REVISING YIELD, DIRECTION, AND SIGNAL TYPE

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ABSTRACT

Herein we present a review of three topics regarding infrasound signal analysis. For atmospheric nuclear explosions we review empirical yield estimates and bearing estimates for events at the Nevada Test Site. The events discussed have announced yields. Data were recorded by infrasound array stations operated by the United States during atmospheric testing.

In the third area we compare several characteristics of observed infrasound signals returned from stratospheric heights and thermospheric heights. The data come from four source types: atmospheric nuclear explosions, high explosive (HE) chemical explosions on the surface, earthquakes with previously detected stratospheric signals, and earthquakes for which stratospheric signals were not detected. The signal characteristics compared include: amplitude, travel velocity, azimuth and duration. In addition rough estimates of thermospheric-signal frequency of detection are presented.
OBJECTIVES

We present information about characteristics of infrasound signals from nuclear and conventional explosions and from moderate earthquakes. A comparison of stratospheric signals and thermospheric signals for three infrasound data sets is made that highlights some interesting relations. Finally we show some period-yield data for a set of atmospheric nuclear tests.

RESEARCH ACCOMPLISHED

Comparison of Some Characteristics for Stratospheric and Thermospheric Infrasound Signals

As more infrasound signals are reported, the opportunity for comparison of different signal types becomes obvious. Two types of interest are the signals that represent energy returning from the stratosphere and from the thermosphere, S and T signals respectively. Generally these two will exhibit different travel velocities as is well known. Other characteristics of the received signals would be of interest as well, such as azimuth deviation, duration and detection frequency. Here we will summarize results from a comparison S and T signals from three data sets, (Mutschlecner and Whitaker, 2006). These comparisons are of interest for purposes of identifying observed signals and for use in propagation studies. As researchers add to the observed signal database, such comparisons can be extended to additional sources and observations. Mutschlecner and Whitaker, 2006, then is a first step in this area. Future work may change some of the results we present, as would be expected for a field of active research.

For this investigation three data sets have been employed: (1) atmospheric nuclear explosions, (2) HE chemical explosions on the surface, (3) earthquakes with previously detected S signals.

Atmospheric Nuclear Explosions

The Nevada Test Site (NTS) nuclear explosion data used here were reported in 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. 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. Mutschlecner et al., 1999, (hereafter 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. The seasonal effect on amplitude is shown in Figure 1 for data at Bishop.

The average travel velocities for the T arrivals are: St. George, 228 m/s; Bishop, 218 m/s; and China Lake, 209 m/s. There is reasonable consistency, especially to the east and west. The values of 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 were shown (MWA) to have an average value of 294 m/s.

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 at 95%. 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 greatly reduced amplitudes. For Bishop three T signals had no corresponding S signals or 5 %. These occurred during the counterwind or "winter" period for Bishop. At China Lake only one T signal had no accompanying S signal. For Bishop three T signals had no corresponding S signals or 5 %. These occurred during the counterwind or "winter" period for Bishop. At China Lake only one T signal had no accompanying S signal.

We compare S and T amplitudes (reported in the Reed report) by normalizing the S signal amplitudes for the stratospheric wind as discussed in MWA using the Stratospheric Circulation Index from Webb (1966), then taking the ratio of normalized S amplitude to T amplitude, \( A_S/A_T \). Figure 2 shows the results for St. George and Bishop. Overall the average ratios are for Bishop, 4.7; for St George, 3.3; and for China Lake 7.4. We see that the normalized S amplitudes (equivalent to a zero wind value) are larger than the T amplitudes.
The Reed data were taken with single sensor stations so no azimuth data are available.

HE Data

A number of high explosive tests have been monitored for infrasound signals by the 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 0.04 to 4880 tons of explosive (ANFO). Observations were carried out at both fixed and specially deployed temporary infrasound arrays. The arrays typically consisted of four microphones. Unlike the nuclear explosion data, these include a wide range of distances from 250 to 5300 km. A portion of these data previously were discussed by Davidson and Whitaker (1992), and Whitaker et al. (1990). A set of 24 measurements, all of which had well-defined S signals, were investigated for T signals. The events are listed in Table 1.

Figure 1: Log of $A_S$ (diamonds) and $A_T$ (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 by -2 to provide clarity. While the S signal values show a clear seasonal variation, the T signals values appear to have no seasonal changes.

Figure 2. The ratios of wind-normalized S signal amplitudes, $A_S$, to T signal amplitudes, $A_T$, are shown versus day of year for the St. George UT (squares), and Bishop CA (diamonds), nuclear data.
Table 1: List of HE events.

<table>
<thead>
<tr>
<th>EVENT</th>
<th>DATE: DOY</th>
<th>WEIGHT (TONS)</th>
<th>SITES</th>
</tr>
</thead>
<tbody>
<tr>
<td>MILL RACE</td>
<td>9/16/81: 259</td>
<td>600</td>
<td>1</td>
</tr>
<tr>
<td>PRE-DIRECT COURSE</td>
<td>10/7/82: 280</td>
<td>24</td>
<td>2</td>
</tr>
<tr>
<td>DIRECT COURSE</td>
<td>10/26/83: 299</td>
<td>600</td>
<td>4</td>
</tr>
<tr>
<td>MINOR SCALE</td>
<td>6/27/85: 178</td>
<td>4800</td>
<td>2</td>
</tr>
<tr>
<td>MISTY PICTURE</td>
<td>5/14/87: 134</td>
<td>4880</td>
<td>5</td>
</tr>
<tr>
<td>MISERS GOLD</td>
<td>6/01/89: 152</td>
<td>2400</td>
<td>8</td>
</tr>
<tr>
<td>DISTANT IMAGE</td>
<td>6/20/91: 171</td>
<td>2400</td>
<td>2</td>
</tr>
<tr>
<td>MINOR UNCLE</td>
<td>6/10/93: 161</td>
<td>2400</td>
<td>3</td>
</tr>
</tbody>
</table>

The S signal travel velocities were in the range of 280 to 300 m/s, while the average for T signals was 228 m/s, all quite comparable to the nuclear data.

The T signals data came from examination of hardcopy records because the digital data are no longer available. Our detection frequencies for T signals are more likely lower bounds because, for some of the data, analysis was not carried out at lower frequency and some contributions may have been missed. With this caveat, the frequency of observation with T signals was found to be 42%, 10 T signals and 24 S signals.

The average normalized S amplitude to T amplitude ratio was found to be 2, a little less than the nuclear set. Average S signal duration was 7.9 minutes and 1.0 minute for T signals. For azimuth deviation, S signals averaged 5.1 degrees and T signals averaged 6.0 degrees.

Earthquake Data

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 magnitudes is from 4.4 to 7.9 and the distances from about 400 to 4000 km.

The S signals travel velocities were in the normal stratospheric range, while those of the T signals average 243 m/s with a full range of 200 to 270 m/s. T signal detection frequency was 37%, and is probably a lower bound. Azimuth deviations were 2.5 degrees for S signals and 3.3 degrees for T signals, similar to other data sets. Average durations were 18 minutes for S signals and 58 seconds for T signals. In Figure 3, we show the distribution of azimuth deviation for the S signals.

Interestingly the earthquake data for the ratio of normalized S amplitude to T amplitude show a departure from the other sets. Here the ratio averaged 0.4 with a range from close to 0.1 to 0.7. This difference in ratio may be due in part to source differences because explosions are point sources and the earthquakes have extended areas of ground motion.

Earthquakes may have more energy at larger elevation angles than explosions. This could be examined with detailed ground motion data for some earthquakes and deriving emission patterns. It should be noted, the ratio here is that using the normalized S amplitude, adjusted to zero wind. Because of wind effects, there are times when the raw S amplitude will be larger than the T amplitude.

![Figure 3: Distribution of azimuth deviations for earthquakes in Mutschlecner and Whitaker, 2005.](image-url)
Azimuth Deviations from Some NTS Events

Olmstead (1951, 1953, and 1954 reports de-classified) gives data on azimuth deviations and other characteristics for atmospheric nuclear events in three operations. The azimuth results are shown in Figure 4 below. The operations were Buster Jangle (B-J), 1951 at the Nevada Test Site; Ivy, 1952 in the Pacific; and Upshot Knothole (U-K), 1953, at the NTS.

Figure 4: Observed azimuth deviations for three operations.

For illustration, we have taken the observations for each operation and determined a standard azimuth deviation for the operation. The results are shown in Table 2.

Table 2: Summary standard deviations in azimuth for three atmospheric test operations.

<table>
<thead>
<tr>
<th></th>
<th>U-K</th>
<th>B-J</th>
<th>Ivy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Std dev azimuth (degrees)</td>
<td>3.96</td>
<td>3.75</td>
<td>5.66</td>
</tr>
</tbody>
</table>

These are quite similar to deviations seen for other data sets. The value for Operation Ivy is larger because of one large deviation for each event, though not from the same station.
Period and Yield

We have gathered some period-yield for six US atmospheric nuclear test operations. Some of the data appear in the reports by Olmstead in the references, while other data are in old records that are not easily available. All events used had announced yields taken from the test summary report DOE/NV-209-Rev 15. Periods were averaged over the results for stations reporting. The period is that of the main acoustic arrival, interpreted as that from stratospheric heights. Earlier, ReVelle (1997) had given two representation of the period yield relation, applicable for two ranges of source size. For comparison, here we use just one fit over all the events considered. Test operations from which data came are shown in Table 3. The data are shown, with the regression line, in Figure 5.

Table 3: Operations used in period – yield relation.

<table>
<thead>
<tr>
<th>OPERATION</th>
<th>ABBREVIATION</th>
<th>YEAR</th>
<th>TEST AREA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greenhouse</td>
<td>G-H</td>
<td>1951</td>
<td>Pacific</td>
</tr>
<tr>
<td>Buster-Jangle</td>
<td>B-J</td>
<td>1951</td>
<td>NTS</td>
</tr>
<tr>
<td>Tumbler-Snapper</td>
<td>T-S</td>
<td>1952</td>
<td>NTS</td>
</tr>
<tr>
<td>Ivy</td>
<td>Ivy</td>
<td>1952</td>
<td>Pacific</td>
</tr>
<tr>
<td>Upshot-Knothole</td>
<td>U-K</td>
<td>1953</td>
<td>NTS</td>
</tr>
<tr>
<td>Redwing</td>
<td>R-W</td>
<td>1956</td>
<td>Pacific</td>
</tr>
</tbody>
</table>

Figure 5: Infrasonic yield vs period for some atmospheric nuclear tests.

The regression gives, independent of other fits:

\[ Y = 4.0 \times 10^{-3} P^{3.26} \quad \text{or} \quad \log(Y) = -2.4 + 3.26 \log(P) \]  

(1)

where \( Y \) is in kilotons and \( P \) is in seconds. The regression has a \( R^2 \) of 0.93 and a standard deviation of the fit (log) of 0.15, or a factor of 1.41 in physical units. These apply to this particular analysis.

It should be noted that the relation is for surface and low altitude explosions, essentially point sources. High altitude events would require some adjustment for altitude scaling (Baker, 1973). In addition for moving sources, such as
bolides, accounting for the line source physics must be made. Two recent contributions addressing this for meteors and bolides are Edwards et al., 2004, and Edwards et al., 2006.

**CONCLUSIONS AND RECOMMENDATIONS**

We have summarized data on the period yield relationship for atmospheric explosions, reviewed azimuth deviations for explosions and moderate earthquakes and compared characteristics of stratospheric returns and thermospheric returns. Because data and analysis limitations with some of the data, we could have missed some thermospheric signals. In terms of frequency of detection, duration, and azimuth deviation, the sets are reasonably consistent. From a number of source types, we find azimuth deviations to be within six degrees (standard deviation) and apply to S or T signals. Average travel velocities for T signals range from 200 m/s to 270 m/s. The fit to the yield period relation shown here is within a factor of two (from the standard deviation of this regression).

**REFERENCES**


