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Automated Infrasound Signal Detection Algorithms Implemented In MatSeis - Infra Tool

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Automated Infrasound Signal Detection Algorithms Implemented In MatSeis – Infra Tool

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Abstract

MatSeis's infrasound analysis tool, Infra Tool, uses frequency slowness processing to deconstruct the array data into three outputs per processing step: correlation, azimuth and slowness. Until now, an experienced analyst trained to recognize a pattern observed in outputs from signal processing manually accomplished infrasound signal detection. Our goal was to automate the process of infrasound signal detection. The critical aspect of infrasound signal detection is to identify consecutive processing steps where the azimuth is constant (flat) while the time-lag correlation of the windowed waveform is above background value. These two statements describe the arrival of a correlated set of wavefronts at an array. The Hough Transform and Inverse Slope methods are used to determine the representative slope for a specified number of azimuth data points. The representative slope is then used in conjunction with associated correlation value and azimuth data variance to determine if and when an infrasound signal was detected.

A format for an infrasound signal detection output file is also proposed. The detection output file will list the processed array element names, followed by detection characteristics for each method. Each detection is supplied with a listing of frequency slowness processing characteristics: human time (YYYY/MM/DD HH:MM:SS.SSS), epochal time, correlation, fstat, azimuth (deg) and trace velocity (km/s).

As an example, a ground truth event was processed using the four-element DLIAR infrasound array located in New Mexico. The event is known as the Watusi chemical explosion, which occurred on 2002/09/28 at 21:25:17 with an explosive yield of 38,000 lb TNT equivalent. Knowing the source and array location, the array-to-event distance was computed to be approximately 890 km. This test determined the station-to-event azimuth (281.8 and 282.1 degrees) to within 1.6 and 1.4 degrees for the Inverse Slope and Hough Transform detection algorithms, respectively, and the detection window closely correlated to the theoretical

stratospheric arrival time. Further testing will be required for tuning of detection threshold parameters for different types of infrasound events.

Acknowledgement

The author thanks Dr. Rod Whitaker from Los Alamos Earth & Environmental Sciences for his suggestion to investigate the Hough Transform as a possible method for the automation of infrasound signal detection, also for Dr. Whitaker's insightful discussions regarding infrasound signal processing and signal detection definition. Additionally, Chris Young and Mark Harris provided technical contributions through their review of this manuscript.

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1. Introduction

Infra Tool was first released for public distribution with MatSeis-1.7 (Hart and Young, 2002). The original versions of Infra Tool were designed to evaluate the signal processing method known as frequency slowness analysis, S(ω), as described by Young and Hoyle (1975). Frequency slowness analysis (i.e. correlation, azimuth and slowness) is now recognized as one method for determining when a coherent signal arrived at an infrasound array (McLaughlin et al. 2000, Brown et al. 2001, Whitaker et al. 2002, Garcés et al. 2002, and Noble and Tenney, 2003). Although frequency slowness analysis is used to process infrasound array data, the methods for determining if and when a signal of interest was recorded are still manually driven. An experienced analyst must review the processing results and determine if certain criteria are met that would indicate the arrival of an infrasound signal. The difficulty with visually inspecting band-limited, or raw infrasound array data for coherent signals is that infrasound data can be very noisy (i.e. signal-to-noise ratio ≈ 1). However, an interesting feature of current infrasound signal processing technique used by Infra Tool is that it can typically extract signals even when the SNR is close to, or below one.

Whitaker et al. (2002) described a detection scheme for infrasound signals based on the frequency slowness processing implemented in Infra Tool stating, "…one would look for constant azimuth signals having some correlation above a threshold and duration longer than some minimum". Utilizing this description of signal detection, we developed an automated routine for detection of these signals. The detection routine follows a set of threshold settings based on the output from frequency slowness analysis.

The critical aspect, in signal detection, of these routines was to devise a method for determining when the azimuth data being considered had stabilized to a constant direction. Two methods were developed to determine when the azimuth data had stabilized: Hough Transform and Inverse Slope methods. We also propose a structure for the automated detection(s) output file for use in association of infrasound arrivals from multiple infrasound arrays.

2. Basic Detection Scheme

Current work on infrasound signal detection follows from the recognition that frequency slowness processing, S(ω), of a coherent infrasound signal produces a repeatable pattern in the generated outputs (i.e. correlation, azimuth and slowness), as outlined by Whitaker et al. (2002). The typical pattern from frequency slowness processing (FSP) of a coherent signal can be qualitatively described as follows: time delay correlation between the different elements of the array rise above a background value, azimuth stabilizes to a constant direction (with observed standard deviation and variance), and the apparent slowness of the arriving signal stabilizes to a constant value. Because infrasound signals characteristically exhibit these same features, an algorithm could be formulated to automatically identify processed infrasound array data with such characteristics. Our goal was to add the ability for automated infrasound signal detection to the publicly available software Infra Tool through the MatSeis-1.8 release.

Starting with the existing Infra Tool graphical user interface (distributed with the publicly available software package MatSeis-1.7 through the NEM R&E web site: https://www.nemre.nnsa.doe.gov/cgi-bin/prod/nemre/matseis.cgi), which implements the frequency slowness processor described by Young and Hoyle (1975), work proceeded to include an automated detection scheme described above into the existing Infra Tool MATLAB code. To do this, several new interactive threshold controls were added to Infra Tool. These controls are: correlation threshold that must be exceeded, slope limit in azimuth (defined in ±degrees per second), number of samples (minimum of 2 samples required), standard deviation observed in azimuth, and, finally, the gap observed in azimuth data (it has been observed that, depending on the processing parameters used, even coherent signals may have variations in azimuth and, therefore, gaps in consecutive processing points). The detection controls are shown in Figure 1.

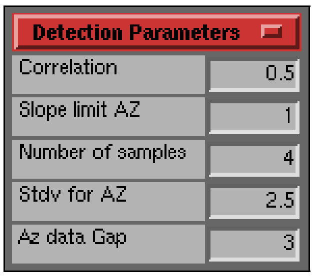


Figure 1 – Screen shot from Infra Tool illustrating the new interactive threshold parameters for controlling the detection algorithm. Current threshold settings include correlation, slope limit in azimuth, number of samples being considered, standard deviation in azimuth, and gap in azimuth data. (The values shown here are dependent on waveform processing parameters used, i.e. window duration and overlap.)

Infrasound array processing used by Infra Tool follows a prescribed set of steps, as demonstrated below, with example parameters in brackets:

1. Select section of raw waveforms to process from an infrasound array. [1 hour of raw data, sampled at 10 Hz: yields 36000 data samples or 3600 seconds]
2. Filter waveforms to band-limited region. [band-limited to 0.5-3 Hz]
3. Select maximum slowness value and quantized slowness plane increment [400 seconds/deg max slowness ≈ 0.278 km/second, and 40 increments]
4. Select signal processing window length in seconds, which determines the minimum numbers of processing steps (if 0% window overlap). [30 second window = 300 samples; 36000 samples total / 300 samples window = 120 processing steps]
5. Select the degree of overlap between consecutive processing steps. [50% overlap between consecutive processing steps]
6. Combine minimum processing step length with overlap to obtain the actual number of processing steps. [30 seconds* 50% = 15 seconds; 3600 seconds/15 seconds = 240 actual processing steps]
7. Compute actual signal processing steps. At each processing step, three values result: correlation, azimuth and slowness.

To determine the presence or absence of a signal, the output must be further analyzed. We have devised two methods to accomplish this task: Hough Transform and Inverse Slope. The objective of signal detection routines is to search the output of frequency slowness processing and find regions that pass the threshold criteria.

3. Hough Transform Method

Brown et al. (2002) first proposed the Hough Transform (HT) for use in infrasound signal detection. The Hough transform was developed by Paul Hough (1962) and patented by IBM. It became a standard tool in the domain of artificial vision for the recognition of straight lines, circles and ellipses. The Hough transform is particularly robust to missing and noisy data.

For each combination of point data, in data space S_d, the characteristic relation of the desired feature is back-projected to its parameter space P. In our case, the characteristic relation is that of a line, i.e. y=mx+b, and parameter space P is two-dimensional, i.e. slope (m) and y-intercept (b). Each combination of point data (x_i , y_i) in S, where i=1,..,N (N is the *Number of samples* detection parameter, and describes the number of point data under consideration), defines a relationship between the parameters in P and the characteristic relation (see Equations 1 and 2). All data belonging to the curve of interest (i.e. horizontal line) are mapped to a single location in parameter space, thereby turning the problem into one of finding a population peak in parameter space.

$$m = -\left(\frac{y_j - y_i}{x_j - x_i} \right) \tag{1}$$

$$b = y_i - x_i \left(\frac{y_j - y_i}{x_j - x_i} \right) \tag{2}$$

The HT detection scheme used by Infra Tool requires a minimum number of processing steps (i.e. N) must be completed. Then the set of detection threshold parameters can automatically be evaluated every time a new processing step has concluded. Referring to Figure 1, N=4 processing steps (controlled by the detection parameter field: *Number of samples*) would have been completed before initiating the detection part of the code.

This implementation of the Hough Transform is designed to detect horizontal lines embedded in randomly scattered 2-dimensional point data. The boundaries are known, and fixed between 0 and 360 degrees of azimuth in y, while only having a minimum number of points (i.e. N) for consideration in x. The user sets the *Number of samples* detection parameter, which control the number of points considered in x. All the combinations of the data, (x_i ,y_i), (i.e. the number of combinations of N points taken two at a time, see Equation 3) are used to compute the slope and y-intercept.

$$Combinations = \left(\frac{N!}{2!(N-2)!} \right) \qquad (3)$$

For example, if N=4, we take the 6 combinations of point pairs to compute the slope and y-intercept. Parameter space P is quantized for the slope between ± (slope limit in azimuth+1), by 0.1 increments and the y-intercept between 0 and 360, by 2-degree increments. The quantized parameter space represents an accumulator matrix, A, which is incremented if the slope and y-intercept calculated from a pair of data, (using equations 1 and 2), fall within the limits of A. Matrix A is then searched for the row and column where the maximum accumulation occur.

The row of A containing the maximum number of accumulations is associated to a slope value, which is the representative slope for the data used in that processing step. For each step during frequency slowness processing, the HT is applied to determine the representative slope for N data being considered. Once each processing step is completed the results (i.e. correlation, azimuth data standard deviation, and representative slope) are compared with the detection threshold criteria. At points where the detection parameter thresholds are passed the data are flagged as HT detections.

As described earlier, coherent signals arriving at an infrasound array will exhibit regions of constant azimuth. The Hough Transform is used to identify these regions of constant azimuth. When combined with processing steps exhibiting higher correlation and low azimuth data standard deviation, this routine identifies the arrival of an infrasound event.

4. Inverse Slope Method

The Inverse Slope (IS) is another method for determining the representative slope in scatter point data. We use linear least squares fitting to compute the slope and y-intercept for N azimuth data points, which minimizes the sum of the squared residual by finding the best fitting straight line through the set of points (Davis, 1986). The computed slope value in combination with correlation and azimuth data standard deviation from the frequency slowness processing routine constitutes a second method for infrasound event detection.

We construct the problem:

$$\vec{d} = A \cdot \vec{p}, \qquad (4)$$

where,

$$\vec{d} = \begin{bmatrix} y_1 \\ \vdots \\ y_i \end{bmatrix}, \qquad (5)$$

$$A = \begin{bmatrix} x_1 & 1 \\ \vdots & \\ x_i & 1 \end{bmatrix}, \text{ and} \tag{6}$$

$$\vec{p} = \begin{bmatrix} slope \\ y - \text{int}\,ercept \end{bmatrix}, \tag{7}$$

then solve the inverse problem: $\vec{p} = A^{-1} \cdot \vec{y}$ to get the representative slope and y-intercept. This is only possible if the matrix A is invertible. Matrix A represents the operator matrix of partial derivatives of *y* with respect to parameters in *p*, which relate the parameters in *p* to the *d*.

We solve for the representative slope and y-intercept that minimize the residuals in the least-squares sense for the considered data. (An L1-norm technique could be used as well if it was desired to down-weight the data to remove effects from outliers.) For each step during frequency slowness processing, the IS method is used to determine the representative slope for the N data being considered. Once each processing step is complete, results are compared with the detection threshold criteria. Where the detection parameter thresholds are passed, the data are flagged as IS detections, thereby automating the task of signal detection in infrasound data streams.

5. Detection Output File

With the ability to automatically detect infrasound signals, we propose a format for an output file containing the detection information. The top of the file lists the names of array elements processed. Next in the output file we list the IS detections followed by the HT detections, which may consist of single, multiple, or no detections by one or both detection methods. For each detection a list giving the centered processing window time, first in human time format (i.e. YYYY/MM/DD HH:MM:SS.SSS) then in epochal time, followed by the respective correlation, fstat, azimuth and trace velocity values. For example:

```
Stations Processed:  DLI01,DLI02,DLI03,DLI04

Inverse Slope Method: Detection - 1
1999/10/16 10:34:07.800   940070047.80  0.615    5.39  253.8  0.336
1999/10/16 10:34:17.800   940070057.80  0.473    2.59  251.6  0.312
1999/10/16 10:34:27.800   940070067.80  0.535    3.60  253.8  0.336
1999/10/16 10:34:37.800   940070077.80  0.686    7.75  253.8  0.336

Hough Transform Method: Detection - 1
1999/10/16 10:34:07.800   940070047.80  0.615    5.39  253.8  0.336
1999/10/16 10:34:17.800   940070057.80  0.473    2.59  251.6  0.312
1999/10/16 10:34:27.800   940070067.80  0.535    3.60  253.8  0.336
1999/10/16 10:34:37.800   940070077.80  0.686    7.75  253.8  0.336
```

In this case both methods found the same signal with equal durations.

6. Example – Watusi Chemical Explosion

To demonstrate the September 28, 2002 Watusi chemical explosion was chosen for analysis. Data were downloaded from Center for Monitoring Research web page (http://www.cmr.gov/rdss-bin/all_sides_rdss.pl?/rdss-bin/infra.pl), Library: *Ground Truth*, Category: *GNT/A*. The selected event was number 6 in the list with julian date: 2002271, origin time: 09/28/2002 21:25:17 and location 37.0990N 116.092W. A four-character code was assigned as CSCU (**C**hemical **S**urface explosion **C**onfirmed as originating in the **U**nited States). The experimental four-element DLIAR infrasound array in New Mexico was processed.

The raw waveforms are illustrated in Figure 2, and span time duration of approximately 2 1/2 hours. The raw data does not reveal specific processing issues, however, review of the array element spectrograms (Figure 3) readily demonstrate several short duration energy arrivals. From analysis of the spectrograms, we can determine a lower limit on the processing window length (>30 seconds, if 50% overlap assumed) to use when setting the frequency slowness processing parameters so that these short duration events (~10 seconds) are not detected.

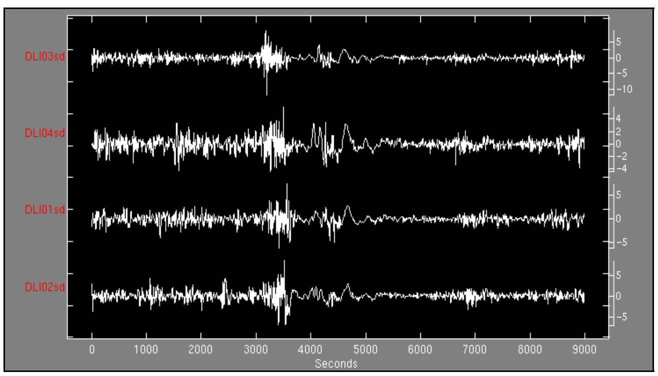


Figure 2 – Raw waveforms from DLIAR infrasound array for the September 28, 2002 Watusi chemical explosion were used to test the Hough Transform and Inverse Slope methods automated detection algorithms described here. The location given for this ground truth events is 37.0090N and 116.0920W.

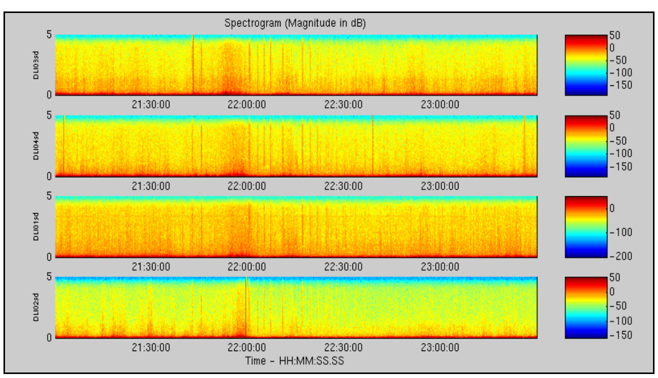


Figure 3 – Spectrogram plots of DLIAR data for September 28, 2002 Watusi chemical explosion. Not apparent when viewing the waveform time series are broadband energy packets of short duration (~10 sec).

The data were first windowed, and filtered to the 0.5-3.0 Hz band using a second order butter-worth filter. For processing a 30 second window with consecutive 50 % overlapped windows, the number of processing steps is 599. The detection thresholds were set: correlation > 0.5, slope limit in azimuth = ±1 deg/(processing step*overlap % = 15 sec), number of samples = 4 (one minute duration of stable azimuth), standard deviation in azimuth < 2.5, and gap allowed between consecutive detections = 1.

The results of processing the data, with the newly added detection algorithms, using Infra Tool are shown in Figure 4.

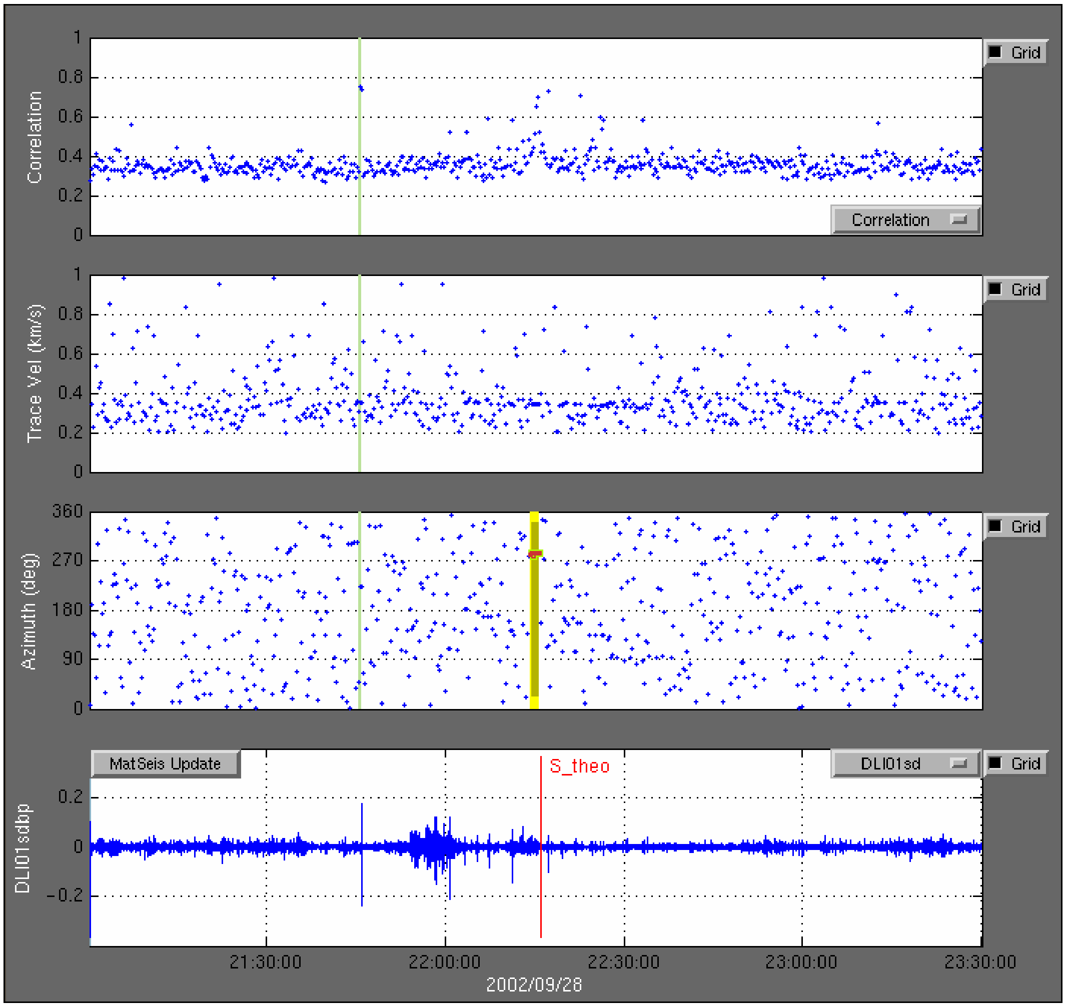


Figure 4 – Results for processing DILAR array for the September 28, 2002 Watusi chemical explosion. The window axes from top to bottom are correlation, trace velocity, azimuth and filtered time series (labeled on left hand side of axes). The blue points within the correlation, trace velocity and azimuth axes represent the results of frequency slowness signal processing of the 599 windows defined by windowing parameters.

The green window located at ~21:45:00 is automatically set to the maximum correlation value; in this case it is related to one of the broad-band energy arrivals illustrated in the spectrogram. Infra tool calculates and displays a summary of correlation, fstat, azimuth and velocity for the green window, it can be expanded and moved by the user. The bright and dark yellow bars in the azimuth window define detections for the Inverse Slope and Hough Transform methods, respectively. In the filtered waveform window the theoretical stratospheric arrival time is displayed, and labeled *S_theo*. Moving and expanding the green window over the data spanning the detection regions, the results are summarized in the *Windowed Values & S.D.* fields of Infra Tool. This was done for the IS detection and the summary is displayed in Figure 5.

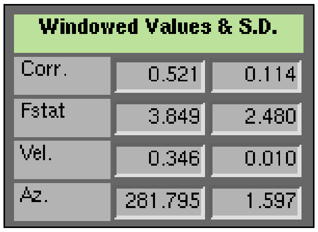


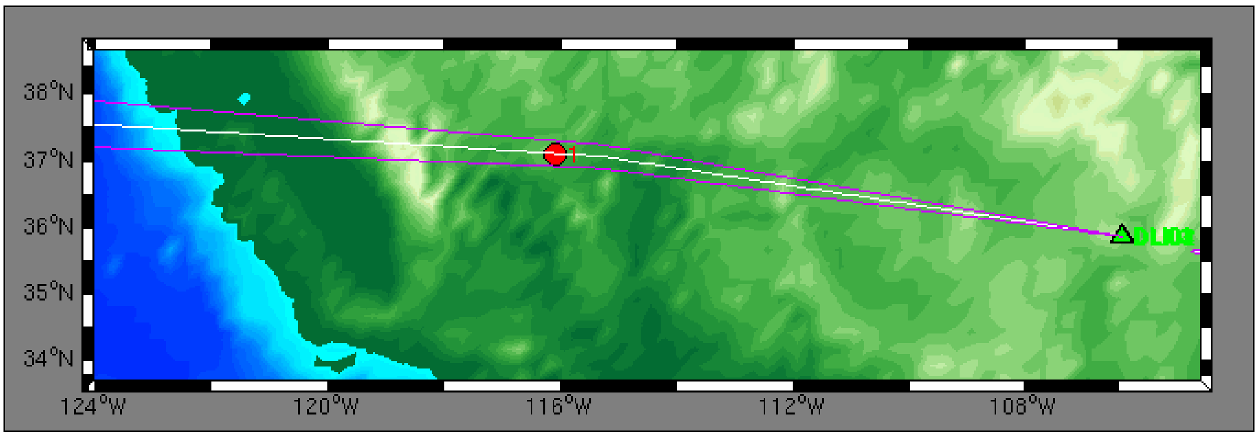
Figure 5 – Setting the windowed values box, within Infra Tool, the correlation, fstat, trace velocity (km/s) and azimuth (deg) data can be quickly summarized. The first, second and third columns give the data type, mean and standard deviation, respectively of the windowed data.

The trace velocity of 0.346 ± 0.01 km/sec for this event falls within the expected acoustic velocity regime. Another way to analyze the detection results is to write the results to a file and use another program to assist in the interpretation. The *Write Detection File*, function within Infra Tool was used to save the detection results to a file. The detection file for the Watusi chemical explosion is shown in Table 1.

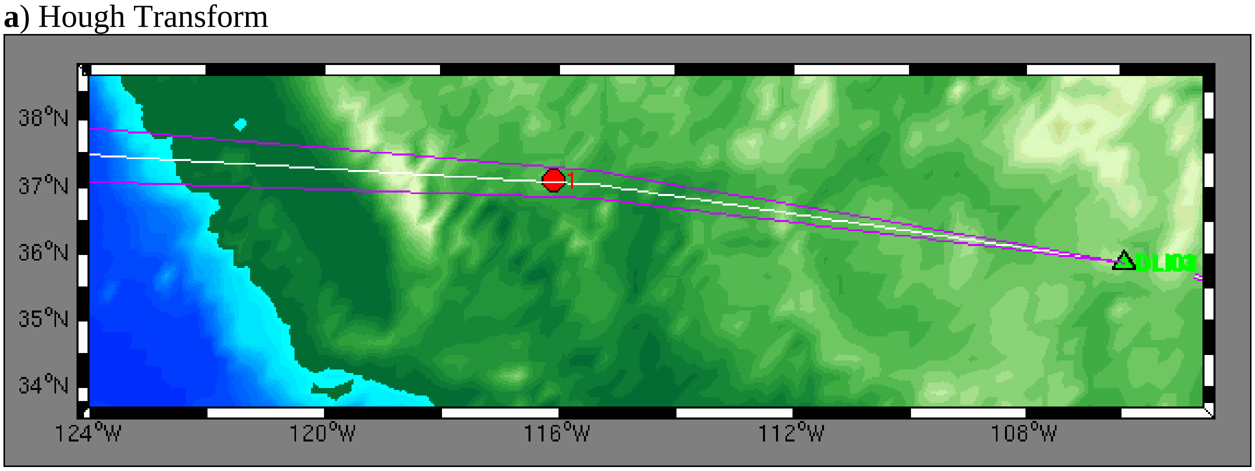
```
Stations Processed:  DLI01,DLI02,DLI03,DLI04

Inverse Slope Method: Detection - 1
2002/09/28 22:14:15.400   1033251255.40  0.402    1.69  279.8  0.368
2002/09/28 22:14:30.400   1033251270.40  0.420    1.89  282.7  0.341
2002/09/28 22:14:45.400   1033251285.40  0.446    2.22  279.2  0.345
2002/09/28 22:15:00.400   1033251300.40  0.515    3.24  282.7  0.341
2002/09/28 22:15:15.400   1033251315.40  0.652    6.48  282.7  0.341
2002/09/28 22:15:30.400   1033251330.40  0.695    8.11  282.7  0.341
2002/09/28 22:15:45.400   1033251345.40  0.519    3.31  282.7  0.341

Hough Transform Method: Detection - 1
2002/09/28 22:14:30.400   1033251270.40  0.420    1.89  282.7  0.341
2002/09/28 22:14:45.400   1033251285.40  0.446    2.22  279.2  0.345
2002/09/28 22:15:00.400   1033251300.40  0.515    3.24  282.7  0.341
2002/09/28 22:15:15.400   1033251315.40  0.652    6.48  282.7  0.341
2002/09/28 22:15:30.400   1033251330.40  0.695    8.11  282.7  0.341
```

Table 1 – Detection results file listing processed array elements (i.e. DLI01, DLI02, DLI03, and DLI04), detection method and processing results within detection limits. Data listed are human time, epochal time, correlation, fstat, azimuth (deg) and trace velocity (km/s)).

Viewing this file we see that the IS method detected a signal with a duration of 1.75 minutes, while the HT method detected a signal with duration 1.5 minutes. One final check of the detection methods is to look at the azimuth data and see if it crosses the ground truth origin location. The theoretical arrival time of the stratospheric phase for this event at the DLIAR array is 22:16:09.6, and the detection onset occur at time 22:15:00.4 (ISM) and 22:15:15.5 (HT). This gives stratospheric residual arrival times of approximately 69.2 sec for the ISM and 54.2 sec for the HT. The station-to-event azimuth as determined from the detection file data is 281.8 ± 1.6 degrees for IS and 282.1 ± 1.4 degrees for HT. In Figure 6a (HT) and 6b (IS) the station-to-event great circle path is plotted along with upper and lower bounds, as defined by the standard deviation (i.e. ±1.6 degrees and ±1.4 degrees). The event is bounded within the standard deviation paths. This example shows the usefulness of an automated detection routine for post-processing of infrasound array data.



a) Hough Transform



b) Inverse Slope

Figure 6a and 6b – MatSeis's Map Tool illustrating the location of the DLIAR infrasound array, the Watusi origin location (labeled 1), detection window determined station-to-event azimuth path (white great circle path) 282.1 degrees for HT and 281.8 degrees for IS, and the azimuth standard deviation bounds (magenta great circle paths) ±1.4 degrees for HT and ±1.6 degrees for IS.

In this example the detection algorithms produced similar detection results, where at high or moderate SNR the algorithms perform equally well. Further testing on synthetic and ground truth data should be done to determine which algorithm performs best at lower SNR and to determine the detection threshold parameters for detection of signals of varying duration.

7. Conclusion

Two automated signal-processing routines for Infrasound signal detection are given: Hough Transform and Inverse Slope. Upon processing infrasound array data using frequency slowness analysis yields three outputs per processing step: correlation, azimuth and trace velocity (or slowness). The key to infrasound signal detection was to find consecutive processing steps where the azimuth is constant (flat) and the correlation increased above background. Both methods are used to determine the representative slope for a specified number of point data. The representative slopes are then used in conjunction with their associated correlation values to determine if and when an infrasound signal was detected. A detection output file format is also proposed listing the processed array elements, followed by detections for each method. Each detection is supplied with a listing of correlation slowness processing characteristics: human time (YYYY/MM/DD HH:MM:SS.SSS), epochal time, correlation, fstat, azimuth and trace velocity.

As an example the ground truth event obtained from the Center for Monitoring Research web page was processed using the four-element DLIAR infrasound array located in New Mexico. This test determined the station-to-event azimuth (281.8 and 282.1 degrees) to within 1.6 and 1.4 degrees for the Inverse Slope and Hough Transform detection algorithms, respectively, as well as the detection window being closely correlated in time to the theoretical stratospheric arrival time. More testing will be required for tuning of the detection threshold parameters for different types of infrasound events.

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