THERMOSPHERIC INFRASOUND SIGNALS

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ABSTRACT

The primary signals considered for the detection of explosions by infrasound are stratospheric, that is, signals received after reflection from stratospheric layers near 50 km in height. However, thermospheric signals may also be an important means of detection. Thermospheric signals are produced by reflections from atmospheric layers at about 110 to 130 km.

An analysis has been carried out of thermospheric signals from atmospheric nuclear tests at the Nevada Test Site out to distances of about 250 km. Stratospheric signal amplitudes are very dependent upon stratospheric winds and hence have a seasonal variation. In contrast it is found that thermospheric signal amplitudes have little or no seasonal variation. This is because the sound velocities at thermospheric heights are always sufficient to produce signal returns. As a result, thermospheric signals are more easily interpreted since no correction for the effects of wind are required.

It is found that thermospheric amplitudes may be very competitive with stratospheric amplitudes during a portion of the year and, in fact, will dominate during conditions of strong stratospheric counterwind conditions. Thus thermospheric signals should also be considered in the operational methods for detection of explosions in the atmosphere. We have detected thermospheric signals out to at least 500 km for which the attenuation law appears to follow that for stratospheric signals. Further work will be needed to determine the range attenuation for greater distances. Current predictions indicate that thermospheric signal amplitudes will be about 1μ bar at 2000 km for a 1-kT nuclear event

Because of the much greater height of the return layer for thermospheric signals, their average travel velocities are much smaller than for stratospheric signals. Here average velocity is defined as the surface distance to the source divided by travel time. Typical stratospheric velocities are about 290 m/s, whereas thermospheric velocities are only about 220 m/s. As a result the arrival times of thermospheric signals may be considerably later than those of stratospheric signals. For example, at a distance of 500 km the interval between the signals is about nine minutes.

For circumstances where both stratospheric and thermospheric signals are detected at a station two useful determinations can be made: (1) the value of the directed stratospheric wind speed that is neeed for normalization of stratospheric signal amplitudes and (2) an estimate of distance to the source.

Key Words: infrasound signal propagation, thermosphere, stratosphere, atmospheric wind

I. **Introduction and Background**

Stratospheric (S) infrasound signals, that is, those returned from the stratospheric region of the atmosphere by refraction, are generally expected to be the primary signal from medium to small size explosions in the atmosphere and many other sources. Thermospheric (T) signals also may be returned to earth from thermospheric regions of the atmosphere at about 110 to 130 km in height or more. T signals can be shown to be highly competitive with, or even exceed S signals in amplitude, during favorable periods of the year. Thus it is important to understand the general characteristics of the T signals and to search for these signals along with the conventional search for S signals as a part of CTBT monitoring activities.

We have used a data set of signals from NTS atmospheric nuclear tests for a preliminary assessment of the characteristics of T signals. The NTS data were reported by Reed (1969) and have been analyzed in depth by Mutschlecner et al (1999). The observations were made at several stations surrounding NTS. In the present report we utilize the data taken at a station at Bishop, California, to provide examples. Bishop is at an average distance of about 211 km from NTS and at an azimuth of 278^{o} from NTS. Others stations in the data set give general confirmation of the Bishop results.

II. T Signal Velocities

Figure 1 compares the average velocity of the observed S and T signals at Bishop. Average velocity, V, is defined at the great circle distance from source to receiver on the surface divided by the signal transit time. In this example it is seen that the S signals have V from about 270 to 300 m/s. We believe, from a more detailed study of all stations, that there is a seasonal dependence of the S signal velocities. By contrast the T signals show much lower values of V ranging from about 200 to 250 m/s. On occasion, even lower values are seen and an example is seen in the figure at about 150 m/s. The comparatively low values of V for T signals compared to S signals can be understood as a result of the much higher return altitude for T rays as illustrated in Fig. 1.

Of course, the consequence of the lower values of V for T signals is that the arrival times will be later than for S signals from an event. Figure 2 gives an illustration of the time delay between S and T signals as a function of distance. The upper line indicates the time delays for downwind conditions (i. e. signals propagating in the direction of stratospheric wind flow) and the lower line for counterwind conditions. Notice that the time delays can be very large, reaching, for example, about 19 minutes for a distance of 1000 km. While Fig. 2 provides general guidance, a more exact calculation should be made for any specific case. The possible large time delay between the S and T signal arrivals suggests that in many instances T signals inadvertently may be ignored after a large S signal has been detected. Observers should be aware of this and attempt to detect T signals as well.

III. T Signal Amplitudes

Figure 3 shows the yield-scaled amplitude of the atmospheric nuclear explosions for S signals at Bishop versus day of the year. Several years of data are contained in this plot. Yield scaling is done by dividing the peak-to-peak amplitudes by the factor W^n where n= 0.456. Further details of the scaling are given by Mutschlecner et al (1999). There is a very large seasonal dependence in the scaled amplitude--over three decades of variation. This effect is caused by the seasonal stratospheric wind variation. For comparison Fig. 4 shows the yield-scaled amplitudes of T signals for Bishop. Here we see a much smaller variance--about one decade. Data from all of the stations suggest that there is no seasonal variation in the T signals. We adopt a value of 1.29 for log of the T signal peak-to-peak amplitude (_b) of a 1-kT nuclear explosion at a distance of about 215 km (one bounce from the source).

Figure 5. compares seasonal predictions for S and T amplitudes. The calculation is for a 1 kT explosion at a distance of 500 km propagating toward an azimuth direction of 270^{o}. The S signal amplitude, A_S, in _b is given by

$$log\ A_s = 1.36 + 0.016\ V_d \qquad (1)$$

where V_d is the component of wind speed (m/s) at an average height of 50 km directed towards the observer from the source. A statistical model is used for the winds at mid northern latitudes. Further details of this formulation are given by Mutschlecner et al (1999). The figure indicates that the predicted T signal will be larger than the S signal during a significant portion of the year. Similar calculations have been made for a series of azimuths. The results are given in Figure 6 which shows the percentage of a year in which T signals will be competitive with S signals in amplitude versus azimuth. We arbitrarily define "competitive" as meaning that a T signal amplitude is at least 1/2 of the S signal amplitude. Notice that there is strong asymmetry between east and west, with the west showing considerably greater T signal competition than does the east. Figure 6 demonstrates that T signals may be of importance during significant parts of the year. Of course this example is specifically for mid-northern latitudes and is statistical in nature. For other locations of interest appropriate calculations could be made.

IV. Range Determination from S and T Signals

If both S and T signals are observed from the same source at a station, it is possible to determine a distance to the source from the difference, _t, in the arrival times of the two signals. This procedure is of course in common usage for seismic signal analysis. The distance, R, is given by

$$R = \Delta t\left(\frac{1}{V_t} - \frac{1}{V_s}\right) \tag{2}$$

where V_t and V_s are the average velocities for T and S signals respectively. The difficulty in this determination of R is that the values of the two average velocities vary with propagation conditions which may be a function of location and time of the year.

To illustrate this use of S and T signals we use a simple approximation of 219 m/s for V_t and for V_s : 294 m/s for downwind conditions and 285 m/s for counterwind conditions. These values were obtained from our general analysis of data from all stations. Figure 7 shows the absolute value of the percentage error between the true distance and the distance given by Eqn. 2 for Bishop. The average error is about 17 percent. Presumably better accuracy could be given by an improvement in the ability to predict the best values for V_t and V_s . Ultimately, with an increasing data base from CTBT monitoring and other sources this improvement should be possible. The ability to estimate a distance that is independent of triangulation using multiple station detections may be a very useful tool in some instances.

V. Determination of the Directed Wind Component from T and S Signals

When both S and T signals are observed from a source the local value of V_d may be obtained. It can be shown that the use of the amplitudes A_s and A_t from S and T signals respectively gives

$$V_d = \frac{1}{k}\left[\left(log\ A_s - log\ A_t\right) - \left(log\ A_{cs} - log\ A_{ct}\right)\right] \tag{3}$$

where k is the wind effect normalization parameter for S signals taken here as 0.019 s/m. log A_{cs} and logA_{ct} are respectively the values of S and T signal log amplitudes for one kT and zero stratospheric wind; their values are taken as 1.87 and 1.29. These parameter numbers are for a first-bounce distance and are derived by Mutschlecner et al (1999). The values will be somewhat different for larger distances. The expression assumes that the attenuation with distance is the same for S and T amplitudes. Figure 8 shows the values of V_d derived from Eqn 3 for Bishop from pairs of S and T signals compared with the wind from a statistical model appropriate to that location. There is good general agreement between the derived values and the statistical model. Of course the derived values of V_d reflect actual stratospheric conditions at the time of each event while the model values represent a statistical average which can vary by significant amounts from real conditions at times.

Determinations of V_d by the use of S and T amplitudes may be very useful for two purposes. First, the determined value of V_d for an event permits the normalization of the S signal amplitude to zero wind conditions by

$$log\ A' = log\ A_s - k\ V_d \quad (4)$$

where A' is the normalized amplitude. This normalization is necessary to permit interpretation of any signal.

Second, the determination of values of V_d from signals at various times in the CTBT infrasonic network would permit an improved statistical basis for the global stratospheric wind, especially in the areas of the network stations. Of course this improvement would be cumulative over time but could be done with any sources which provide both S and T signals such as those from earthquakes.

VI. Summary

The examples provided for T signals are based upon the first-bounce location of Bishop. It will be important to understand whether the results also apply to longer distances. At the present time this work has not been extended to greater distances but an effort will be made to do this. Unfortunately data for T signals at greater distances may be somewhat sparse because of the emphasis upon the generally stronger S signals.

There are some indications of T signals characteristics at larger distances. A detection by us of S and T signals at a distance of 517 km (about a two-bounce distance) from a high explosive test gives excellent agreement with the amplitude predicted on the basis of the first-bounce data. A study of the modeling of signals from a 1 kT surface burst by Dighe et al (1999) shows that T signals are expected at a distance of 1175 km. However the average velocity of the principal T signal is higher than we find at first-bounce locations. In another study ReVelle et al (1999) have examined evidence for T signals at larger distances from surface explosions. In this work the existence of high-frequency T signals is emphasized.

Clearly, T signals can be an important aspect of CTBT monitoring by providing confirmation of S signal results. It is noteworthy that the T signal amplitudes apparently would not require the normalization for wind effects needed by S signal amplitudes. Useful byproducts of the analysis of pairs of S and T signals are an estimate of the distance to the source from a one-station observation and a determination of the effective value of the directed stratospheric velocity, V_d. Further work will be required to better understand T signals at long distances.

Acknowledgements

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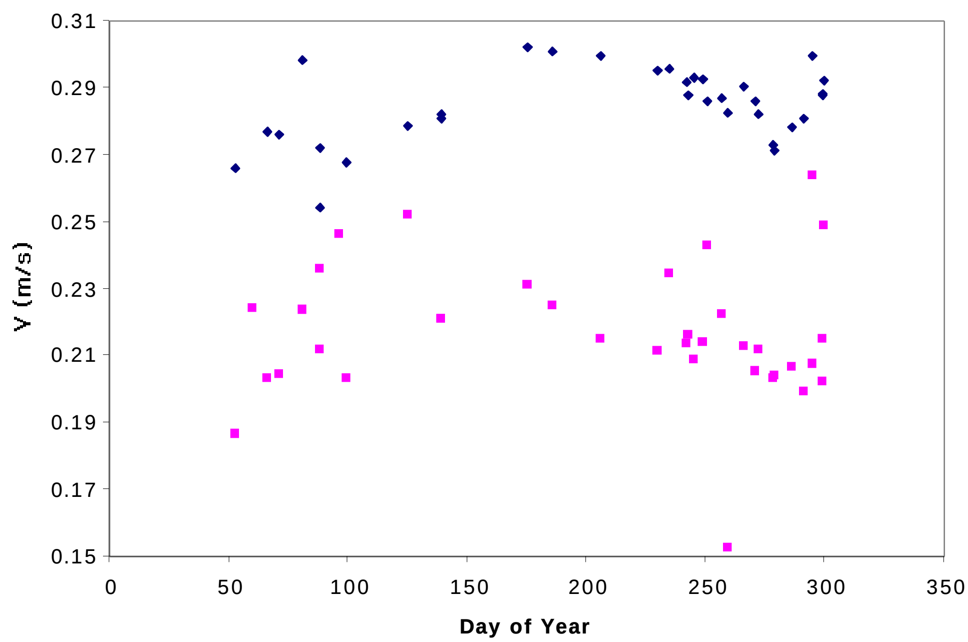

Figure 1. Observations at Bishop of the average propagation velocity of stratospheric signals (diamonds) and thermospheric signals (squares).

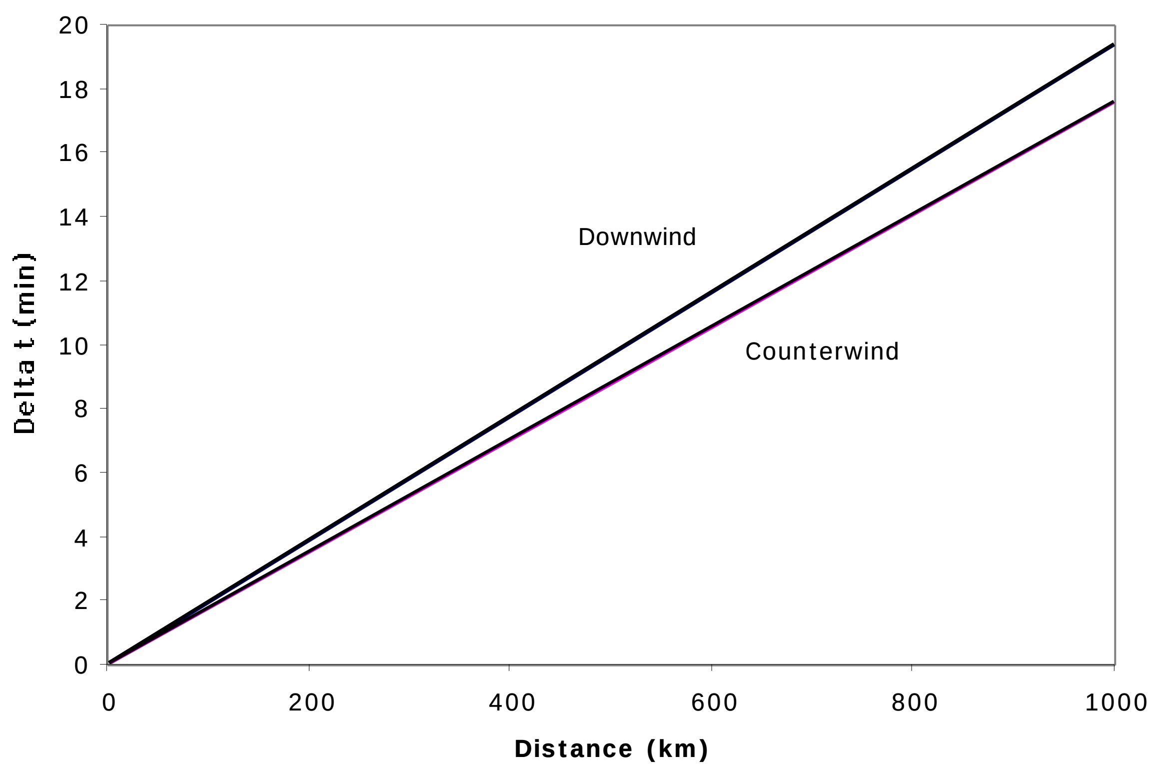

Figure 2. The time difference between stratospheric and thermospheric signal returns as a function of distance.

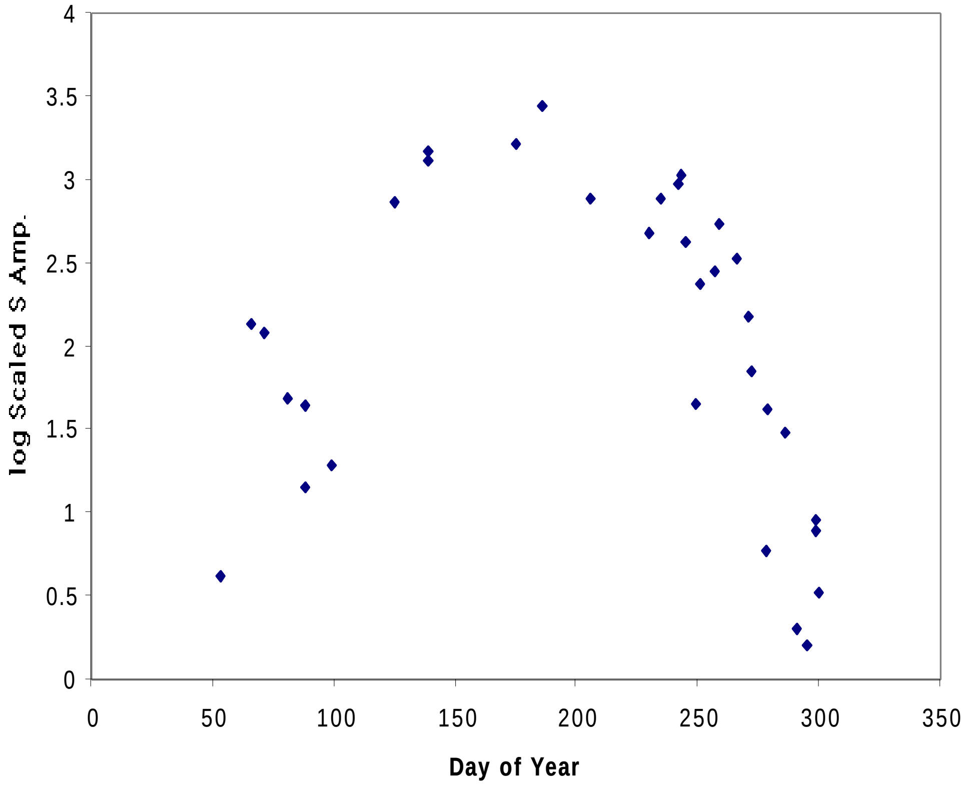

Figure 3. The logarithm of yield-scaled stratospheric signal amplitudes versus day of the year as observed at Bishop, California.

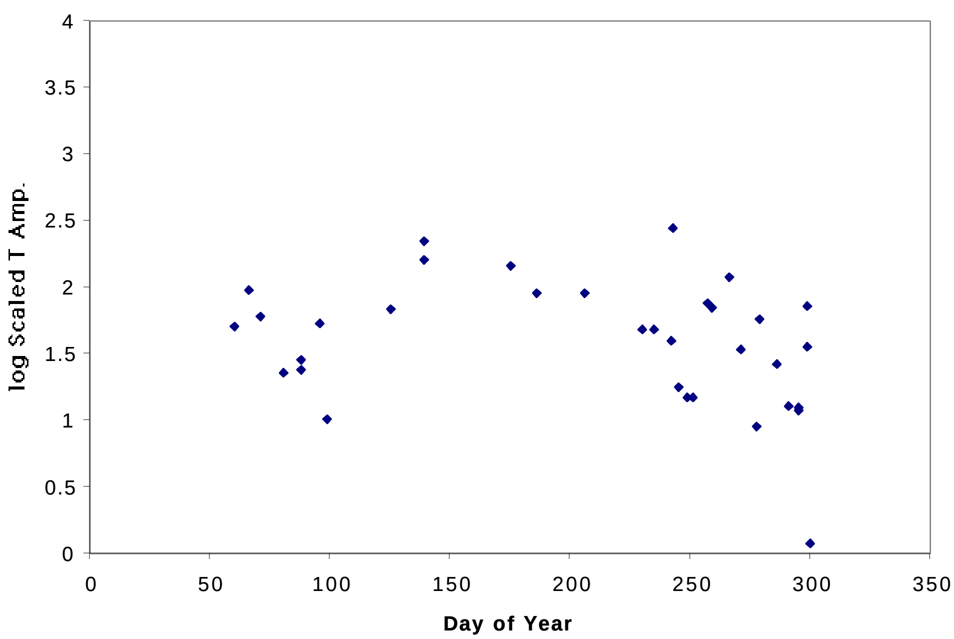

Figure 4. The logarithm of yield-scaled thermospheric signal amplitudes versus day of year as observed at Bishop, California.

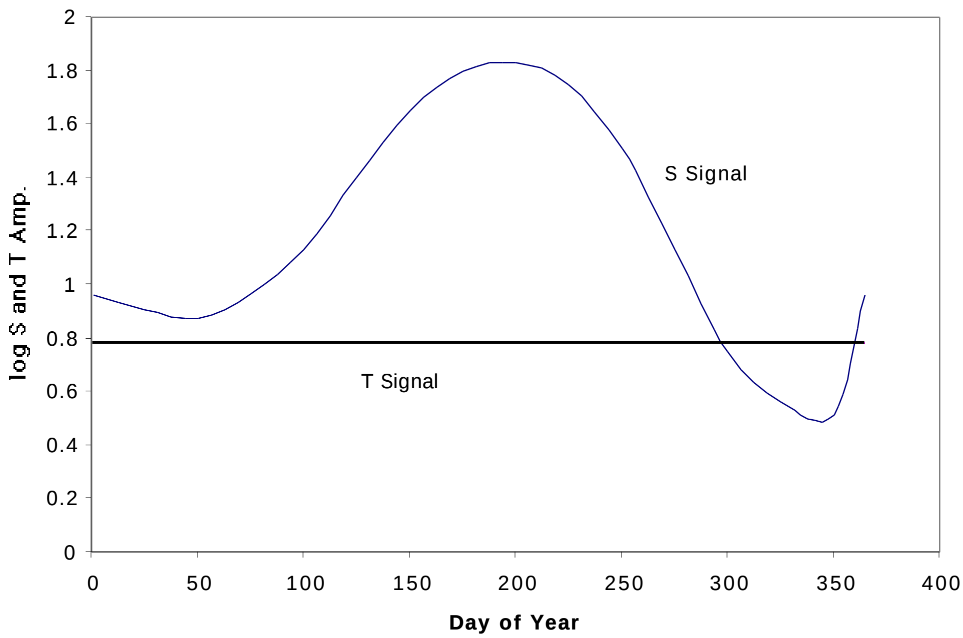

Figure 5. A comparison of the logarithm of amplitude for stratospheric signals (curve) and thermospheric signals (line) as a function of day of the year. Predictions are for a 1 kT atmospheric burst at a distance of 500 km. with signals propagating directly to the west at mid-northern latitudes.

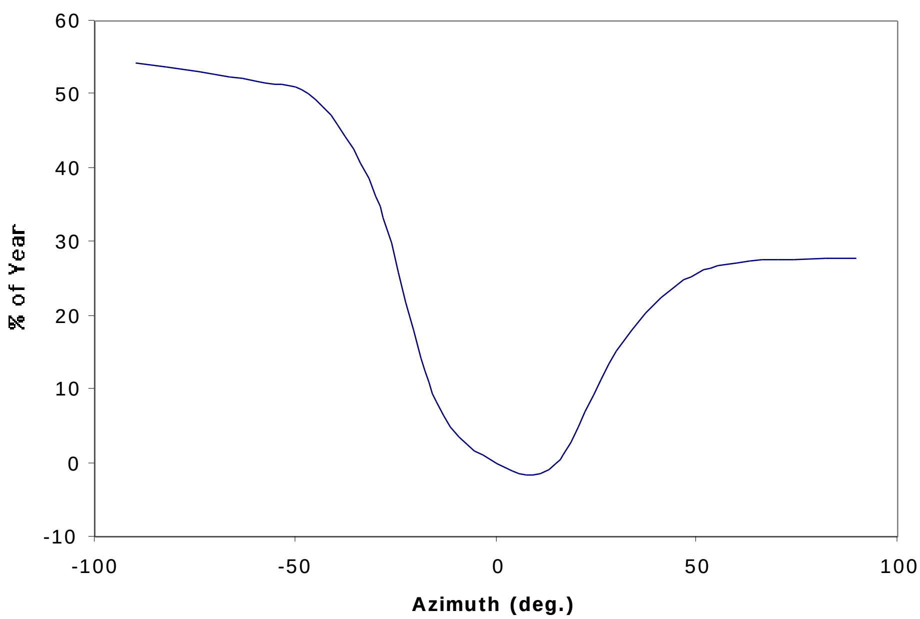

Figure 6. Percentage of the year during which thermospheric signal amplitudes are competitive with stratospheric signal amplitudes versus azimuth. Azimuths are positive to the east and negative to the west.

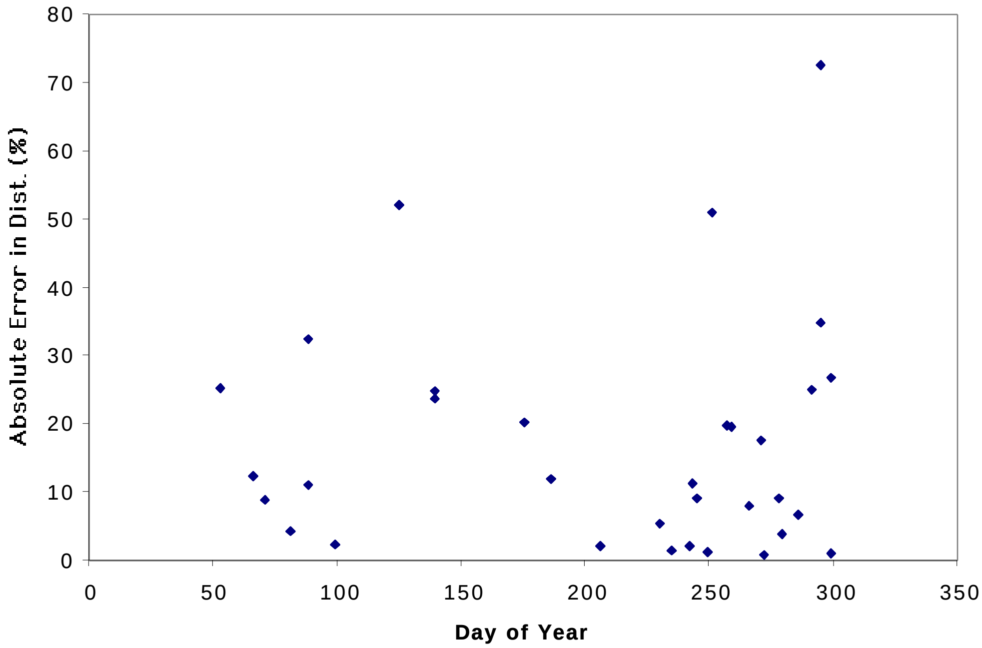

Figure 7. Absolute values of percentage error in the determination of distance for stratospheric-thermospheric signal pairs at Bishop, California versus day of the year.

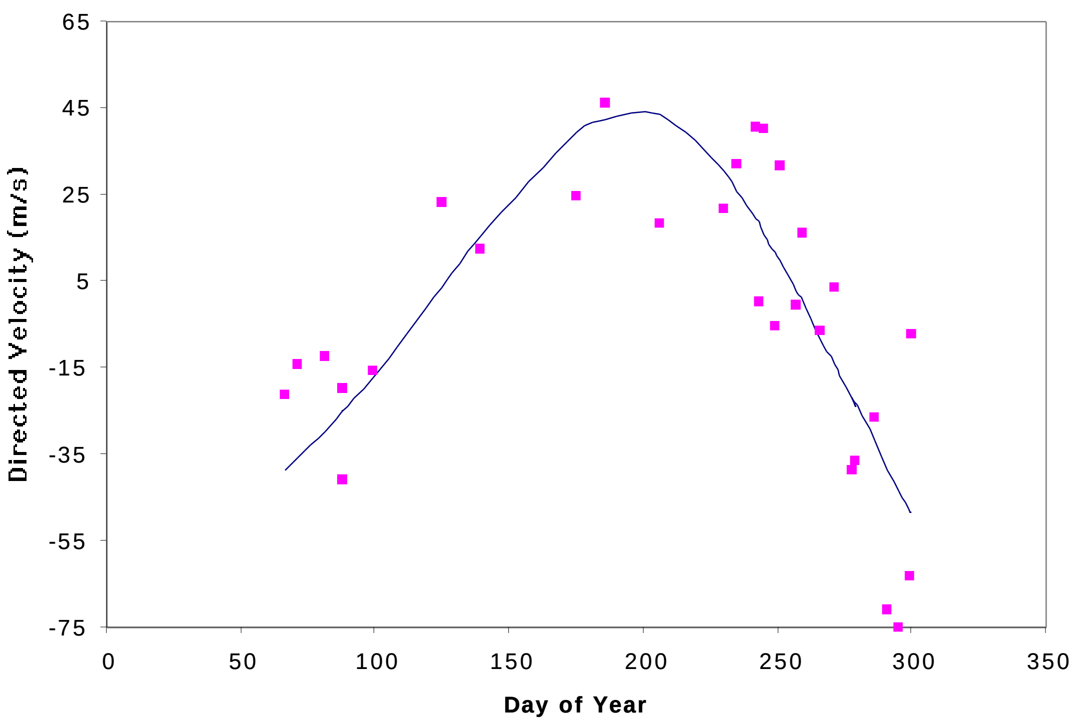

Figure 8. A comparison of the stratospheric directed velocity from a statistical model with the velocity derived from pairs of stratospheric and themosoheric signal amplitudes observed at Bishop, California. The statistical model is shown as a line and the dervived values as squares