)/ct = u/c + u\Delta t/ct \tag{6}$$

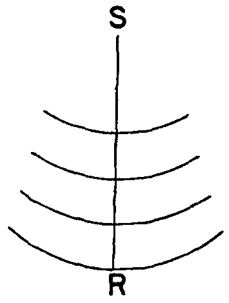

FIG. 1. Sound waves in a stationary medium.

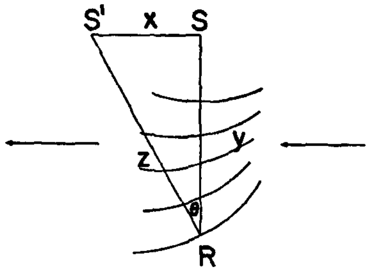

FIG. 2. Sound waves in a moving medium.

TABLE 1. Results of wind corrections.

Date	Geographical* azimuth	Observed* azimuth	Wind correction	Observed azimuth +wind correction	Error with wind correction: (geographical azimuth−observed azimuth) +wind correction	Error without wind correction: geographical azimuth−observed azimuth
23 July 1962	2° 44′	1° 36′	1° 03′	2° 39′	05′	1° 08′
27 July 1962	7° 02′	5° 27′	1° 23′	6° 50′	12′	1° 35′

* From true north.

TABLE 2. Meteorological data—27 July 1962.

Altitude (1000 ft)	Temperature (degrees centigrade) 0640–0820	0900–1030	Wind direction & speed (degrees/knots) 0640–0820	0900–1030
Sfc	23.3	26.3	150/2	200/3
5	20.8	22.0	170/4	193/4
10	11.3	11.6	227/3	209/4
15	0.3	1.7	53/11	59/6
20	−7.4	−7.8	198/2	227/3
25	−16.1	−15.5	187/4	183/11
30	−27.6	−26.1	209/8	202/11
35	−39.2	−39.1	234/11	215/11
40	−52.3	−52.8	227/4	315/2
45	−64.3	−61.1	232/10	252/15
50	−67.9	−68.7	262/16	223/16
55	−72.5	−72.7	175/4	205/4
60	−66.7	−68.3	103/18	124/12
65	−60.3	−63.1	79/25	89/24
70	−58.4	−57.2	86/27	89/27
75	−54.1	−55.2	79/34	94/29
80	−52.3	−52.2	95/36	83/33
85	−45.8	−40.5	90/32	98/29
90	−45.2	−45.2	101/32	99/30
95	−45.6	−45.4	74/41	82/41
100	−43.1	−42.7	83/53	88/51
105	−38.9	−39.1	98/53	100/45

and since $u\Delta t \ll ct$,

$$\tan\theta \simeq u/c, \qquad (7)$$

where θ is the approximate error in the azimuth of detected sound due to the motion of the medium and u is the motion of the medium which is the wind acting on the wave front during its travel along the plane of propagation; therefore, the approximate error in azimuth of a detected sound wave is a function of the wind component normal to the sound wave's propagation path through the atmosphere and of the speed of sound.

3. Data

As a part of Project Banshee, a 500-pound high-explosive charge was detonated over the White Sands Missile Range at each of the following times and altitudes:

23 July 1962, 0914 11.57″ MST at 104,499.8 ft msl
27 July 1962, 0859 57.28″ MST at 103,676.0 ft msl.

Meteorological data between the surface and 105,000 ft msl were collected by radiosonde observations during the time periods 0640–0820 and 0900–1030 hours MST on 27 July 1962; examination of these data as listed in Table 2 indicates rather constant conditions for the period covered. The data used in ray tracing and analysis of cross-wind effect were those collected between 0640 and 0820 hours MST.

Meteorological data on 23 July at 0900 hours were available only up to 55,000 ft msl, and conditions between 55,000 and 105,000 ft msl were estimated from data collected at 0630 and 1340 hours. Examination of the data listed in Table 3 indicates that the estimated data between the surface and 55,000 ft msl from the 0630 and 1340 observations are comparable to the observed data at 0900. Since atmospheric conditions appear to have changed little between 0630 and 1340 hours, the data above 55,000 ft msl for 0900 could be estimated reliably from these observations.

The sound from the explosions was detected by a microphone array located on the surface about 30 miles south of the explosion sites. The condenser-type microphones were located 1500 feet apart in a square array which permits a determination of the azimuth along which the sound wave is moving as it crosses the array. The accuracy of these azimuth determinations is a function of the accuracy with which the time of arrival of the sound wave front at the microphones can be determined. Time of wave arrival was accurate to ±0.003 second, resulting in an overall azimuth error of ±11 minutes. The observed azimuths obtained with the microphone array were less than the geographical azimuth indicating an integrated wind effect from east to west (Table 1). Inspection of the meteorological data listed in Tables 2 and 3 shows that easterly winds occurred primarily above 55,000 ft msl.

4. Results

Ray tracing computations provided information on the rays which travelled a horizontal distance nearly equal to the observed horizontal distance between the explosion site and microphone array. The wind normal to the plane of the propagating sound wave, or cross wind, was determined for 5000-ft layers between the altitude of the explosion and the earth's surface. The integrated cross wind between the surface and explosion altitude was determined by weighting the cross wind within

TABLE 3. Meteorological data—23 July 1962.

Altitude (1000 ft)	Temperature (degrees centigrade)				Wind direction & speed (degrees/knots)			
	Observed			Estimated mean from	Observed			Estimated mean from
	0630	1340	0900	0630 & 1340	0630	1340	0900	0630 & 1340
Sfc								
5	25.3	30.0	25.5	27.6	102/2	143/4	327/3	
10	14.0	15.1	14.5	14.5	250/9	265/3	263/9	
15	3.5	3.2	2.9	3.3	265/6	199/11	214/5	
20	−7.2	−6.7	−7.7	−6.9	185/9	240/12	196/7	215/9
25	−16.5	−15.8	−16.3	−16.1	206/11	220/11	196/15	213/11
30	−27.9	−27.3	−28.9	−27.6	162/12	248/14	220/10	209/10
35	−40.5	−39.4	−40.4	−40.0	183/10	259/19	232/10	234/12
40	−52.3	−51.6	−51.8	−52.0	259/8	313/13	300/9	247/10
45	−62.0	−61.9	−62.2	−62.0	285/9	125/3	325/8	276/3
50	−69.9	−70.3	−68.5	−70.1	48/18	201/14	113/13	97/4
55	−68.6	−70.6	−70.3	−69.6	124/14	72/10		102/11
60	−68.1	−67.1		−68.6	69/9	106/22		96/15
65	−60.7	−61.1		−60.9	78/23	95/11		83/17
70	−57.1	−57.6		−57.3	75/29	107/19		88/23
75	−55.5	−56.2		−55.8	91/32	79/22		85/27
80	−48.7	−50.8		−49.8	105/26	66/28		84/26
85	−48.0	−49.5		−48.7	73/21	82/37		78/29
90	−47.3	−45.0		−46.1	66/21	94/33		83/26
95	−47.2	−42.0		−44.6	70/39	99/34		83/35
100	−43.0	−40.2		−41.6	83/49	103/36		91/42
105	−39.7	−37.0		−38.3		91/32		91/32

each 5000-ft layer by the sound wave's travel time through that layer.

The error in the observed azimuth due to the cross-wind effect was computed from

$$\tan^{-1}\theta = ut(6080.20)/(3600)(d),$$

where θ= difference between geographical and observed azimuth (Table 1), u= total weighted normal wind, knots, t= travel time between source and detector, seconds, d= horizontal projection of geographical distance between source and detector, feet.

The results as listed in Table 1 show that a correction for the cross-wind effect on propagating sound is required to obtain accurate determinations of the azimuth of the origin of detected sounds.

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