

**MULTIPLE-ARRAY DETECTION, ASSOCIATION AND LOCATION OF INFRASOUND AND
SEISMO-ACOUSTIC EVENT—UTILIZATION OF GROUND TRUTH INFORMATION**

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ABSTRACT

Detecting infrasonic arrivals is more complex than detecting seismic arrivals since temporal variations in atmospheric conditions and local noise are substantial on the spatial scale of typical arrays. In order to obtain the optimum signal detection, we assess detectors that distinguish the signal from both correlated and uncorrelated noise. One approach to this detection problem is implementation of the F-detector, which employs the F-statistics, and cross-correlation technique separating correlated and uncorrelated signals. We test a modified F-detector that applies an adaptive procedure to identify variations in correlated noise, thus reducing false alarms. Using the modified F-detector, we investigate the temporal variation in the adaptive nature of the detector for a number of sites in the Korean Peninsula. In this study, six seismo-acoustic arrays in South Korea (BRDAR, CHNAR, KMPAR, KSGAR, TJIAR, and YPDAR), which are cooperatively operated by the Korean Institute of Geoscience and Mineral Resources (KIGAM) and Southern Methodist University (SMU), were used. We tested the sensitivity of the detection procedure to the adaptive window used to estimate the C parameter that characterizes the correlated noise and impacts the false alarms rate. The C values are found to be stable over long time periods for arrays within the peninsula but show variations under high wind velocity conditions for adaptive windows as short as 1 hour for arrays on islands or near the coast. This result suggests that optimal detection processing requires careful characterization of background noise level and its relationship to environmental measures such as wind speed and azimuth at individual arrays. In order to further understand variations in background noise, the 10th, 50th, and 90th percentile noise spectral densities were estimated. The noise estimates show a strong wind speed effect on acoustic noise; for example, the spread between the 10th and 90th percentiles is about 40 dB at 0.1 Hz. For arrays on islands or near the coast, the noise power densities are higher and also indicative of higher wind speeds. Ultimately, this work will provide a basis for defining optimum detectors that will provide a basis for locating infrasound events using multiple arrays.

OBJECTIVES

This project is designed to develop an automated methodology for event detection and location of seismic and infrasound data from seismo-acoustic arrays and apply the methodology to regional networks for validation with ground truth information. In previous years we have developed the detection and location framework. Additionally, the importance of ground truth datasets in refining atmospheric propagation path effects has been investigated. Recent work that is reported here focuses on the characteristics of the infrasound detectors that provide the input to the automated location procedures.

RESEARCH ACCOMPLISHED

Motivation—Automated Detectors for Infrasound

The infrasonic signal contains the information that will be used for tasks such as event location and characterization; the noise is everything else that complicates signal detection and analysis. By improving the signal-to-noise ratio (SNR) through the processing of array data (closely spaced but individual sensors), detection of events that cannot be uniquely identified on a single station is possible. However, the problem is that parts of the noise field—for example, seismic noise generated by trains or heavy industry—may be coherent across the array. This type of noise can obstruct data analysis and signal identification. Moreover, for infrasound, unlike seismic signals that travel through the solid Earth, the detection is complicated by temporal variations in atmospheric conditions (Arrowsmith et al., 2008), and the signal as well as the noise can be dependent on time-varying weather conditions. The dominant sources of noise, such as weather systems, ocean waves, rivers, and cultural noise, in some cases can produce coherent noise across an infrasound array that is time-dependent. Le Pichon et al. (2004) also notes that ocean activity such as microbaroms and surf-generated waves are examples of common sources of infrasound noise that is linked to seasonal changes. Therefore, the understanding of these processes and how they vary among arrays is important work ultimately providing an approach to and physical basis for distinguishing signals from correlated noise. The data from these noise sources may also be important in characterizing environmental effects.

Relationship between Wind Velocity and Infrasonic Noise

We analyzed the relationship between infrasound noise characteristics and wind velocity and direction using datasets from six South Korean seismo-acoustic arrays (BRDAR, CHNAR, KMPAR, KSGAR, and YPDAR) that are cooperatively operated by KIGAM and SMU (Figure 1). The Baengnyeong island array (BRDAR) and the Yeonpyeong island array (YPDAR) are installed in the west sea next to the Korean Peninsula and are surrounded by ocean, as is KSGAR, which is on the east side of Korean Peninsula (Figure 1). CHNAR, KMPAR, and TJIAR are located within the continent. All arrays except for KMPAR have weather channels measuring wind velocity, wind azimuth, and temperature,

Figure 2 shows the relation between wind velocity and the average maximum amplitude of the filtered waveform with respect to various frequency bands (0.5–1 Hz, 1–2 Hz, 2–4 Hz, 4–8 Hz, and 8–16 Hz). Absolute infrasound noise levels were estimated for each of the arrays for a total of 7 days (Julian days 079 and 081–086) in 2010 at BRDAR (BRD42), CHNAR (CHN05), KSGAR (KSG12), and TJIAR (TJI10). Due to late installation, YPDAR data were excluded from this analysis. Wind velocity estimates were made by calculating the average wind velocity value during 15-minute intervals with moving windows. The maximum infrasound amplitudes were determined first for 1 second intervals and then averaged over 15 minutes with a moving window in a manner consistent with the wind velocity estimates. Infrasound amplitudes on all channels increase as wind speed near the sensor increases. Woodward et al. (2005) suggested that wind-induced noise for International Monitoring System (IMS) stations increases with increasing wind speed and that the absolute micropressure amplitudes increase as wind velocity increases. The range of wind velocities and noise levels is the greatest for BRDAR and is reflective of its location on an island, while CHNAR and TJIAR have a very narrow distribution of noise levels, with low values from 0.5 to 4.0 Hz. The low wind velocities at TJIAR may also reflect local topographic effects. Background noise at BRDAR, CHNAR, KSGAR, and TJIAR is affected by wind velocity, with ocean waves acting as a possible secondary source, leading to higher noise levels at BRDAR and KSGAR.

To examine the spectral properties of the noise, the filtered waveforms are analyzed using Welch's method (Welch, 1967) producing a single power spectral estimate from an average of spectra taken at regular intervals over a specific time duration (Hedlin et al., 2002). Four waveform segments, each 204.8 s long, were extracted from the first 15 minutes of each hour, following the data processing steps of Hedlin et al. (2002). A 10 percent cosine taper was applied to the front and back of each time series and then zero-padded to avoid truncation effects. A single

spectral estimate was derived from the average of the four spectra. Using three weeks of data recorded in all arrays, a total of 454 power spectral density estimates were made for each site. Estimates for BRDAR, CHNAR, KMPAR, KSGAR, and TJIAR used Julian days 074–094, while estimates for YPDAR used Julian days 260–262, 264–268, and 270–280. Figure 3 displays 10th, 50th, and 90th percentile noise levels at all frequencies from 0.0025 Hz to 20 Hz. The narrow band noise spikes between 1 Hz and 20 Hz at all arrays are a result of radios at the sites interacting with the data acquisition system. The microbarom peak is centered at 0.2 Hz in all arrays. Hedlin et al. (2002) notes that the overall spectral shape is due to atmospheric phenomena that produce significant energy at less than 0.1 to 1 mHz. The spread between the 10th and 90th percentiles at BRDAR and YPDAR is larger (>40 dB) than the spread at other arrays (40 dB) at 0.1 Hz, which means the background noise variation is higher in the case of BRDAR and YPDAR in the low-frequency band. In the high-frequency band (1–10 Hz) where many of our signals are observed, the spread in noise values between arrays tends to be similar. Thus the most significant difference between arrays located on islands and those on the continent is that there is more background noise at the island sites at lower frequencies.

Figure 4 plots, against wind speed, the power densities at several frequencies—0.02 Hz, 0.05 Hz, 0.1 Hz, 0.25 Hz, 0.5 Hz, 1 Hz, 2.5 Hz, and 5 Hz—at BRDAR, TJIAR, CHNAR, and KSGAR during the spring. As expected, wind speeds are site dependent. TJIAR and CHNAR, located in the center of peninsular, have relatively low wind velocities compared to BRDAR and KSGAR, which are close to the ocean and have wind velocities as high as 17 m/s and 13 m/s, respectively. The noise power density at TJIAR is the lowest but increases, with the wind velocity, up to 4 m/s. All sites are strongly affected by wind speed; however, the background noise of CHNAR and TJIAR are less affected than those of BRDAR and KSGAR. In addition, the distribution of the power density at BRDAR is somewhat more scattered than the distribution at KSGAR. This additional result suggests that, in the case of BRDAR, the noise power density may be influenced by additional local site characteristics, possibly related to the ocean environment. In all cases, the noise power density in the band between 0.0025 Hz and 20 Hz is strongly dependent on wind speed.

Figure 5 quantifies the seasonal variation of wind azimuth for BRDAR, CHNAR, and KSGAR. The data were processed in the same manner as the wind velocity data, using a total of three weeks of data for spring (Julian days 074–094, 2010), summer (Julian days 166–186, 2010), fall (Julian days 260–262, 264–268, and 270–282, 2010), and winter (Julian days 357–365, 2010 and Julian days 001–012, 2011). The most-consistent wind directions occur in the winter and are from the northwest. The variation in wind azimuth is correlated with array location. Array site performance is better when the wind azimuth and speed show little variation (Hedlin et al. 2002), as happens during the winter in Korea. Therefore, based on this analysis we would expect more-reliable detection results during the winter. Arrowsmith and Hedlin (2005) indicate that for their study area there are more detections during the winter than during the summer.

Implementation and Testing of Detection

One recent approach to the detection problem for temporal variations in background noise uses the F-statistic (Blandford, 1974) as the detection method. This procedure has been incorporated into InfraMonitor2.6 (Arrowsmith et al., 2008). Automatic detection is based on the F-statistic calculated as the power on the beam divided by the average over all channels of the power of the difference between the beam and the individual array channels as defined

$$F = \left(\frac{J-1}{J} \right) \frac{\sum_{n=n_0}^{n_0+(N-1)} \left[\sum_{j=1}^J x_j(n+l_j) \right]^2}{\sum_{n=n_0}^{n_0+(N-1)} \left(\sum_{j=1}^J \left\{ x_j(n+l_j) - \left[\frac{1}{J} \sum_{m=1}^J x_m(n+l_m) \right] \right\}^2 \right)},$$

where J is the number of sensors, $x_j(n)$ is the waveform amplitude of the n th sample of the mean-free time series from sensor j , l_j is the time-alignment lag obtained from beamforming, and n_0 is the starting sample index for the processing window. In the case of a signal or noise burst that is incoherent across the array, the amplitude will increase with the increasing beam's residual at the same time, and the ratio remains the same.

In the presence of correlated noise, the theoretical F-statistic is distributed as $CF_{2BT, 2BT(N-1)}$, where B is the bandwidth of the filtered data in the length of the processing (detection) window, T, over which the power is averaged; N is the number of array elements; and C is given by

$$C = \left(1 + N \frac{P_s}{P_n} \right)$$

with P_s/P_n denoting the ratio of correlated noise power to uncorrelated noise power (Shumway et al., 1999). By comparing the observed distribution of F-statistic ($F_{2BT, 2BT(N-1)}$) to the theoretical F-distribution, one can estimate a time-dependent scaling factor, C, and map the observed F-statistics in the time window to the theoretical ones and thus utilize the standard p-value to declare a detection. The standard F-detector is modified so that it is adaptive in time, capturing changing noise characteristics with new estimates of C made for subsequent adaptive windows when the total time window duration is larger than for the adaptive window. In this analysis, data were processed with the following parameters: time window (20 s), overlap (50%), p-value (0.01), and adaptive windows (1, 12, and 24 hours).

Characterization of the Adaptive Nature of the F-Detector at Various Arrays

Figure 6 reproduces the C-value variations estimated for BRDAR, CHNAR, and KSGAR as a function of time. Three different durations of the adaptive window (1, 12, and 24 hours) were independently applied to these datasets (Julian day 085, 2010). Using the 24-hour adaptive window, the C-value for BRDAR (1.2) is higher than the C-values for the other two arrays (1.1). For the 1-hour adaptive window, BRDAR has C values as large as 1.6, with significant time variation, possibly related to the time variations in island wind conditions as documented earlier. In the case of the 12-hour adaptive window at CHNAR and KSGAR, the C-values using 1-hour windows are the same as that estimated using the 24-hour adaptive window.

The C-values at KSGAR are stable and do not correlate with wind velocity. Something in addition to the wind velocity itself may be affecting the C-value estimates at BRDAR and, to less extent, at CHNAR. It is possible that the adaptive process at BRDAR may be affected by small local events under low-noise conditions. In other words, if wind velocity is very low, infrasound sensors can be very sensitive to small local events such as movement of a tree or car, construction work, or any of a variety of human activities if they are close to the array. Under these conditions the background noise level at low wind velocity is slightly higher than that observed for other arrays, and the C-value increases due to this coherent noise source. On the other hand, the interpretation in case of high wind velocity needs additional consideration.

Further noise analysis was undertaken for BRDAR in order to refine the relationship between wind velocity and C-value over 33 days (Julian days 085–117, 2010). Each C-value was calculated using a 1-hour adaptive window to assess the temporal variations, yielding a total 24 × 33 points in Figure 7. Wind directions of 120° to 180° and 300° to 360° dominate Baengnyeong island during the spring, with the highest velocity associated with directions from 300° to 360°. As in the previous analysis, the C-value increases with decreasing wind velocity, up to 2.3 in case of wind velocity less than 1 m/s.

The number of detections (Figure 8, bars) calculated by InfraMonitor2.6 with the 1-hour adaptive window for BRDAR, CHNAR, and KSGAR during one day (Julian day 085, 2010) was compared with wind velocity (Figure 8, lines) averaged over 1-hour segments. As discussed above, the C-values are dependent on wind velocity during each adaptive window. The trend in wind velocity follows diurnal variations, and the number of detections follows the wind velocity trend. Wind velocities from 0 to 9 hour in coordinated universal time (UTC) (daytime, from 9 am to 6 pm, in local time) for all arrays except KSGAR generally have high values, up to 6 m/s, with low values during local nighttime. In the case of KSGAR, wind speed rises to over 6 m/s during nighttime, reducing the number of detections. This is likely related to the site characteristics, such as surrounding mountains and ocean. The number of detections increases when wind velocities are low values at all arrays, especially CHNAR, and is consistent with the International Data Centre (IDC) report that detections based on the PMCC algorithm (Cansi, 1995) increased under low wind velocity and low absolute micropressure (Woodward et al., 2005). It was further shown that most detections during low wind velocity conditions were false alarms (Woodward et al., 2005) caused by local events or other sources of coherent noise. During the daytime, there are few detections at CHNAR and KSGAR, but at BRDAR the number of detections can, in some circumstances, rise under increasing wind conditions. This result suggests that at BRDAR there is some other coherent noise source, such as ocean waves or local events.

CONCLUSIONS AND RECOMMENDATIONS

Proper detection processing requires an understanding of background noise levels and their relationship to environmental parameters such as wind speed, wind azimuth, and possibly surf noise. In this study we find that in general infrasound amplitudes on all channels increase as wind speed near the sensor increases. In order to fully characterize the background noise estimates at each site, the 10th, 50th, and 90th percentile noise spectral densities at all frequencies were calculated for each array. These estimated noise spectra are time dependent, and the spread between the 10th and 90th percentiles is large, about 40 dB at 0.1 Hz. This spread in noise power is especially large for the arrays on the islands, with generally higher values that are correlated with higher wind speeds. All array sites in this study are affected by wind speed, but the effect is reduced for the continental arrays, thus illustrating that both the wind speed distribution and the noise levels are site dependent. In the case of arrays near the ocean, the noise power density is influenced by additional local site characteristics, possibly related to the ocean environment. Finally, the data indicate that the most-consistent wind directions occur in the winter and are from the northwest in South Korea. This result suggests that more-reliable detection results would be expected during the winter.

F-detector as implemented in InfraMonitor2.6 (Arrowsmith et al., 2008) enables us to improve signal detection under noise conditions that change with time. The C-values estimated in this analysis show little temporal change for arrays within the continent but strong variations in C with time (adaptive windows as short as 1 hour) at the island arrays. This temporal variation correlates with wind speed at each array. In the unique case of BRDAR, the C-value increases with decreasing wind velocity. This result suggests that local signals, regarded as the correlated noise, might be affecting the detection process at this site. Additionally, it was shown that the number of detections increases when the wind velocity falls to low values at all arrays.

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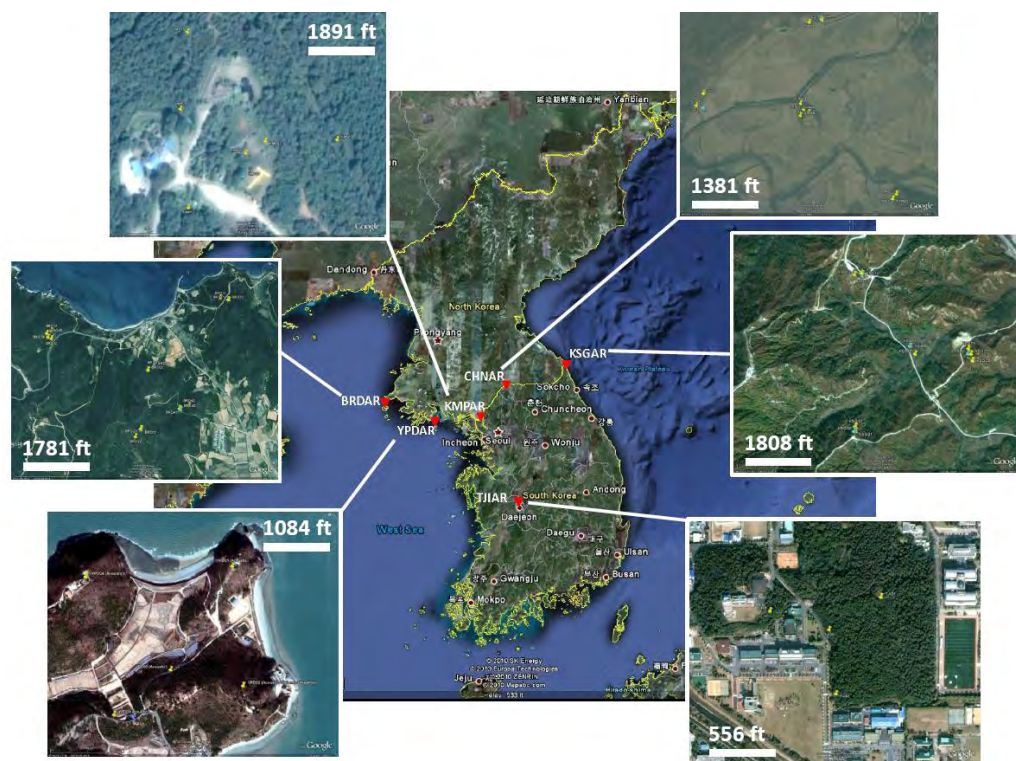


Figure 1. Locations of the sesimo-acoustic arrays in South Korea. Yellow push-pins in each image designate the location of individual array elements.

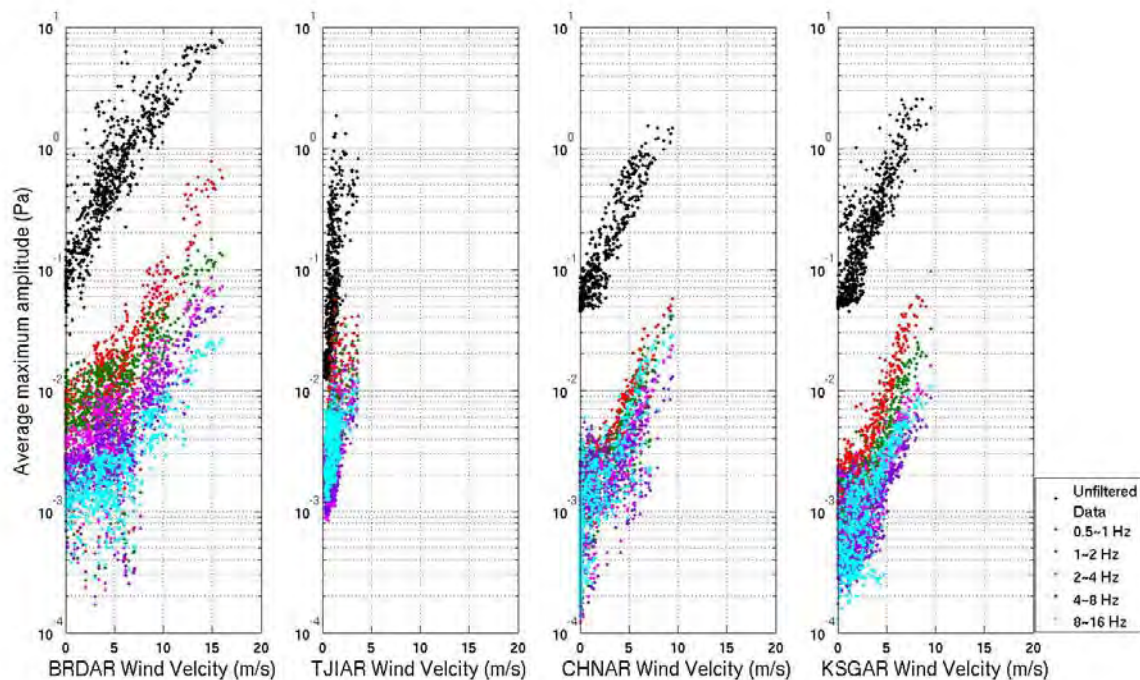


Figure 2. Relationship between wind velocity and average maximum amplitude of the filtered infrasound waveforms (0.5–1 Hz, 1–2 Hz, 2–4 Hz, 4–8 Hz, and 8–16 Hz) during 7 days (Julian days 079, 081–086) at BRDAR, TJIAR, CHNAR and KSGAR.

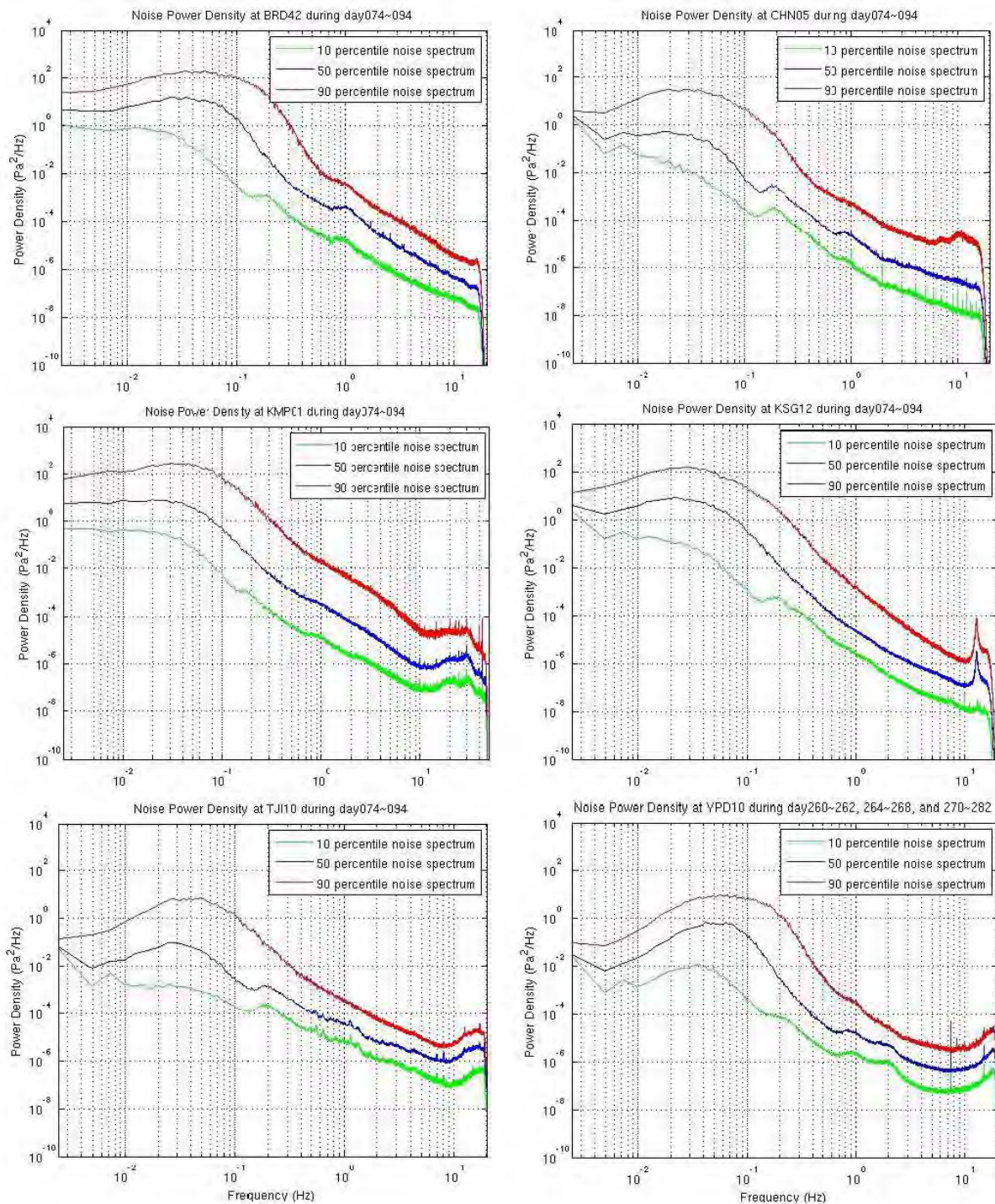


Figure 3. Infrasonic noise power density at BRDAR(42), CHNAR(05), KMPAR(01), KSGAR(12), TJIAR(10) during Julian days 074~094 (2010) and YPDAR(10) during Julian days 260~262, 264~268, and 270~282 (2010).

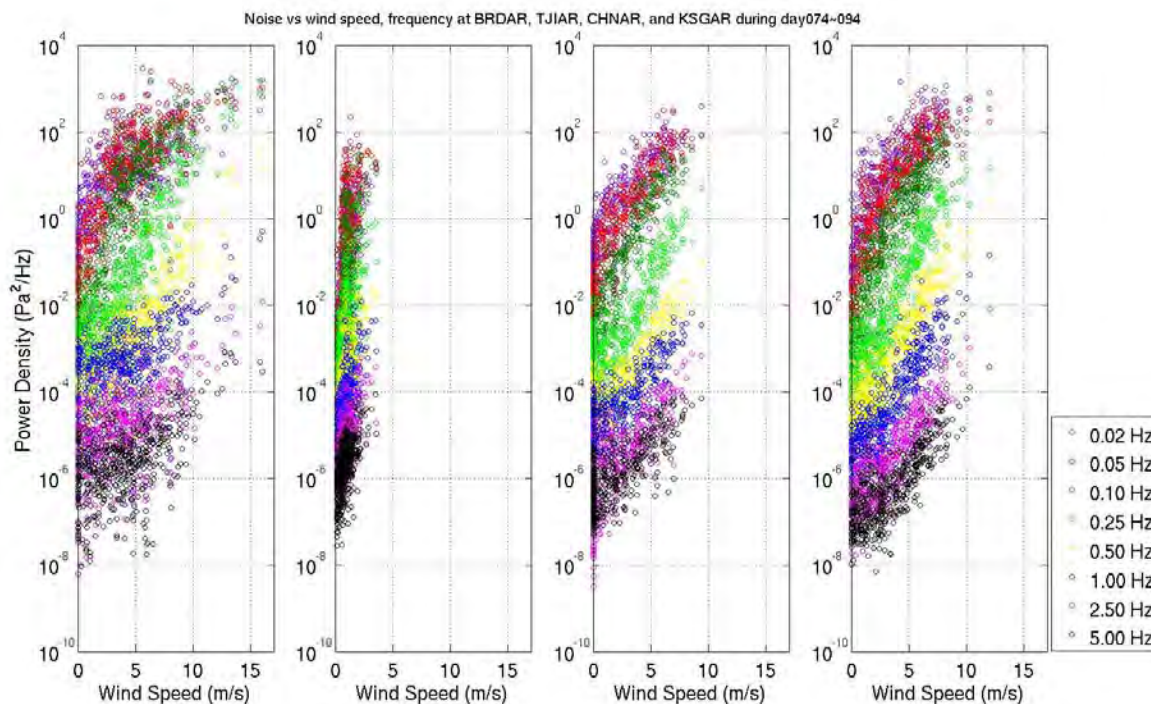


Figure 4. The four panels document the strong dependence of infrasonic noise on wind speed and frequency at the four sites in Korea during the spring.

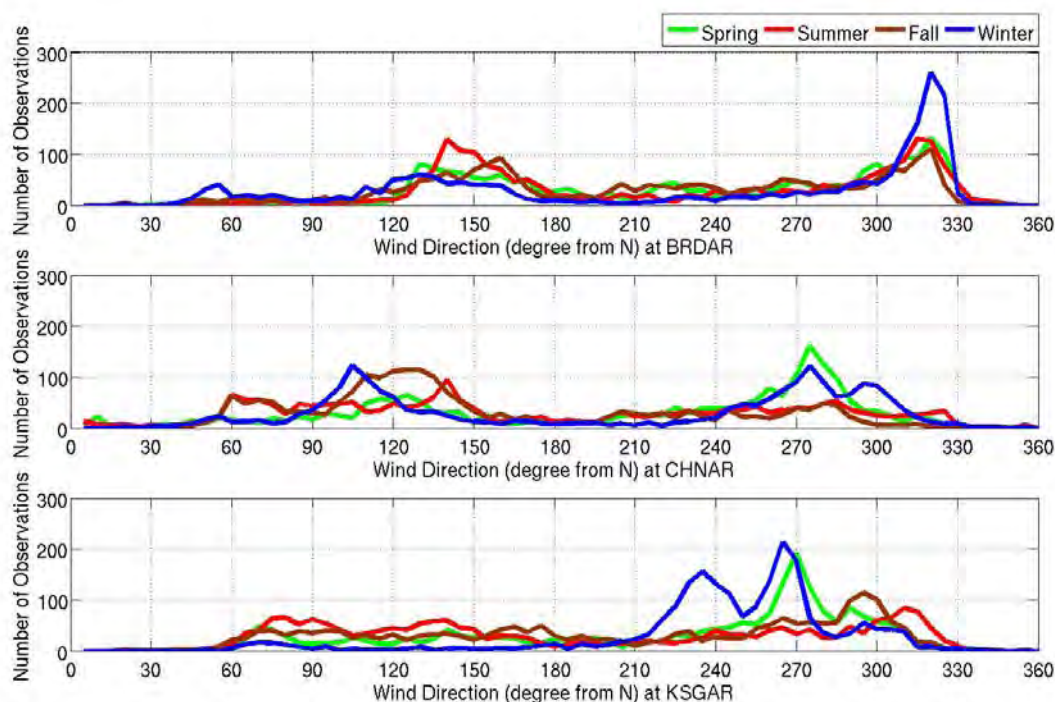


Figure 5. The number of observations as a function of wind direction at BRDAR, CHNAR, and KSGAR in Korea for spring (Julian days 074–094, 2010), summer (Julian days 166–186, 2010), fall (Julian days 260–262, 264–268, and 270–282, 2010), and winter (Julian days 357–365, 2009, and Julian days 001–012, 2010).

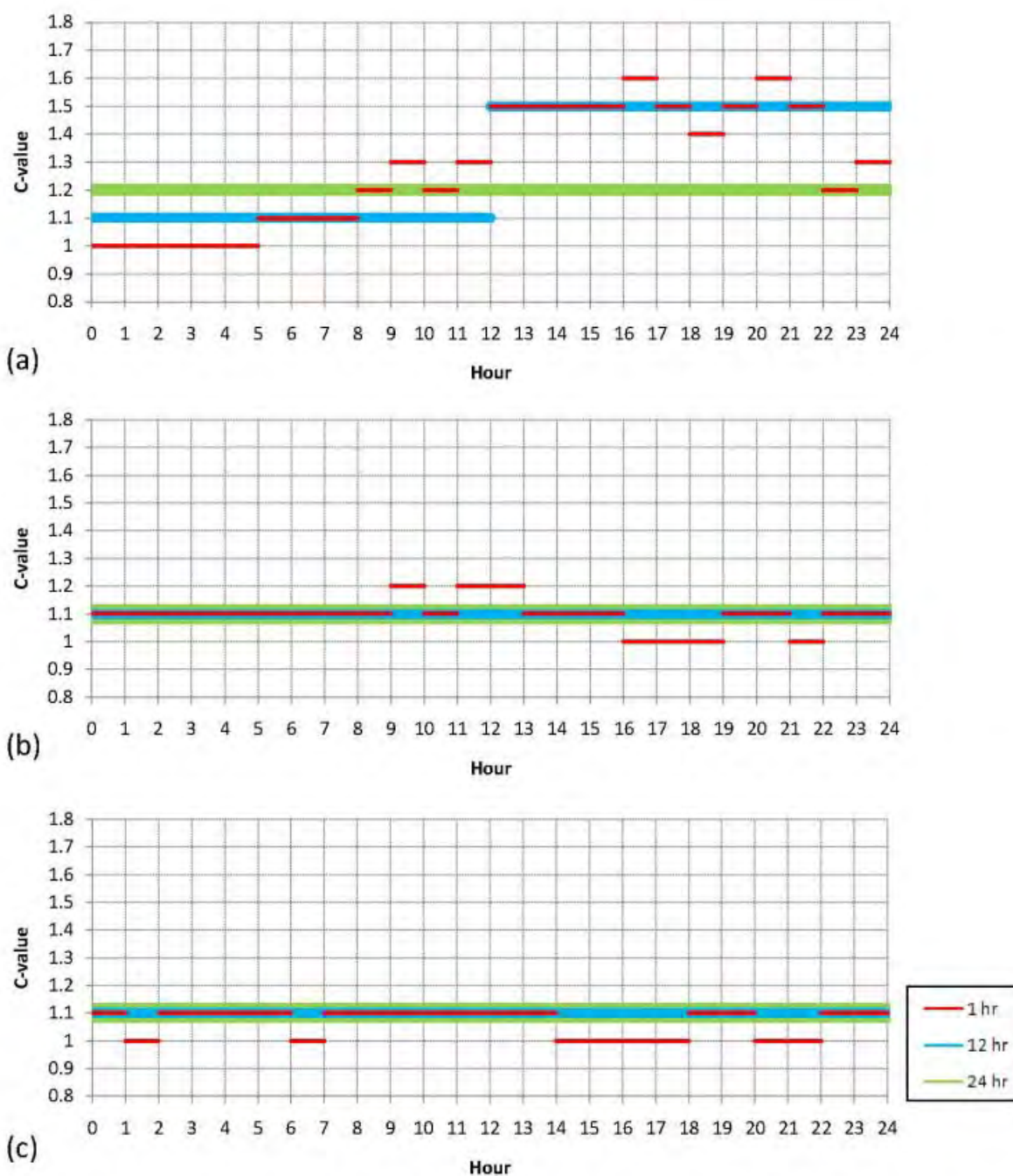


Figure 6. C-value variation with time for (a) BRDAR, (b) CHNAR, and (c) KSGAR on day 085, 2010 (hr in UTC).

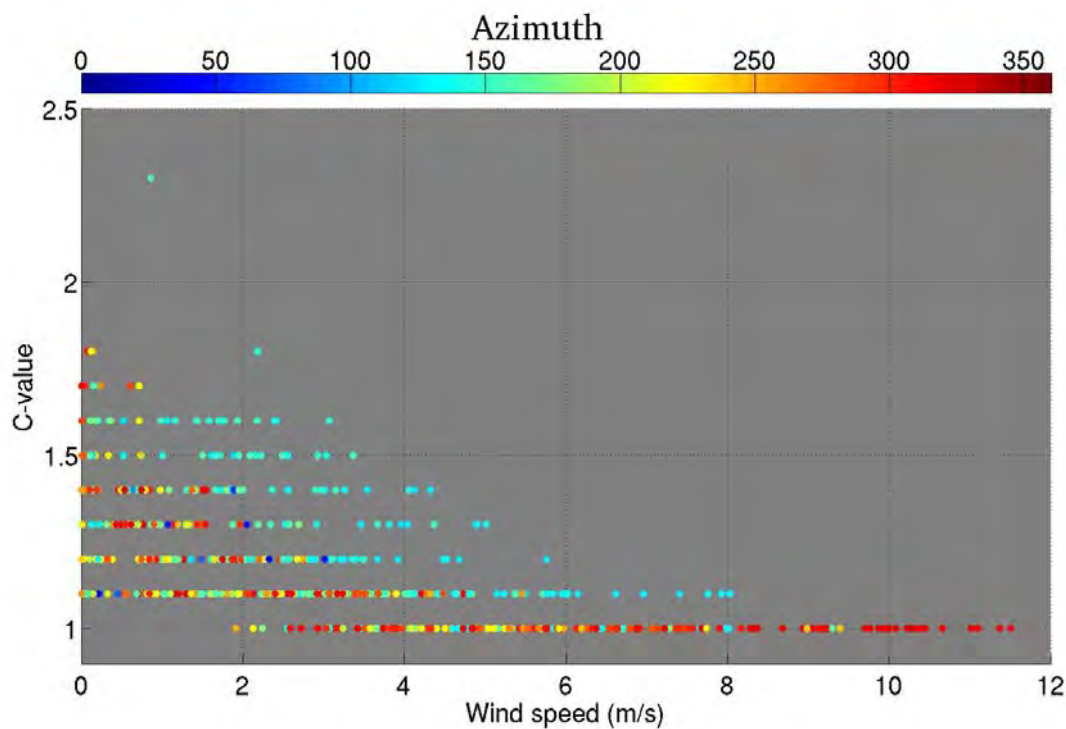


Figure 7. Relationship between wind speed, wind direction, and C-value for 33 days (Julian days 085–117, 2010) at BRDAR.

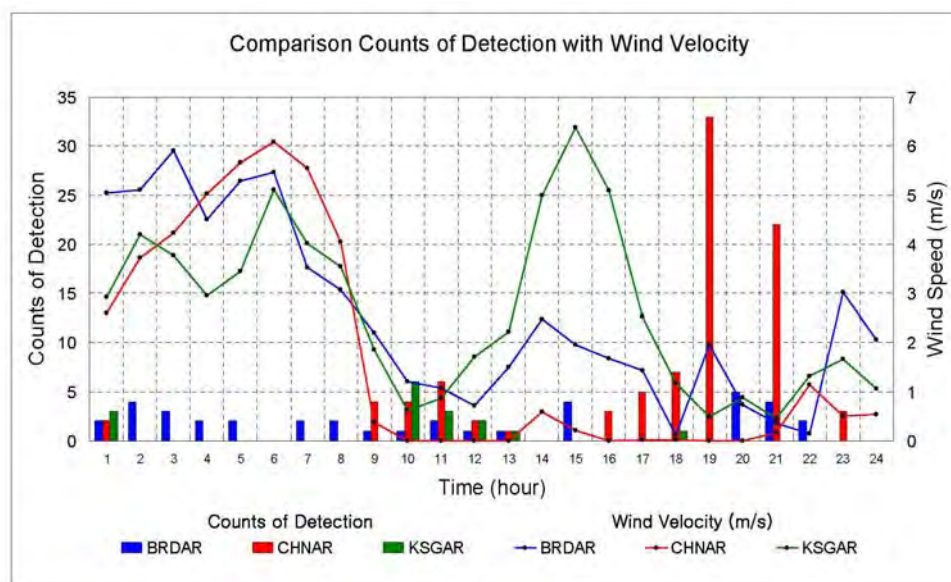


Figure 8. Relationship between number of detections and wind velocity for one day (Julian day 085, 2010) at BRDAR, CHNAR, and KSGAR.