EVALUATION OF INFRASONIC DETECTION ALGORITHMS

Milton A. Garcés and Claus H. Hetzer

University of Hawaii, Manoa

Sponsored by Defense Threat Reduction Agency

Contract No. DTRA01-00-C-0106

ABSTRACT

Infrasound array IS59, Hawaii, also known as the KONA array, started operations on May 25, 2000, and was certified into the International Monitoring System in December of 2001. In order to interpret the KONA data, various analysis tools have been acquired, developed, and evaluated at the Infrasound Laboratory (ISLA) of the University of Hawaii. These include modified versions of Sandia National Laboratories' MatSeis, Los Alamos National Laboratory's InfraTool, STA/LTA-based automatic detectors, and the Progressive Multi-Channel Correlation (PMCC) method. Evaluation of various detection algorithms during routine analysis of the KONA array data demonstrated that PMCC was not as vulnerable to spatial aliasing as frequency-domain detection methods, and it allowed detection of signals below the noise level, which is not possible with a STA/LTA detector. PMCC is presently used to produce automatic bulletins of signals detected by KONA. Phase names based on source identification have been devised to aid in classification. Detector results are subjected to a minimum-correlation/minimum-family-size filter, and both filtered and unfiltered bulletins are produced. The bulletins, which are not subjected to analyst review, provide Phase, Date and Time UT, Azimuth, Slowness, Correlation, Median Frequency of Detection, RMS Amplitude, and Family Size. Filtered detector results are written to CSS .arrival tables, which are subject to analyst review. Future work should concentrate on the development of an automatic, intelligent event identification algorithm that can screen the large amount of events picked by automatic detectors.

OBJECTIVE

The aim of this paper is to discuss the infrasonic signal detection algorithms that have been tested at the Infrasound Laboratory (ISLA), which operates the KONA array. The detection parameters for the signals that are routinely recorded will also be discussed.

RESEARCH ACCOMPLISHED

Summary of Analysis Techniques

In the first two years of the project, a suite of array-processing algorithms was evaluated. Initially, a combination of STA/LTA, F-K, and correlation analyses was used to obtain the arrival azimuth and trace velocity of high-frequency signals. Long-duration, emergent arrivals were detected using the Los Alamos National Laboratory's (LANL) InfraTool. Automatic detections were performed with these algorithms, and the methods and types of signals observed by the KONA array were presented in Garcés and Hetzer (2001). In December 2001, evaluation of the Progressive Multi-Channel Correlation (PMCC) detector (Cansi, 1995) was initiated. The PMCC detector has been automated and is the primary detection system presently implemented at the ISLA.

Description of the PMCC detector

PMCC is a time-domain detector that uses the correlation between various groupings of three sensors, *i,j,k*, to obtain an estimate of the consistency of the closure relation

$$r_{ijk} = \Delta t_{ij} + \Delta t_{jk} + \Delta t_{ki}\,, \qquad (1)$$

where Δt_{ij} is the time delay between the arrival of a signal at sensors *i* and *j* (Cansi and Klinger, 1997). If the consistency is below a certain threshold, a detection is registered. This detector has performed well in KONA for signal-to-noise ratios (S/N) that are close to unity and for all signal frequencies.

The PMCC algorithm is based on analysis of overlapping windows of data. The cross-correlation function of the data from two stations determines a time delay Δt_{ij}; and the mean quadratic residual of the closure relations (Eq. 1) of the sub array triplets yields the consistency of the signal. A subset or all of the array elements can be used for an initial time-delay calculation, which yields an initial value of arrival azimuth and slowness. Using these values, the consistency for additional elements can be progressively calculated. These additional array elements are directed into the calculation by examining a shorter section of the time window determined by a specified bearing and slowness range. If the point of maximum correlation requires a significant variance in azimuth, velocity, or time, the arrival is discarded. This optimizes computation time over a large array, and also allows initial false alarms caused by the presence of correlated noise in the first array subset to be eliminated when not present in further subsets (Cansi, 1995).

During the PMCC calculation, each time window is filtered into a number of frequency segments using a specified suite of filters, and the results are analyzed individually for similarity in azimuth, slowness, and consistency. A detection must satisfy specified trace velocity limits, arrival azimuth variation limits and duration limits, and must appear on a specified minimum number of stations. Each frequency band within each time window represents a "pixel" of data (Figure 1a) and each pixel is analyzed independently. Pixels adjacent in time and/or frequency are compared, and nearest-neighbor groups of pixels with similar characteristics are classified as "families" (Figure 1b). Families that conform to a specified range of sizes are placed in a table of detections.

In order to run the algorithm in near real time, a simple script must be used to generate an initialization file that contains all of the parameters necessary to determine the detection thresholds, as well as the names of and paths to the data files. This initialization file can then be passed to the PMCC executable file, which processes the waveform data and generates a file containing the aforementioned table of families. Each variation in the detection parameters requires a separate run of the detector with a unique initialization file.

For the KONA array, ISLA runs PMCC on all four elements using two sets of detection parameters ("high-frequency" and "microbarom" sets) for routine event processing, with two additional sets ("high-speed" and "very-low-frequency") in development (Table 1a). Each set uses a suite of second-order Chebyshev filters, with passbands shown in Table 1a. Detection parameters include analysis-window length and overlap, maximum consistency, minimum and maximum frequency and trace velocity, and maximum azimuthal variation permissible for inclusion in a family. Other parameters are dependent on these. The PMCC parameters act as logical "and" constraints, where all conditions must be satisfied for the detection to be registered. The resulting table of detection families is sorted and recorded in the "unfiltered" PMCC bulletin, then analyzed and filtered using various parameter thresholds (Table 1b), which act as logical "or" constraints, where satisfaction of any is sufficient for acceptance. A "filtered" bulletin and a Center for Seismic Studies (CSS) arrival table containing arrival time, azimuth, slowness, amplitude, and phase are created using the detections that are within the thresholds. The waveform data in the local CSS database is stored in 4-hour segments, and the PMCC detector processes an entire segment at once, two hours after its normal ending time (to ensure maximum data inclusion). The four iterations through the waveform data currently require about 20-30 minutes of computation time per 4-hour segment on a dual-processor 900-MHz SunBlade 2000 running Solaris 8. Both filtered and unfiltered bulletins of detections are produced weekly (Table 2).

Event Detection Parameters

The *high-frequency* parameter set uses a passband of 0.5-4 Hz, which effectively screens out the dominant low-frequency energy and allows comparatively low-amplitude events to be detected. Before being written to the arrival database, the arrivals are classified by phase. Currently ISLA personnel use a simple azimuth-based classification scheme derived from past observations of similar high-frequency events (Garces and Hetzer, 2001). Azimuthal ranges that include a known or hypothesized source are given a phase identification based on that source. Current phase classifications include surf noise, signals from the Pohakuloa Training Area, and possible volcanic signals; other signals are given a phase identification that signifies "origin unknown". Events that are believed to be local to the Big Island and its shoreline tend to show higher median frequencies than events that are not associated with specific regions (Figure 2). This is to be expected due to the higher attenuation of high-frequency energy with increasing range.

Surf Arrivals

Detections from azimuths of 234±10° and 320±10° are classified as surf events, with assigned phase names of "ik" and "iws" respectively. The signals generally occur as sets of impulsive, evenly spaced arrivals (Figure 3) with relatively high (> 2 Hz) frequency content (Figure 2). These arrivals are believed to be produced by ocean waves trapped within specific bays along the coast of the Big Island, and have an average root-mean-square (RMS) amplitude of 2.99 mPa. During periods of high activity, groups of surf signals will often be sufficiently closely spaced in time such that the PMCC detector will treat them as a single, long-duration event. Other azimuths may also contribute surf signals, but not with the consistency of the two areas specified above.

Pohakuloa Training Area Arrivals

Detections from 65±30° are identified as coming from the Pohakuloa Training Area and are assigned to the "ip" phase. Pohakuloa events generally occur as clusters of one or more irregularly spaced impulsive arrivals (Figure 4), and tend to have fairly high (> 2 Hz) frequency content (Figure 2). They have an average RMS amplitude of 4.99 mPa. Other signals from this azimuth may be more emergent with poor S/N.

Volcanic Arrivals

Detections from 110±10° are identified as coming from the general direction of Pu'u O'o, the active vent of Kilauea Volcano. These signals are tentatively assigned to the "iv" phase and have a RMS amplitude of 7.13 mPa.. To date the majority of these events have featured a S/N of approximately unity. Despite their relatively high amplitude, the events tend to occur at lower frequencies (mean frequency of detection is 0.9 Hz), where the noise floor is higher. This precludes visual analysis of the arrivals. Some tentative correlations have been found between infrasonic events and peaks of thermal activity in the Pu'u 'O'o crater.

Microbarom Arrivals

Detections in the 0.1- to 0.5-Hz frequency band are assigned the "im" phase and are believed to be generated by ocean wave interactions caused by severe weather, often at distances of several thousand kilometers. The arrivals have an average RMS amplitude of 12.57 mPa. Correlation has been drawn between the arrival azimuth of microbarom events (Figure 5) and areas of increased surface wave height. Microbarom energy has been shown to have promise in the field of storm tracking; for a more detailed treatment of this topic see Garcés *et al*. (2002).

Other Detection Parameters

The bands that are currently under development will contain events of a less general nature. For example, the "high-speed" band should be mostly useful for events propagating oblique to the ground, such as bolides or aircraft passing overhead, and for events that exhibit seismic phase velocities, such as earthquakes that disturb the microphone. The "very-low-frequency" band will be used for detecting mountain-associated waves that may be generated by Hawaii's and Maui's massive volcanic peaks. Currently the events in these bands are not recorded in the arrival tables or the filtered bulletins, but are present in the unfiltered bulletins (Figure 6).

CONCLUSIONS AND RECOMMENDATIONS

The detections of infrasonic signals in Hawaii have been improved through the evaluation of various array-processing algorithms. The effectiveness of the PMCC event detection algorithm at KONA has been demonstrated. Further research on this topic should include the development of real-time event detection and identification algorithms. Real-time detection could include implementation of the Antelope system, which can be run concurrently with the PMCC software for comparative evaluation. Event identification procedures could incorporate neural network techniques, and may permit the construction of a more concise automatic bulleting.

REFERENCES

Cansi, Y. (1995). An automatic seismic event processing for detection and location: The P.M.C.C. method. *Geophysical Research Letters*, **22**, 1021-1024.

Cansi, Y., and Y. Klinger (1997). An automated data processing method for mini-arrays. Newsletter of the European-Mediterranean Seismological Center, **11**, 2-4.

Garces, M, and C. Hetzer (2001). Infrasonic signals detected by the Kona array, Hawaii. *23[nd] Annual DTRA/NNSA Seismic Research Review*, Jackson Hole, 1-5 October 2001.

Garces, M., C. Hetzer, S. Businger and M. Willis (2002). Modeling of microbarom signals in the Pacific. *This volume*.

Garces, M., C. Hetzer, K. Lindquist, and D. Drob (2002). Source location algorithm for infrasonic monitoring. *This volume.*

Table 1. a) Parameters for the two active and two developing sets of detection constraints. b) The secondary constraints used to filter detections into confirmed arrivals. Columns for "High-Frequency" and "Microbarom" sets are currently active and in use at IS59; columns for "High-Speed" and "Very-Low-Frequency" sets are in development.

PMCC Parameter	High-Frequency	Microbarom	High-Speed	Very-Low-Frequency
Window Length	30 sec	90 sec	30 sec	300 sec
Window Overlap	5 sec	20 sec	5 sec	50 sec
Max Consistency	0.2 sec	0.5 sec	0.2 sec	5 sec
Passband	0.5-4.0 Hz	0.1-0.5 Hz	0.5-4.0 Hz	0.033-0.1 Hz
Trace Velocity	0.3-0.45 km/s	0.3-0.45 km/s	0.5-0.8 km/s	0.25-0.45 sec
Min # of Sensors	3	3	3	3
Max Interpixel Time Variation	2 x Window Overlap	2 x Window Overlap	2 x Window Overlap	2 x Window Overlap
Max Interpixel Frequency Variation	0.8 Hz	0.1 Hz	0.8 Hz	0.02
Max Interpixel Azimuth Variation	10°	10°	10°	10°
Max Interpixel Velocity Variation	10%	10%	10%	10%

ISLA Parameter				
Correlation	0.6	0.7	N/A	N/A
Family Size	14	N/A	N/A	N/A

Table 2. Sample filtered bulletin from the high-frequency parameter set showing information typically stored for each arrival. These arrivals satisfy one or both of the ISLA parameters shown in Table 1b.

Date	Time	Azimuth	Slowness (s/deg)	Correlation	Median Frequency	RMS Amplitude (mPa)	Family Size	Phase
9-Jul-02	00:02:15	323.2	311.65	0.32	2.96	0.8	37	iws
9-Jul-02	00:04:25	323	313.44	0.44	3.15	0.8	53	iws
9-Jul-02	00:06:45	322.7	312.54	0.45	3.07	0.9	46	iws
9-Jul-02	00:08:25	322.7	314.34	0.33	3.31	0.6	15	iws
9-Jul-02	00:09:15	323	314.34	0.45	3.35	0.7	27	iws
9-Jul-02	00:14:15	322.5	314.34	0.36	3.05	0.7	25	iws
9-Jul-02	00:22:25	316.6	312.54	0.66	2.45	2.1	24	iws
9-Jul-02	00:32:40	40.3	305.54	0.46	3.3	0.8	18	ip
9-Jul-02	00:59:45	48.5	297.21	0.48	2.52	1.5	38	ip
9-Jul-02	01:25:35	49.6	300.49	0.78	0.88	8.4	7	ip
9-Jul-02	01:34:20	57.6	314.34	0.31	2.31	1.2	18	ip
9-Jul-02	01:35:30	59	313.44	0.33	2.45	1.2	42	ip
9-Jul-02	01:37:55	57.3	312.54	0.28	2.39	1.2	19	ip
9-Jul-02	01:39:10	58.9	312.54	0.23	2.47	0.9	15	ip
9-Jul-02	02:15:20	308.1	317.09	0.47	2.3	2	43	iu
9-Jul-02	02:35:20	232.5	326.58	0.52	3.51	0.4	21	ik
9-Jul-02	02:38:15	232.4	324.63	0.44	3.55	0.4	20	ik
9-Jul-02	02:46:55	232.3	325.6	0.41	3.46	0.4	26	ik
9-Jul-02	02:59:15	231.8	322.71	0.32	3.54	0.3	21	ik
9-Jul-02	03:02:30	114.4	303.84	0.65	0.73	7.8	6	iv
9-Jul-02	03:53:45	232.4	324.63	0.44	3.3	0.5	24	ik
9-Jul-02	04:03:20	234.4	327.56	0.4	3.61	0.3	23	ik
9-Jul-02	04:08:15	232	323.67	0.36	3.5	0.3	16	ik
9-Jul-02	04:12:05	234.6	329.54	0.4	3.66	0.3	15	ik
9-Jul-02	04:13:25	232.6	325.6	0.46	3.46	0.9	59	ik
9-Jul-02	04:30:30	232.4	325.6	0.41	3.5	0.4	37	ik
9-Jul-02	04:40:55	75.3	281.85	0.5	3.31	0.5	23	ip
9-Jul-02	04:45:25	232.6	325.6	0.47	3.54	0.5	29	ik
9-Jul-02	04:53:00	232.4	327.56	0.48	3.37	0.5	24	ik
9-Jul-02	05:01:05	233.2	325.6	0.4	3.5	0.4	39	ik
9-Jul-02	05:02:30	232.4	323.67	0.38	3.57	0.4	26	ik
9-Jul-02	05:06:00	233	326.58	0.47	3.45	0.5	16	ik
9-Jul-02	05:08:35	232.7	329.54	0.44	3.55	0.5	19	ik
9-Jul-02	05:29:45	232.8	324.63	0.39	3.52	0.4	29	ik
9-Jul-02	05:41:45	232.5	326.58	0.38	3.55	0.4	14	ik
9-Jul-02	05:53:45	232.6	326.58	0.44	3.28	0.6	191	ik
9-Jul-02	06:01:35	232.2	320.82	0.41	3.6	0.5	34	ik
9-Jul-02	06:05:30	115	309.88	0.61	0.73	9.8	6	iv
9-Jul-02	06:12:25	232.6	325.6	0.42	3.59	0.5	36	ik
9-Jul-02	06:21:55	233.1	327.56	0.46	3.5	0.5	14	ik
9-Jul-02	06:43:20	234	327.56	0.39	3.58	0.5	17	ik

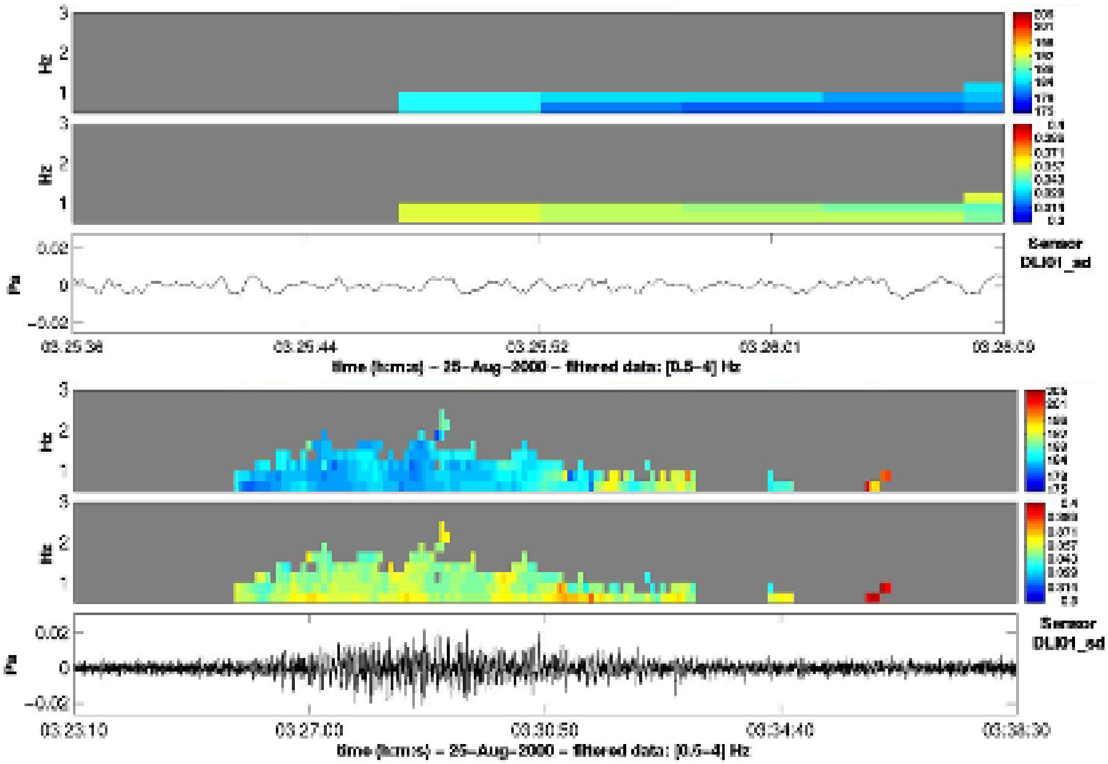

Figure 1. Graphical PMCC windows showing a) the pixel-like nature of an event family (above) and b) a large event family (below). Images are from the bolide event of August 25, 2000 (Garces *et al.*, 2002).

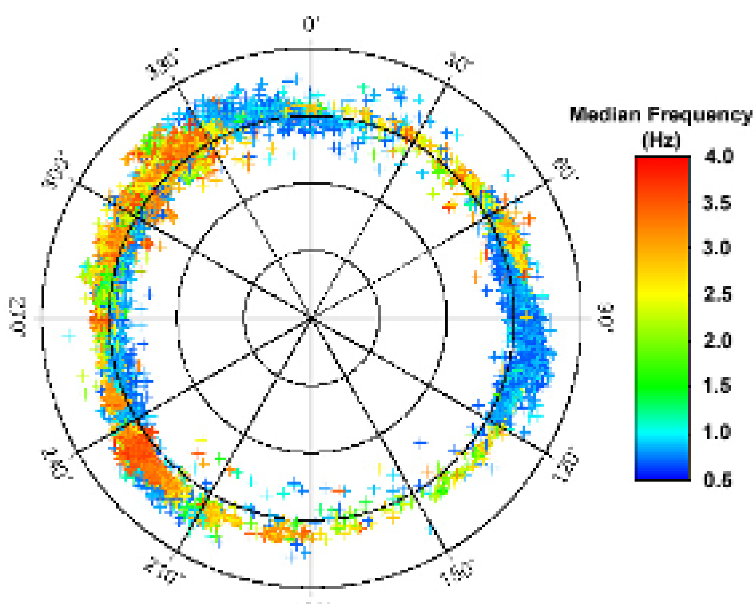

Figure 2. Polar diagram showing azimuth, slowness, and median frequency for arrivals in the "high-frequency" passband detected from January 1-June 30, 2002. Groups of arrivals at 75° (ip phase), 235° (ik phase), and 320° (iws phase) are believed to originate within 50 km of the array. Radial units are seconds/degree, increments of 100.

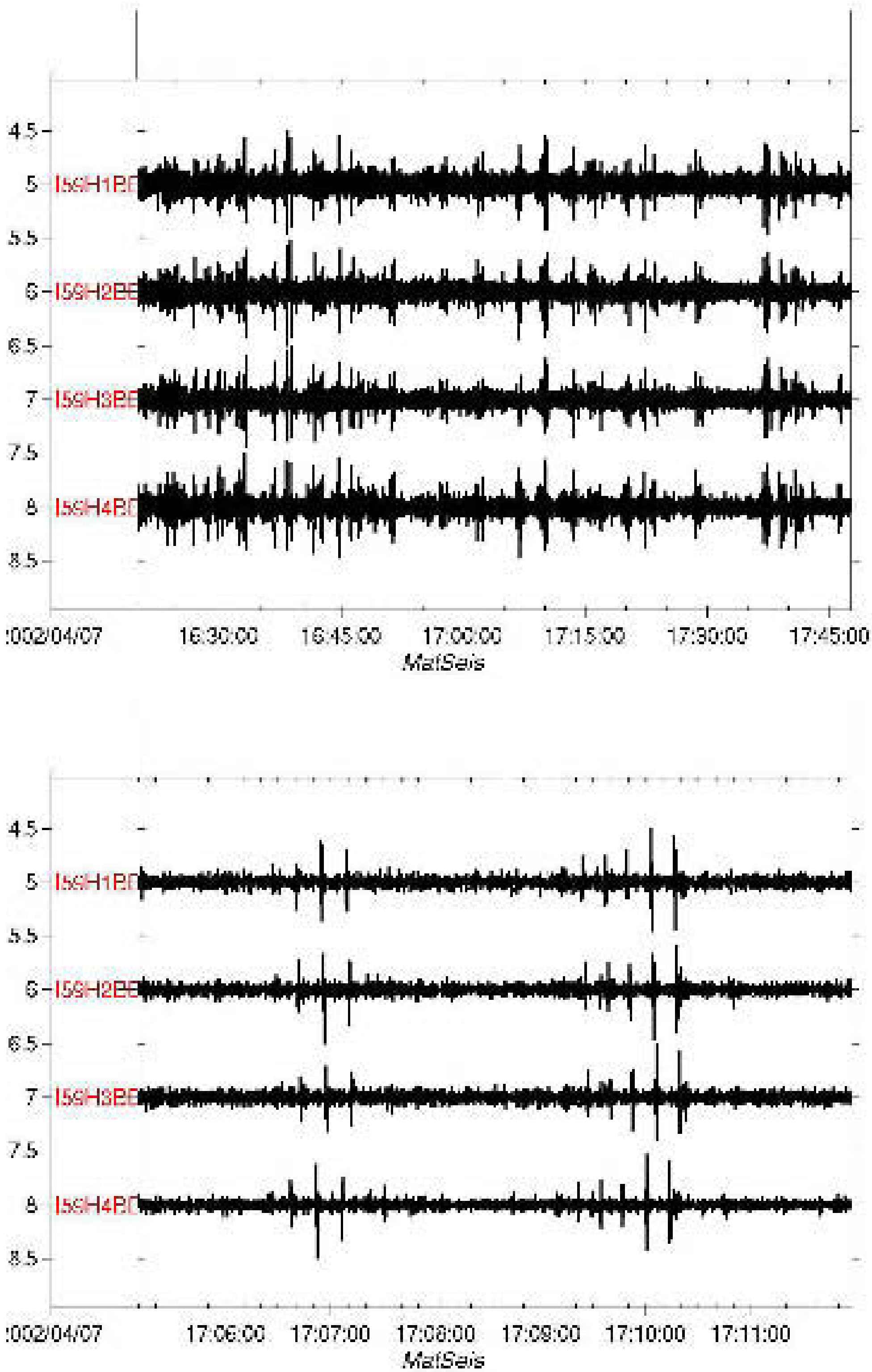

Figure 3. Bandpass-filtered waveform of typical "ik" surf arrival showing regular spacing in time both of groups of arrivals (above) and of individual arrivals (below).

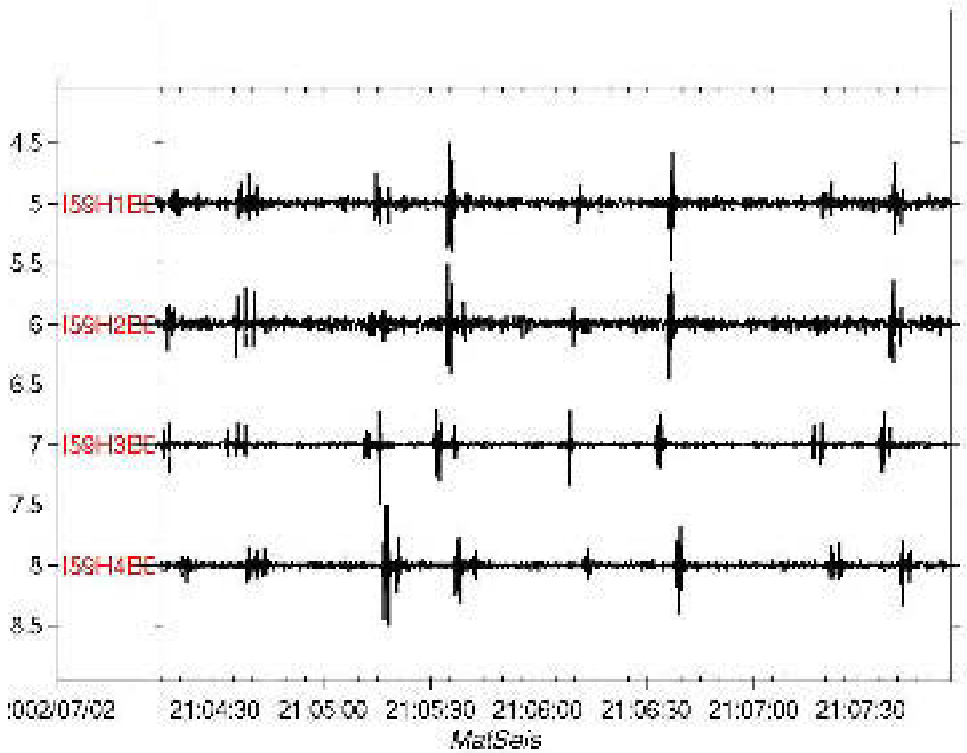

Figure 4. Bandpass-filtered waveform of typical "ip" events showing impulsive quality and irregularity in time.

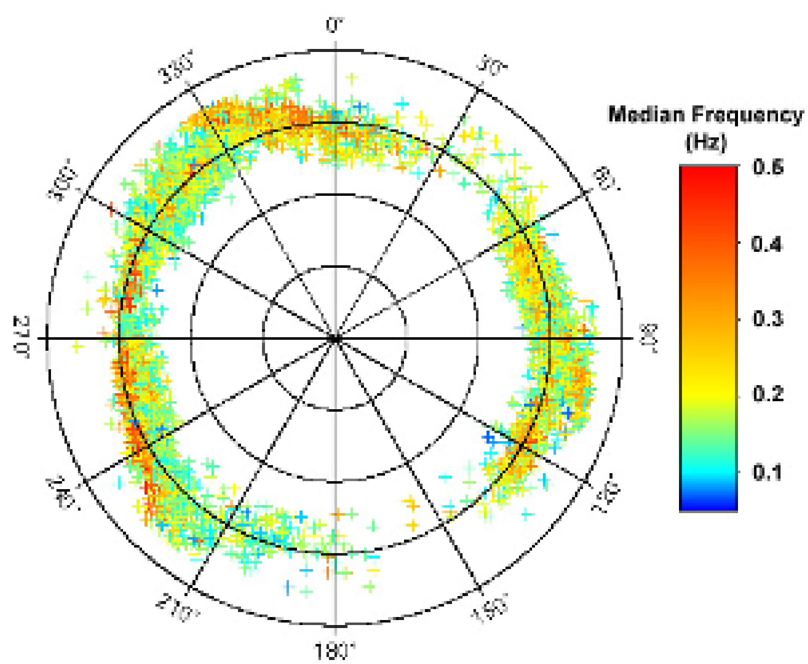

Figure 5. Polar diagram showing arrival azimuth, trace slowness, and median frequency of microbarom events detected from January 1-June 30 2002. Radial units are seconds per degree, increments of 100.

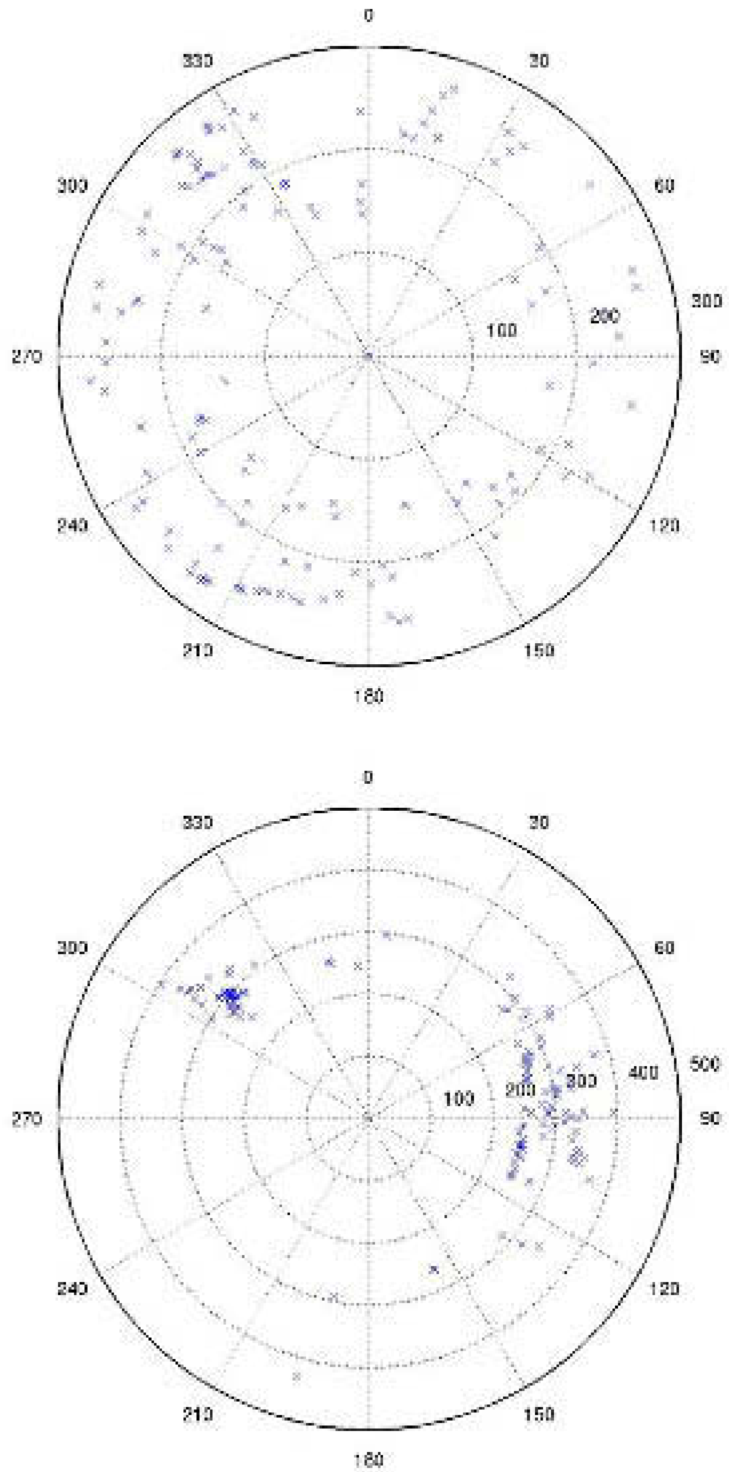

Figure 6. Polar diagrams showing arrival azimuth and trace slowness for detections made by high-speed (above) and very-low-frequency (below) detection parameter sets. Radial units are seconds per degree.