A comparison of infrasound signals refracted from stratospheric and thermospheric altitudes

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[1] Over the last several years, a large number of ground-based infrasound arrays have been established for explosion monitoring as part of the International Monitoring System of the Comprehensive Nuclear Test Ban Treaty Organization. Results from these arrays have become valuable in understanding long-range infrasound propagation in the atmosphere and complement earlier data. Two types of signals are often observed for a given source: those refracted at stratospheric heights and at thermospheric heights. In this contribution we compare several characteristics of these two signal types including observed pressure amplitude, average travel velocity, bearing, and signal duration. For this study we use archival data from atmospheric nuclear explosions, high explosive chemical explosions on the surface, earthquakes with previously detected stratospheric signals, and earthquakes for which stratospheric signals were not detected. We show that the combination of stratospheric and thermospheric signals may provide independent estimates of wind propagation conditions and source characteristics. The observations of both signal types may increase the confidence level of an infrasound signal detection.


1. Introduction

[2] Infrasonic signal detection and interpretation is a significant field of research providing information on source identification and characteristics. Sources of infrasound include earthquakes, explosions, bolides, avalanches, weather disturbances and others. Currently the International Monitoring System of the Comprehensive Nuclear Test Ban Treaty Organization operates about 40 infrasound arrays globally as part of an eventual 60 station network. Others arrays are operated by various organizations for specific research purposes. Such arrays, of low-frequency microphones, detect the small pressure amplitude signals from distant sources and standard array processing tools provide data on source direction (bearing or back azimuth), frequency content, trace velocity, and correlation among others.

[3] Infrasonic signals are acoustic waves propagated through the atmosphere and can be detected at long ranges from the source. The temperature structure and atmospheric winds determine the propagation of the infrasonic signals and the refraction heights from which energy is turned. Two of the most common types of returns are from the stratosphere, near 50 km altitude and referred to here as S signals, and from the thermosphere, around 110 km altitude and referred to here as T signals. Figure 1a illustrates these two paths in an acoustic ray trace model.

\[ A_{T or S} = A_{T or S} \times (W/500)^{0.456} \]  

where \( A_T \) and \( A_S \) are the yield scaled amplitudes, and \( W \) is the event yield in kilotons. A kiloton of nuclear yield is equivalent to 4.18 \( \times 10^{12} \) joules of energy. The scaling law is taken from Mutschlecner et al. [1999] (hereinafter referred to as MWA). \( A_{T or S} \) and other amplitudes discussed throughout are peak-to-peak pressures in \( \mu \)bars. The source of these data is described in section 2.

[4] In order to identify and interpret infrasound signals it is necessary to differentiate between S and T signals by understanding their characteristics. This paper provides an effort to define and to compare those characteristics. As this work shows, atmospheric winds produce a very strong influence on the S signal amplitudes while the T signals are relatively independent of the wind structure. This allows for a potential determination of a stratospheric wind parameter by use of S and T signal amplitudes.

[5] Figure 2 presents an example of an important difference between the S and T signals. Figure 2 shows infrasonic pressure amplitudes from Nevada Test Site (NTS) atmospheric nuclear explosions observed at Bishop, CA, at approximately one infrasonic bounce distance nearly directly to the west. The observed thermospheric and stratospheric amplitudes, \( A_T \) and \( A_S \) respectively, have been normalized to a nuclear yield of 1 kiloton HE equivalent by the use of
Figure 1. (a) A sample acoustic ray trace is shown. The rays illustrate the return of infrasound from the stratospheric region at about 50 km and from the thermospheric region at about 110 km. (b) An example of the sound velocity versus altitude in the atmosphere (no wind) is shown.

Figure 2. Log of S (diamonds) and T (dots) signal amplitudes versus day of year for nuclear explosions observed at Bishop, CA. Both amplitudes are normalized to 1 kT; the T log amplitudes have been shifted down by two units to provide separation of the two sets of points. While the S signal values show a clear seasonal variation the T signals values appear to have no seasonal changes.
2. Nuclear Explosion Signals

2.1. Data Set Used

[11] The NTS nuclear explosion infrasound data used here were reported by Reed [1969]. This data set covers observations for the period 1951 to 1958 and is one of the best sets available for completeness and consistency. The yields range from 0.6 to 74 kilotons. Signals were observed with single microphones at 12 stations. The analog recording system had a frequency range of 0.05 to 30 Hz, and the reported amplitudes are peak-to-peak. Only the data from the stations at St. George, UT; Bishop, CA; and China Lake (Inyokern), CA were used, all of which are at about one-bounce locations. Reed reports both S and T signals, which he refers to respectively as ozonospheric and ionospheric signals. MWA have provided a detailed review of these data with an emphasis on the seasonal variations and normalization for the effect of wind on the S signals.

2.2. Travel Velocity

[12] Figure 3a shows the T signal velocity, \( V_T \), for the stations at St. George, Bishop and China Lake. \( V_T \) is the great circle distance from source to receiver divided by the signal transit time. The averages are: St. George, 228 m/s; Bishop, 218 m/s; and China Lake, 209 m/s. There is reasonable consistency, especially for the east and west stations. The values of \( V_T \) cover a fairly large range from about 200 to 260 m/s; there is no indication of seasonal variation. By comparison S signal average velocities, \( V_S \), were shown (MWA) to have a seasonal variation at all stations which appears to be related to the stratospheric wind. An average value for the S signals is 294 m/s. Figure 3b shows spline fits for the S signal velocities for the three stations. Seasonal variations can be seen that are as large as about 14\% in the fits. The variations are azimuthally dependent, and their amplitudes are maximum to the east or west of the source and minimum to the north or south of the source. It is important to note that these results are for stations at approximately one bounce distance from the source.

[13] Under a simplifying assumption that the S and T average velocities primarily reflect the propagation path distances we can predict the velocity ratio, \( V_S/V_T \), by the reciprocal of the path lengths for a single bounce signal. This is roughly 330 km/270 km or 1.22. For comparison the average S/T velocity ratio is about 294 m/s/220 m/s or 1.34. This suggests that a substantial part of the S and T velocity differences are produced by the path differences.

2.3. Frequency of Detection

[14] The percentage of events with T signals is only 40\% for St. George, 57\% for Bishop and 67\% for China Lake. By contrast, S signals were detected on average for 95\% of the events. At St. George there were five T signals observed with no corresponding S signals or 5\%. All of those were during the “summer” or counter-wind period for the station when the S signals have a greatly reduced amplitude. For Bishop three T signals, or 5\%, had no corresponding S signals. These occurred during the counterwind or “winter” period for Bishop. At China Lake only one T signal had no accompanying S signal.

2.4. Amplitudes

[15] In order to compare the amplitudes of the S and T signals it is necessary to normalize the S amplitudes, \( A_S \), for the seasonal effects of stratospheric wind. The normalized values, \( A_{Sn} \), are given by

\[
A_{Sn} = A_S 10^{-kV_d}
\]

where \( k \) is an empirical constant, 0.018 s/m, and \( V_d \) is the component of the Stratospheric Circulation Index (SCI) wind directed from source to receiver. The SCI, as defined by Webb [1966], is an average of the stratospheric wind speed between the altitudes of 45 and 55 km. In principal, other definitions for the stratospheric wind could be employed. A discussion of this normalization and the empirical wind model employed is given in MWA. Thus \( A_{Sn} \) represents what S signal amplitudes would be with a wind
Figure 3. (a) The thermospheric travel velocities, $V_T$, are shown versus day of year for the nuclear explosion T signals at St. George, UT, (squares); Bishop, CA, (diamonds); and China Lake, CA, (triangles). (b) Spline fits to the stratospheric travel velocities for the same three stations are shown versus day of year.

Figure 4. The ratios of wind-normalized S signal amplitudes to T signal amplitudes, $R(A)$, are shown versus day of year for the St. George, UT (squares), and Bishop, CA (diamonds), nuclear data.
velocity of zero. For each event with both S and T signals an amplitude ratio, $R(A)$, is given by

$$R(A) = \frac{A_S}{A_T}.$$ \hspace{1cm} (3)

We have found the yield scaling relations for amplitude are approximately the same for both S and T signals, within the uncertainty of the determinations. Thus in equation (3) the ratio for the amplitudes does not require $W$ scaling. Figure 4 shows an example of the result for the Bishop and St. George stations. The average value of $R(A)$ for Bishop is 4.7. That is, the “wind-free” S signals are on average considerably larger than the T signals, however, the scatter is large. The average $R(A)$ value for St George is 3.3 and for China Lake 7.4. The values determined for the nuclear and other data sets are summarized in Table 1.

![Table 1](image)

**Table 1. T Signal Statistics**

<table>
<thead>
<tr>
<th>Nuc SG</th>
<th>Nuc BI</th>
<th>Nuc CL</th>
<th>HE</th>
<th>EQ</th>
<th>EQ ND</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of events</td>
<td>75</td>
<td>60</td>
<td>48</td>
<td>24</td>
<td>27</td>
</tr>
<tr>
<td>Average distance, km</td>
<td>217</td>
<td>211</td>
<td>212</td>
<td>580</td>
<td>1089</td>
</tr>
<tr>
<td>$W$, kt (J = joules)</td>
<td>0.6–74</td>
<td>0.6–74</td>
<td>0.6–74</td>
<td>0.02–4.88</td>
<td>(2.5 E12 J to 3.1 E14 J)</td>
</tr>
<tr>
<td>$M_L$</td>
<td>Average $V_S$, m/s</td>
<td>294 ± 2</td>
<td>288 ± 1</td>
<td>286 ± 2</td>
<td>293 ± 1</td>
</tr>
<tr>
<td></td>
<td>Average $V_T$, m/s</td>
<td>228 ± 3</td>
<td>218 ± 3</td>
<td>209 ± 3</td>
<td>228 ± 4</td>
</tr>
<tr>
<td></td>
<td>Average Az deviation, deg</td>
<td>40</td>
<td>57</td>
<td>67</td>
<td>5.4 ± 1.1</td>
</tr>
<tr>
<td></td>
<td>T detection, %</td>
<td>3.3 ± 0.4</td>
<td>4.7 ± 0.6</td>
<td>7.4 ± 0.9</td>
<td>2.2 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>Average $R(A)$</td>
<td>3.7 ± 0.4</td>
<td>0.4 ± 0.06</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Average duration, s</td>
<td>61 ± 12</td>
<td>58 ± 7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^a$N(SG), N(BI) and N(CL) are the nuclear events detected by Reed at St. George, UT; Bishop, CA; and China Lake, CA. HE is for the large surface conventional test data, EQ stands for the earthquake data set and EQ ND is for set of nondetections of earthquakes. $W$ for nuclear data is in kt of energy with equivalent values in Joules; $W$ for the HE data is in kt of mass with the kg equivalents shown.

$^b$The HE data comprise eight events with a total of 24 independent observations.

2.5. Signal Durations

[16] Because the original signal traces are not currently available, the signal durations cannot be given. However, one of the observers of the nuclear data, J. W. Reed (private communication, 2006) has indicated that the T signals were (1) rather sharp features, (2) generally of lower amplitude than the S signals and (3) typically consisted of only one oscillation compared to multiple oscillations of the S signals. Because the observations were made from stations with single microphones, no azimuth information could be determined.

3. High Explosive Data

3.1. Data Source

[19] A number of high explosive tests have been monitored for infrasound signals by Los Alamos National
Laboratory. The tests were conducted at the White Sands Missile Range in New Mexico by the Defense Nuclear Agency (now the Defense Threat Reduction Agency). The test explosives were on the surface except for one at a small elevation and varied in size from 24 tons to 4880 tons of ammonium nitrate and fuel oil. A mass of one ton (2000 pounds) is equivalent to 907.185 kg. Observations were carried out at both fixed and specially deployed temporary infrasound arrays. The arrays typically consisted of four Chaparral II microphones with passbands of 0.1 to 10Hz. Array apertures were nominally 100m. Unlike the nuclear explosion data, these include a wide range of distances from 250 to 5300 km. A portion of these data were discussed previously by Davidson and Whitaker [1992], Whitaker et al. [1990], and Whitaker et al. [1994]. A set of 24 measurements, all of which had well-defined S signals, was investigated for T signals. The events are listed in Table 2.

3.2. Travel Velocities
[20] The average T signal velocity was 228 m/s in substantial agreement with those for the nuclear explosion data. Figure 6 shows the observed T signal velocities.

3.3. Frequency of Detection
[21] Potential T signals were ranked for quality as follows: Q = 0, no detection; 1, weak to very weak possible; 2, possible; and 3, probable detection. Six observations were of quality 3 and four of quality 2. Thus the percentage of detections of quality 2 and 3 together was 42%. Fourteen of the events had T signals of quality 1 or no detection. The weighted detection probability for all of the data was 45%. All of the T signal detections had corresponding S signals.

3.4. Signal Amplitudes
[22] For five of the detections amplitudes $A_S$ and $A_T$ were available and these provided values of the ratio $R(A)$ as defined by equations (2) and (3). For all detection cases values of signal power were available for the S and T signals. The powers, $P_S$ and $P_T$, for the S and T signals respectively are averages of the squares of the corresponding amplitudes averaged over a sampling window (typically 20 s). From these ratios, $R(P)$, were calculated by

$$R(P) = (P_S/P_T)^{0.5} 10^{-4Vd}$$

in which the square root results from a conversion from a power ratio to a proxy amplitude ratio. Observational values for the stratospheric winds were used rather than a model. Figure 7 presents $R(P)$ for the HE signals. The quality-weighted averages of $R(A)$ and $R(P)$ are 2.2 and 3.7 respectively but the variations are substantial.

[23] Figure 8 compares the relations of the amplitudes to yield-scaled range, $D_0$, for the S and T signals. Only the T signals of quality 2 to 3 are used. Yield-scaled range is a conventional variable for scaling pressure data from explosions and is defined by

$$D' = D/(2W/1000)^{0.5}$$

where $W$ is in tons of HE and $D$, the range, in km. The least squares fit for the S signals is

$$\log(A_{S0}) = 4.61(.23) - 1.34(.09) \log(D')$$

while that for the T signals is

$$\log(A_{T3}) = 3.43(.35) - 0.97(.15) \log(D').$$

The set for the T signals is limited in size, but within the uncertainties of the determinations, the slopes of the relations are similar. The relation in equation (8) differs

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Table 2. DNA Sponsored Explosive Tests

<table>
<thead>
<tr>
<th>Event</th>
<th>Date, DOY</th>
<th>Weight (tons) (Values in kg)</th>
<th>Array Sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mill Race</td>
<td>16 Sep 1981, 259</td>
<td>600 (5.44E5 kg)</td>
<td>1</td>
</tr>
<tr>
<td>Predirect Course</td>
<td>7 Oct 1982, 280</td>
<td>24 (2.18E4 kg)</td>
<td>2</td>
</tr>
<tr>
<td>Direct Course</td>
<td>26 Oct 1983, 299</td>
<td>600 (5.44E5 kg)</td>
<td>4</td>
</tr>
<tr>
<td>Minor Scale</td>
<td>27 Jun 1985, 178</td>
<td>4800 (4.43E6 kg)</td>
<td>2</td>
</tr>
<tr>
<td>Misty Picture</td>
<td>15 May 1987, 134</td>
<td>4880 (4.43E6 kg)</td>
<td>5</td>
</tr>
<tr>
<td>Misier’s Gold</td>
<td>1 Jun 1989, 152</td>
<td>2400 (2.22E6 kg)</td>
<td>8</td>
</tr>
<tr>
<td>Distant Image</td>
<td>20 Jun 1991, 171</td>
<td>2400 (2.22E6 kg)</td>
<td>2</td>
</tr>
<tr>
<td>Minor Uncle</td>
<td>10 Jun 1993, 161</td>
<td>2400 (2.22E6 kg)</td>
<td>3</td>
</tr>
</tbody>
</table>

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Figure 6. For the HE data set the values of $V_T$ are shown versus day of year.

Figure 7. For the HE data set the values of $R(P)$ are shown versus day of year.
only slightly from that given by Whitaker [1995] and should be considered the improved version, resulting from some additional data and the correction of one error.

3.5. Signal Durations

[24] A significant problem in identifying T signals lies in the duration of the signal train, or coda, of the preceding S signal. The predicted time of the T signal arrival may be in the S signal train with consequent difficulty of T signal identification. In addition, the T signals apparently are of much shorter duration than S signals. While the durations of the S signals average about 7.9 min those for T signals average only 1.0 min. Figure 9a illustrates the durations for the S signals and 9b for the T signals.

[25] Figure 10 gives examples of amplitude waveforms for four T signals. The signals are not only of short duration but often seem to be of an impulsive nature unlike the character of most S signals which have multiple-peak, somewhat sinusoidal, characters.

3.6. Signal Azimuths

[26] The average absolute value of the observed minus predicted azimuth difference for the T signals is $5.4 \pm 1.1^\circ$ where the predicted azimuth is that along the great circle path from the observer to the event. For S signals the average absolute value for the differences is $6.0 \pm 1.1^\circ$. The closeness of the two values helps to assure that the T signals were not found erroneously by allowing a wide departure from the predicted azimuths. The azimuth departures for the S and T signals for individual events are in generally good agreement, however a small number have significant differences. Table 1 provides a summary of the characteristics of the HE T signals. A discussion of sources of azimuth deviations is given in the Conclusions section. An early study on refraction effects due to upper atmospheric winds on travel speeds and azimuth can be found in Georges and Beasley [1977]. More recently Garces et al.

4. Earthquake Data

4.1. Data Source

A set of 24 earthquakes with well-determined S signals was selected from a larger set previously investigated by Mutschlecner and Whitaker [2005]. The selection was based primarily upon earthquakes for which the predicted arrival time for possible T signals was larger than that of the ending times of the observed S coda. This was done to avoid, as much as possible, the difficulty of clearly separating a T signal from the preceding S signal.

The earthquakes were observed by infrasound arrays at Los Alamos, NM and at St. George, UT over the period of 1985 to 2002. The range of seismic $M_L$ magnitudes is from 4.4 to 7.9 and the distances from about 400 to 4000 km. Thus a substantial variation in event circumstances is included. As with the HE data set, a subjective quality estimate, $Q$, was given to each case ranging from 0 (no T signal detection) to 3 (highly probable detection). Table 1 summarizes the results.

4.2. Travel Velocity

The $Q$-weighted travel velocity is 243 m/s. Thus the T signal velocities of this and the earlier two data sets are in reasonable accord. Figure 11a shows the values of $V_T$ versus date.

4.3. Frequency of Detection

The T signals rated with quality of 2 to 3 were seen in 37% of the data while no T detections occurred for 21% of the data. These values are comparable with those found for the HE data but less than those for some of the nuclear explosion data. All of the T signals had corresponding S signals; however, two had very weak or dubious S signals.

Figure 10. Examples of waveforms are given for four HE event T signals. Abscissa ticks are at second intervals and ordinates are signal voltage. The events are (a) Misty Picture, (b and c) Misers Gold, and (d) Distant Image. (e) For comparison a waveform is also shown for an S signal from Misty Picture. The long S signal train is contrasted with the rather short T signal in Figure 10a.
4.4. Amplitudes

[31] Ratios of the S to T signal amplitudes were calculated by equations (2), (3) and (6). \( R(A) \) was calculated for three of the events and \( R(P) \) for all. The values of \( R(A) \) and \( R(P) \) were in good agreement for these three events.

Figure 11b shows \( R(P) \) versus day number. There is a large variance in the values. Two "summer" or counter wind events, not shown, have very different values than the others. The average value for the "winter" or downwind events is 0.40, which is substantially different from the ratios found for the preceding data sets. While a normalized amplitude-magnitude relation was found for S signals by Mutschlecner and Whitaker [2005], a similar relation cannot be established for the T signals because of the comparative sparseness of the T signal data and a limited range of seismic magnitude. However, such a relation for T signals cannot be excluded by this data.

4.5. Durations

[32] As with the HE data, earthquake T signals' durations are short averaging only 58 s. The complete S signal data set durations were considerably longer with a mean of 18.5 min. Mutschlecner and Whitaker [2005] discussed the S signal durations showing that they are correlated with seismic magnitude. This correlation may be explained with a model involving the extent of the source region for the signal. For the relatively sparse T signal data no correlation of duration with seismic magnitude is seen.

[33] Le Pichon et al. [2006] present amplitude and duration data as a function of seismic magnitude (\( M_L \)) for a set of larger magnitude events. These data show satisfying agreement with the data presented by Mutschlecner and Whitaker [2005] and the combined data cover a magnitude range from four to nearly nine in \( M_L \).

4.6. Azimuths

[34] The mean of the absolute deviations, from predicted values, of the T signal azimuths is 3.6 ± 0.5°. For the complete set of S signals the mean of the absolute values was 2.5 ± 0.3°. There is generally good agreement between the T and S signal deviations for the events, except for a small number of instances. The azimuths discussed here are for peak signal power and/or signal correlation. Azimuths may be observed to deviate from the epicenter direction as seismoacoustic coupling processes occur at distances from the epicenter.

5. Earthquakes Without S Signals

[35] A substantial set of earthquakes was investigated by Mutschlecner and Whitaker [2005] and found to have no S signals. In general, the explanation for the absence of the signals was that the predicted signal-to-noise values were too small for expected detection. A subset of 12 of these earthquakes was examined for the presence of T signals. These had a seismic magnitude range from 3.3 to 4.6. This search was to investigate the possibility that the T signal strengths might be substantially greater than those for the S signals and hence detectable.

[36] In this subset it was found that one event had a weak possible T signal (\( Q = 1.5 \)) and a second earthquake was a very weak possible detection (\( Q = 0.5 \)). Hence there is no evidence for good T signal detections in this subset of earthquakes.

6. Discussion

6.1. Data Set Comparisons

[37] The three data sets, which have definite T signals, provide useful information for intercomparison. Two types of explosion sources are included, nuclear and HE, that are generally considered to be "point" sources, and the third source, earthquakes, are extended surface sources. The distance coverage ranges from first bounce at about 200 km to 4000 km with reasonable overlap. The seasonal coverage has some overlap as well with nearly full year coverage for the nuclear and earthquakes and about 70 d of coverage in the spring-summer for the HEs.

[38] The travel velocities of the T signals are reasonably consistent among the data sets: the nuclear signals average about 220 m/s, the HEs 228 m/s and the earthquakes 243 m/s. The overall range of values is from about 190 to 260 m/s. Modeling results by Gibson and Drob [2005] gave T velocities ranging from about 195 m/s during westward propagation to 220 m/s during eastward propagation at distances from about 400 to 460 km. Their results also...
show small seasonal variations and an absence of signals during portions of the year.

[39] The average absolute values of the azimuth deviations are $6.0 \pm 1.0^\circ$ for the HE and $3.6 \pm 0.5^\circ$ for the earthquakes. The T signal durations average 1.0 min for the HE set and a similar 0.97 min for the earthquakes. Indirect evidence also suggests that the nuclear T signals are very short.

[40] A search for significant correlations was made for the values of $V_T$ and azimuth deviations with day number, azimuth and, for earthquakes, $M_L$. No correlations were found.

[41] There are two caveats for the results of this study. First, for the HE and earthquake data the typical frequency band pass was 0.5 to 3.0 Hz. It is possible that T signal characteristics change in other frequency regions. Christie et al. [2005] point out that the propagation of some signals, especially to long distance, is highly dependant upon the band pass used; lower frequencies appear to favor such signals. However, for the nuclear events in this study, the frequency range was large (0.05 to 30 Hz). Second, for the HE and earthquake signals the amplitudes were typically from a fraction of a $\mu$bar to a few $\mu$bars. In contrast, the nuclear signals ranged from a few $\mu$bars up to about 170 $\mu$bars. Application of the results to T signal prediction should take these ranges into account.

6.2. T Signal Detection and Amplitudes

[42] The detection of T signals ranges from about 53% for nuclear events to 37% for earthquakes. These low rates probably are produced chiefly by the generally lower amplitudes and shorter durations for T signals compared to the S signals. Also the nuclear rate is larger because of the much larger amplitudes, the closer distances for these events and possibly because of the larger band pass.

[43] The values of $R(A)$ or $R(P)$ are quite variable for all three event types. This may result primarily from propagation effects. As shown previously for nuclear events, T signals amplitudes are very sensitive to location, at least, near the first-bounce location, but probably at larger distances as well.

[44] The average value of $R(A)$ for the St. George and Bishop nuclear events is 3.9; the China Lake data is anomalously higher at 7.4; the latter is possibly an azimuth effect. The HE data have an average $R(P)$ of 3.7 which is reasonably consistent with the nuclear data. By contrast, the earthquake data have an average value of only 0.4 (excluding two “summer” events). Thus the earthquake data have lower values of S amplitudes and/or higher T amplitudes by nearly a decade compared to the nuclear and HE data. It is possible that this large difference in the values of $R$ could be used ultimately as a rough discriminate of source type for instances in which the source of an infrasound signal is unknown.

[45] Possible additional discriminants between S and T signals are the frequency of maximum energy and the trace velocity, and these were examined for the HE and earthquake data. In these data the T signals did have a slightly lower frequency of maximum energy than the S signals; however, the passband used does not allow us to quantify the effect. The values for the average trace velocity for the HE data were 354 m/s and 410 m/s for the S and T signals respectively. For the earthquakes the values were 350 m/s and 400 m/s for the S and T signals respectively. Trace velocity may provide a rough diagnostic of the two signal types.

6.3. Source Mechanisms

[46] A probable explanation for the difference in the values of $R$ between the earthquakes and the nuclear and HE events lies in the nature of the source mechanisms. The nuclear and HE events have roughly hemispherical shock fronts originating the infrasound. For these it can be expected that the radial pressure components directed toward the S and T signal return regions at different elevation angles above the horizontal will be approximately equal. In comparison, the earthquake source region consists of a portion of the earth’s surface in rapid acceleration with both vertical and horizontal components. Such a source will have a much more complex radiation pattern and will likely have, in cross section, a lobe-like structure. Ray trace modeling suggests that S signals result from radiation coming from an elevation angle ranging from about 0 to 30$^\circ$ above the surface while T signals arise from about 30 to 60$^\circ$. These differences combined with a complex radiation pattern likely produce the effects seen here.

6.4. Stratospheric Wind Determination

[47] Determination of S and T amplitudes for an event permits, in principal, a determination of a stratospheric wind component. Combining equations (2) and (3) results in

$$V_d = \log[A_2/(A_T R(A))] / k. \quad (10)$$

For the Bishop nuclear data the azimuth is such that the zonal component of the SCL, $V_Z$, is nearly equivalent to the values of $-V_d$. Thus equation (10) can be used together with standard values adopted for $R(A)$ and $k$ to estimate $V_Z$. Figure 12 compares the values determined by equation (10) with those of the empirical model wind, from MWA, and shows that the general character of $V_Z$ is captured. The departures from the model are greatest near the end of the year when observed values are known to be extremely variable. The RMS departure from the model is about 16 m/s (excluding the few end-of-year values). This value is nearly identical to the average RMS spread of rocketsonde observation variations, 16.7 m/s, derived from White Sands Missile Range data in McCullough and Novlan [1977]. Thus the departures seen in Figure 12 may be primarily real observational variations from the model.

[48] Other methods for infrasonic stratospheric wind determinations have been suggested. Rind et al. [1973] suggested using microbarom signal trace velocities to determine the effective stratospheric wind velocity and Donn and Rind [1979] applied the concept to signals from the Concorde aircraft. Balachandran et al. [1977] indicated that the frequency of the Concorde signal could provide information on the atmospheric height from which the signal arose. Thus the combination of the two methods could provide wind velocity at a given height. Another method for wind determination has been used by Le Pichon et al. [2005a] and by Le Pichon et al. [2005b]. This concept uses the azimuthal variations of infrasound signals from volcanoes for corrections to a wind model.
The values of the zonal SCI wind components, $V_d$, derived from the S and T signal amplitudes of nuclear explosions observed at Bishop, CA, using equation (9) are displayed (squares) versus day of year. For comparison the values of $V_z$ from a wind model are shown (line).

[50] The differing arrival times for the S and T signals from an event can be used to give an estimate of the source-to-receiver distance. The method is analogous to that used to estimate distances from seismic signals with two clear phases. The estimated distance, $R_E$, is determined from

$$ R_E = \Delta t \left( \frac{1}{(V_T)} - \frac{1}{(V_S)} \right)^{-1} $$

where $\Delta t$ is the difference in arrival times of the T and S signals and $\langle V_T \rangle$ and $\langle V_S \rangle$ are adopted average or standard values for the T and S signal travel velocities respectively.

[51] As a test the method was used to obtain distances estimates for the data sets of this report with 0.29 km/s for $\langle V_S \rangle$ and 0.23 km/s for $\langle V_T \rangle$. The average of the absolute values of the errors in the distance range from about 30 to 50 percent. The causes for the poor distance estimates are the large variance in $V_T$ from the adopted average and a seasonal variation of $V_S$, which is not accounted for here. The use of values for $\langle V_T \rangle$ appropriate to each data set separately reduces some average absolute errors to about 20%. Thus in its present usage the method can provide only rough estimates for distances unlike the seismic use. Such estimates still may be useful in instances where triangulation on a source is not possible and there is ambiguity of possible source location. Ultimately the accuracy could be greatly improved by the use of near real-time atmospheric data combined with modeling methods to give better estimates of the travel velocities.

7. Conclusions

[52] Errors in the observations have been estimated in an effort to understand the observed spreads in the analyzed quantities $V_S$, $V_T$, $R$ and azimuth error, $\Delta \theta$. The underlying uncertainties for $V_S$ and $V_T$ are (1) the receiver-to-source distance which is estimated at 0.5 to 5.0 km depending upon source type and (2) the signal timing uncertainty which is estimated at 10 s or less. All values given are for one standard deviation. The resulting predicted spread in $V_S$ and $V_T$ is about 1%. The observed spreads in average travel velocities are generally four to ten times this prediction. Thus most of the observed spreads in the values are not caused by observational error but are probably real atmospheric effects.

[53] The underlying errors in calculating R through equations (3) or (6) are (1) uncertainty in the observed amplitudes $A_k$ and $A_T$ that is estimated to be about 10% and (2) uncertainty in the values of $k$ and $V_d$ for calculating $A_{Sn}$ from equation (2). It is estimated that $k$ has uncertainty of about 11% and $V_d$ of between 5 and 15 m/s. The uncertainty in $V_d$ is the primary source of spread in the values of $R$ and is dependant on season and azimuth to source. The resulting predicted variance in $R$ is between 25 and 60%; however, the observed variances are considerably larger than this prediction. Hence, again, the observed ranges in $R$ are largely real variation and not due to observational error. The exception to this is for the nuclear explosion data for which the observed spread is close to that predicted.

[54] An estimated maximum azimuth uncertainty is given by the slowness-azimuth grid used in the signal analysis and is about 4.5°. The observed values of the average absolute azimuth error for the S and T signals for the earthquake data are 2.4° and 3.5° respectively. For the HE data the observed values are 6.1° and 5.4° for S and T signals respectively. Hence, a substantial part of the azimuth variances are explained by the analysis process.

[55] In this contribution we have examined stratospheric and thermospheric return infrasound signals from four data sets. The primary results follow.

[56] 1. The amplitudes of S signals vary annually whereas T signals show no apparent annual variation. This is consistent with the predicted effects of the refraction layers and atmospheric winds for the two types of signals. As a result, during part of the year S signals may be considerably larger than T signals. However, T signals can be comparable during a portion of the year and a search for T signals may be more useful during these times.

[57] Because of this variation of S signals and relative constancy of T signals it is possible to use their amplitude ratios to examine wind structure. In particular, the SCI or a similar parameter can be determined.

[58] 2. The average travel velocity of S signals is about 290 m/s. In contrast the velocity for T signals ranges from about 210 to 240 m/s. The path differences for the two types
of signals appear to contribute about 90% of this observed velocity difference.

[69] 3. The T signal average absolute azimuth deviations from predicted values range from 3.6 ± 0.5° for the earthquakes to 5.4 ± 1.1° for the HE observations. While these two values are in accord within their uncertainty ranges, the somewhat lower values for earthquakes may be a result of an unknown source effect.

[60] It is useful to compare the values here with data from three series of U.S. atmospheric nuclear tests. The data were obtained at arrays operated by various U.S. Agencies at distances from about several hundred km to several thousand km. These are Buster-Jangle in 1951, Olmstead [1951]; Ivy in 1952, Olmstead [1953]; and Upshot-Knothole in 1953, Olmstead and Nowak [1954]. The S signal average values were 3.2, 4.9, and 3.3° respectively. Thus values found in the present study are comparable.

[61] Le Pichon et al. [2005b] report azimuth deviations ranging up to about 15° for infrasound observations of volcanic eruptions. However, they point out that these can be explained by the effects of stratospheric and lower thermospheric winds and can, in effect, be used to correct wind models.

[62] 4. T signals are typically of much shorter duration than S signals. For the HE events the ratio of S to T signal durations is about 8 while for earthquakes the ratio is even greater in general but is highly dependent upon the effects of source region extension by seismic effects. T signals also appear to have a more impulsive character than do the S signals. These characteristics together with the average travel velocities can help to differentiate between S and T signals.

[63] 5. The ratio of the S signal amplitude normalized for wind effects to T signal amplitude is about 3 to 7 for the nuclear events and about 2 to 4 for the HE events. In contrast, the earthquake data have an average value of about 0.4 but with a wide variance. This difference between the data sets may be attributable to source radiation characteristics.

[64] Sutherland and Bass [2004] have provided tables for the absorption of sound in the atmosphere up to 160 km. Their tables can provide a prediction of the effects of absorption on the S and T signals of this study from about one to two Hz. The prediction suggests that a substantial part of the determination of the amplitude ratio, R, may be produced by the relative absorption between S and T signals. However, a more complete understanding will require consideration of propagation effects together with absorption.

[65] 6. The detection rates for T signals found here are substantially lower than for S signals and range from about 37% for earthquakes to over 40% for HE and nuclear sources. In contrast, S signal detection rates are typically over 90%. This condition probably results primarily from the generally lower amplitudes and shorter durations of the T signals.

[66] This work has suggested some important aspects of T signals including their comparative strengths with S signals. In particular, the difference between the explosive sources and earthquakes indicates a strong source-sensitive nature. An effort to better model the source physics and the propagation of both S and T signals is desirable and would help to quantify the nature of the source effects suggested here. The very short durations observed for the T signals also are a subject for propagation modeling. In future efforts an examination of the effects of the frequency band pass on T and S signals is needed.

[67] As usual with most studies, it will be of interest to exploit other large databases in future efforts on S and T signal studies. The work indicates that it should be useful to search for and measure T signal characteristics in addition to the usual S signals in any observational infrasound research.

[68] Some of the reports cited in this work are not easily available; however, the authors can provide copies to the interested reader.

References


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