2-D SIGNAL DETECTORS FOR 3-COMPONENT SEISMIC RECORDINGS

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ABSTRACT

Despite much ingenuity in research of optimal signal detector design the simple and universal used STA/LTA detector has a performance literally 'second-to-none' to other often more advanced detectors. In other words, continued research in this field may be considered a bit futile. Our undertaking here has been motivated by some strange observational phenomenon in analysis of seismic recordings from national Norway network stations namely that apparently strong events were not recorded albeit easily visible in corresponding local records. The other, mentally puzzling attitude among seismologists, is that only 1-D detectors (Z-component) are used while at local and regional distance ranges horizontal components often exhibit the strongest not necessarily P-waves signal amplitudes. We are investigating both of these signal phenomena with goal of improving signal detection in a CTBT IMS context.

The two major reasons for non-detected signals are apparently i) a gradual P-amplitude increase (typical of many mid-oceanic events) and ii) spiky records. In the former case, a lag of 5 - 10 sec between the STA and LTA windows respectively often suffice while in the latter case the STA/LTA detector per se is not robust enough to handle spikes. These may naturally be removed by a simple spike filter preceding in time the detector operation but this is not always done. Anyway, the station TRO (Tromsoe, N.Norway) has a poor signal detection performance which is obviously related to a spiky operational environment (housed in a big building). Introducing a Kolmogorov-Smirnov (K-S) type detector where the test statistic is tied to the non-parametric K-S-distribution (not power as for the STA/LTA) signal detection increased significantly. However, not unexpectedly in a non-spiky environment the latter detector had a superior performance.

2-D signal detectors where the test statistics incorporate information extracted from both the vertical and horizontal seismometers are not much discussed in the literature despite often strong signals on the latter components. A prerequisite for 2-D detectors is that i) waveforms are at best weakly correlated between components and ii) also envelopes should be weakly correlated. We have tested both of these assumption on real data (3-C records from the ARCESS array) and found them valid in the frequency ranges 2 - 8 Hz and 1 - 10 Hz respectively. For higher frequencies correlation is strong between all components implying some instrumental defects. So far we have only tried a crude 2-D detector that is a combination of two 1-D STA/LTA detectors on the vertical and horizontal components. For local and regional signals the 2-D test statistics cluster along the diagonal between 'vertical and horizontal' axes while spikes etc are clearly along a single axis. The first 2 stations here, at Ask near Bergen and at Petrozavodsk NW Russia, become operational 10 July, 2000, Data quality and on-line detector performances are comparable or better than standard seismograph stations which costs are an order of magnitude higher than ours at less than $ 1000 each.

Key words: 1-D and 2-D signal detectors, spiky records, Kolmogorov-Smirnov detector, false alarm rates, novel 3-comp. seismograph cost < $ 1000.

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OBJECTIVE

The fundamental task of observational seismology is real time monitoring of earthquake activities and equally important providing high quality data for the research community. During the pioneering years, say 1900 - 1970, universities commonly deployed and operated local and national networks. Not so any more due to increasing costs and sophistication of network operations for which tasks academic institutions are not well suited. In other words, modern seismograph networks including routine bulletin works are mainly handled by various kind of national and governmental agencies like IRIS, ISC, USGS and UN/CTBTO. These agencies provide excellent bulletin and/or earthquake waveform services but are less convenient for specialized research needs like extended time testing of signal detectors and automated event location algorithms. For the latter experiments, an obvious advantage would be to have our own station/network operation which by itself is challenging tasks in terms of low station costs and flexibilities in data managements.

In this work, we first give details on some specific design features on our novel stations which now produce continuous, high-quality seismic recordings. These data are in turn used to check and verify previous theoretical detector design findings which were based on synthetic signals and Gaussian noise waveforms. Of particular interest is naturally the usefulness of 2-D detectors which incorporate jointly both horizontal and vertical components signal parameters in their test statistics.

RESEARCH ACCOMPLISHED

NOVEL SEISMOGRAPH DESIGN

As mentioned, our efforts are motivated by the need for extensive testing of signal detectors and signal source recognition in a flexible manner and not to reinvent the seismograph. Hence, we have used standard, inexpensive instrument components but naturally some modifications are introduced for enhanced performances. Details are as follow:

- Seismometer; We use small, cheap geophones GS-11D (US $ 60/each from Geo Space Corporation, Houston, TX) with natural undamped frequency at 4.5 Hz. However, in combination with an elaborated preamplifier an approximately flat acceleration response is achieved in the 0.5 - 40 Hz frequency range (Fig. 1) which is adequate for short period (SP) signal recordings.

- 19 bits A/D converter - effective spike suppression and quantization noise reduction by oversampling. Our experience indicates that most of spikes in seismic recordings above 8-10 Hz are produced by impulsive noise coming from power lines. Such kind of noise is suppressed in the A/D converter which design includes careful grounding separation. Digital data acquisition systems always use a limited number of bits for signal representation. Recently, costly and precise 24-bits A/D have been introduced into seismograph stations which is sort of sampling "overkill". The reason being that there is no customary preamplifiers or commutators with a dynamic range close to 24-bits. Anyway, it is a well known fact that low-pass filtering of quantization noise improves the accuracy of the A/D-converter. We have taken advantage of this thus in effect converting the standard 16-bits one to a 19-bits A/D-converter (Fig. 2) deemed adequate for SP seismic recording systems. Presently the primary sampling rate is 3150 Hz for each channel, while output sampling rate is 50 Hz.

- Timing - "soft" system time adjusting. Presently we use an accurate GPS clock which controls the data acquisition system time. Even if GPS looses the satellites for a short while, for instance, a few minutes, the time error may exceed the sampling period. If the GPS clock adjusts system time instantly after it regain the satellites, number of samples per second may differ from the preset sampling rate. "Soft" system time adjusting helps us to avoid such situation. The cost of the GPS is about $ 300 but a much cheaper (approx. $ 50) radio clock is under consideration.

- CPU and data storage. We use an inexpensive CPU unit (Intel 486 or Intel 586 at a cost of $ 150) which is adequate for signal detection processing in several frequency bands. Via modem/phone detected signal parameters can be transmitted to the Hub while continuous waveform storage is on a 8 Gigabyte disk (cost about $ 80). Accessing waveform data at the station site via the Web is under consideration albeit we hope that parameterized signal data would suffice for preliminary bulletin production.

Total hardware cost for the above, novel SP 3C seismograph stations is less than $ 1000 even when using the GPS clock while the recording performances match or are even better that of the site-sharing ASK station. Cost comparison is very favorable for our station as the price of just a single seismometer is at least $ 1500. The idea of using inexpensive geophones to mimic responses of standard but costly seismometers via transfer function modeling is not entirely new in seismology (Barzilai et al., 1998) since obviously the Earth is spatially undersampled in this regard. Besides the requirement of cheap instrumentation, station siting and operation should also be inexpensive. A pilot experiment here is installation of one of our station at a local high school where the students would access and analyze their station recordings plus those of other "school" stations on Internet. In this way, we ensure low operational costs retaining participant access to to all data without any additional hardware cost for us.

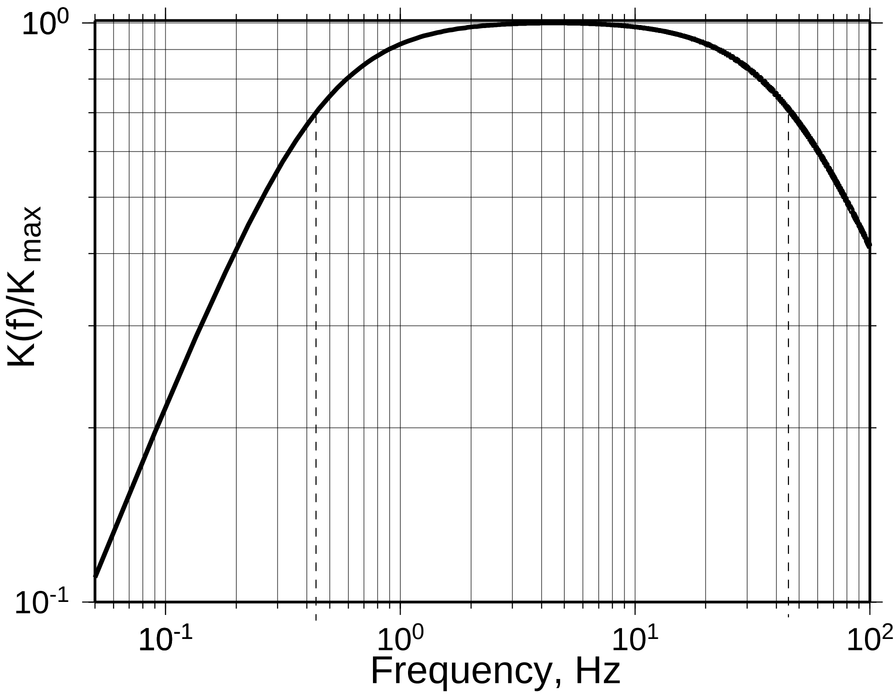

Fig. 1. Approximately flat acceleration response for the GS-11D geophone in combination with our own designed preamplifier. In essence, low-cost geophone transformed to high-cost short period seismometer by smart "response" hardware.

SIGNAL DETECTOR DESIGN

In previous works, Fedorenko et al., 1998, Fedorenko et al., 1999, Husebye and Fedorenko, 1999, we have demonstrated that the wavelet transform may be a more suitable tool than the FFT for signal detection, phase pickings and signal source recognition. This in turn requires that the ambient noise is white which is equivalent to an approximate flat seismometer acceleration response curve. Since most instruments in use measures ground velocities the noise spectra are in general non-flat as shown in Fig. 3 for the ARCESS array center seismometer. To overcome this drawback in the context of signal detection our preamplifier is designed in such a manner as to modify our ground velocity measuring geophones to produce seismometer ground acceleration motions which in case of noise give approximately white spectra (Fig. 3) in the frequency range 1.5 - 20 Hz. The spectral hump at lower frequencies, due to relatively strong microseisms, are in practice of no consequences as this part is removed by bandpass filtering in the detector processor.

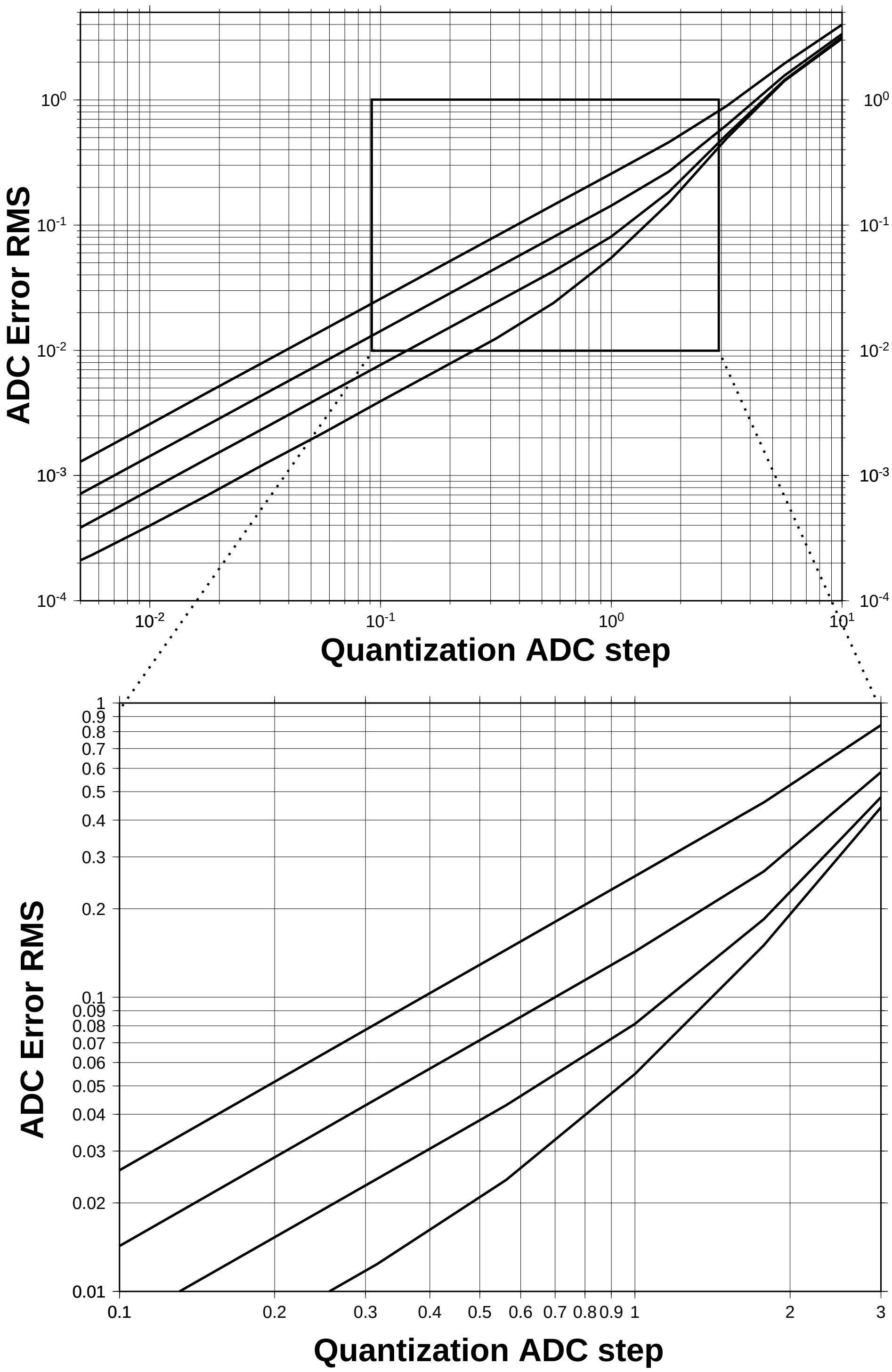

Fig. 2. Quantization noise reduction by oversampling. Upper line at both panels represents ADC (A/D converter) output noise without oversampling, $f_s/f_{\mathrm{out}} = 1$. The next lines correspond to oversampling $f_s/f_{\mathrm{out}} = [4,\ 16,\ 64]$, respectively. Notice that quantization error with oversampling by 64 is approximately 8 times lower (3 bits gain) than without oversampling. Quantization ADC steps are in units of noise standard deviation, ADC error RMS is $\left[\frac{1}{L-1}\sum_{j=1}^{L}(n_j - n_j^q)^2\right]^{1/2}$ where n_j is the initial noise, n_j^q is the quantized noise and L is number of samples in the noise realization.

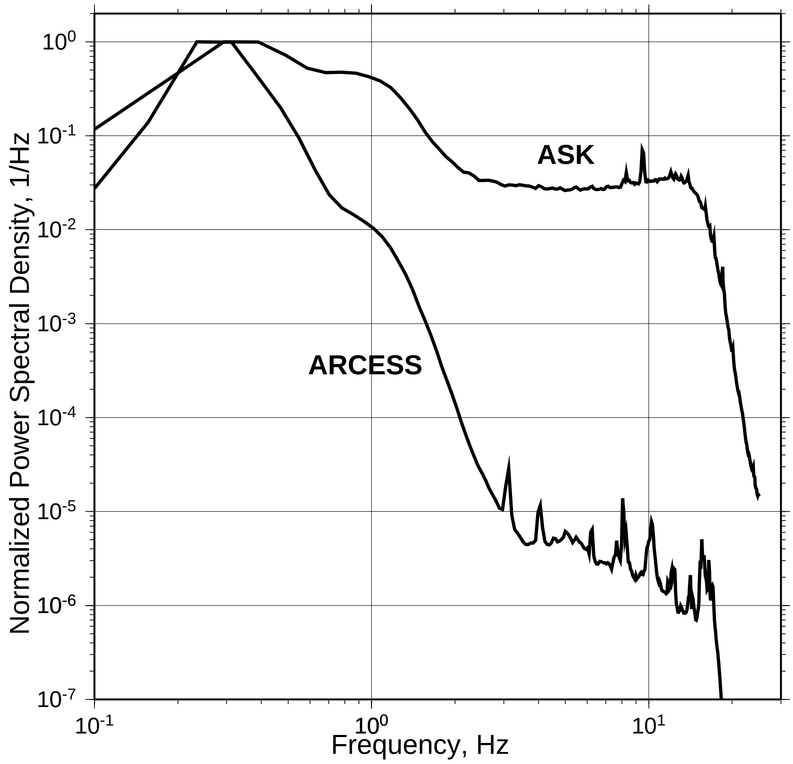

Fig. 3. Normalized power spectral density for ARCESS 3C center station (winter time) and our novel station at ASK (summer time) - in both cases Z-components. Since the noise level in winter is high the normalization gives low level of the high frequency noise at ARCESS. Note, that above 2 Hz the ARCESS spectra follows approximately $1/f$ slope while ASK spectra is almost flat in this frequency range.

In our more theoretical detector studies (Fedorenko and Husebye, 1999) we found that the popular STA/LTA detector has an excellent performance in comparison to many other detectors including the non-parametric Kolmogorov-Smirnov one. It was one exception here namely in case of spiky records often caused by electrical outgauges in buildings were station is housed. Naturally, other kind of electrical disturbances may cause spikes in the recordings. In such cases the STA/LTA detector become literally blinded while the KS-detector was little affected. Instead safeguarding here in terms of 2 different detector systems we build-in a spike 'killer' in the A/D-converter ensuring spike-free records prior to signal detection per se.

The basic requirement here is noise independency between components and the validity of this assumption is demonstrated in Fig. 4. As can be seen, there is no significant noise coherency even at low microseism frequencies (f $<$ 0.5 Hz). In typical signal detector passbands within 2 - 15 Hz the noise coherency is truly small being less than 0.02 units. Besides component independency also valid for component envelopes the noise appears to be Gausssian as presumed in our theoretical detector study. The above results imply that a 2-D detector should outperform the conventional 1-D STA/LTA detector foremost because more signal information is incorporated in the test statistics.

Our 2-D signal detector operates in the three frequency bands which coincide with the corresponding frequency bands in wavelet transforms, namely 1.5625 - 3.125 Hz, 3.125 - 6.25 Hz and 6.25 - 12.5 Hz. The first step is data preparation prior to the detection process itself using IIR (Infinite Impulse Response) Butterworth filters of order 6 to obtain filtered time histories for the $x_k(t)$ ($\mathbf{N}$), $y_k(t)$ ($\mathbf{E}$), $z_k(t)$ ($\mathbf{Z}$) for our 3 frequency bands $k = 1, 2, 3$. The 2-D detector is modeled after the 1-D STA/LTA detector which in the former case is defined as:

$$\begin{aligned} \mathrm{STAH}_k(t) &= \mathrm{IIRF}_{\mathrm{STA}} \left(x_k(t)^2 + y_k(t)^2 \right)^{1/2} \\ \mathrm{STAV}_k(t) &= \mathrm{IIRF}_{\mathrm{STA}} \left(|z_k(t)| \right) \end{aligned}$$

where H=horizontal and V= vertical, IIRF_{STA} defines Bessel low pass IIR filter of order 3 with cut-off at 0.5 Hz. The LTAH and LTAV are defined in a similar manner but with a frequency cut-off at 1/300 sec. The combination of Butterworth prefiltering and Bessel type of filters for forming the STA and LTA test statistics are motivated by the need of suppressing side-lobe detections that is false alarms caused by noise triggering (Steinert et al., 1975).

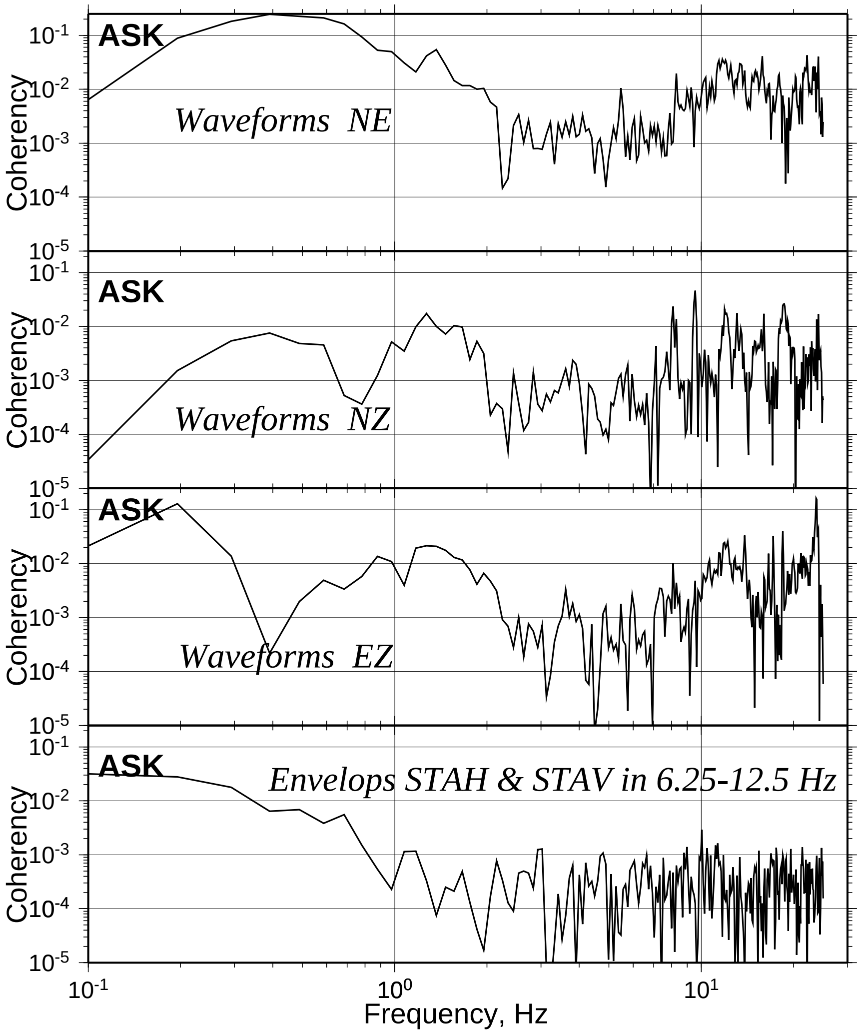

Fig. 4. Observed noise coherency between 3-component waveforms and STAH and STAV envelops. This is original noise waveforms recorded by our novel ASK station of length 60 min presumably free of signals. Coherency at levels of 0.01 or less give component independency for the ambient noise field. Also note that similar results were obtained when noise waveforms were replaced by the corresponding envelopes, in this case the coherency is less than 0.001. In the STA/LTA 2D detector the test statistics are the noise and signal envelopes.

Anyway, we may consider $\text{STAH}_k(t)$ and $\text{STAV}_k(t)$ as approximate envelopes of horizontal $a_h(t)$ and vertical $a_z(t)$ acceleration components in the given frequency bands while $\text{LTAH}_k(t)$ and $\text{LTAV}_k(t)$ are estimates of RMS of the ambient noise. Also, this LTA definition is coincident with the parameter used for record “denoising” in our wavelet processing scheme for picking automatically P- and S-phase onsets (Husebye and Fedorenko, 1999). In order to keep them from being affected by the seismic signal we freeze these values while the detector is in the detection state.

The 2-D detector is taken to be ratio $R_k(t)$ between the STA and LTA that is:

$$R_k(t) = \frac{\left[\mathrm{STAH}_k^2(t) + \mathrm{STAV}_k^2(t)\right]^{1/2}}{\left[\mathrm{LTAH}_k^2(t) + \mathrm{LTAV}_k^2(t)\right]^{1/2}}$$

A signal detection is declared whenever any $R_k(t)$ exceeds a preset threshold currently set at 4.0 for all 3 bands. This setting is rather conservative since we so far have not observed any clear false alarms. Depending on signal shape and duration the detector may be triggered several times during signal "passage". An independent trig requires a time lag of minimum 2 sec while detection state is defined as a time lag less than 60 sec between the last trigger events. We naturally count no of triggs during detection state as this parameter is useful for differentiating between earthquakes and explosions (most 8 triggs) while man made signals like marine air gun activities, human walking near the site etc. often produce more than 20 triggs.

The horizontal and vertical acceleration envelopes are used to obtain the estimate of an acceleration envelop $a_k^{\mathrm{env}}(t)$ and of an apparent incidence angle θ_k

$$\begin{aligned} a_k^{\mathrm{env}}(t) &= \left[\mathrm{STAH}_k^2(t) + \mathrm{STAV}_k^2(t)\right]^{1/2} \\ \theta_k(t) &= \arcsin\left[\mathrm{STAH}_k(t)/a_k^{\mathrm{env}}(t)\right] \end{aligned}$$

Seismic events have $10 < \theta_k(t) < 60$ while spikes and non-seismic events often lay outside this diapason.

RESULTS

Our novel 3-comp. station is co-located with the ASK station of the NSN for easy site access and direct comparison of detector performances. Phase pickings are approximately coincident in time while waveforms are not directly comparable due to velocity versus acceleration responses of these two stations. Neither is detector output directly comparable since the ASK station (SEISAN software; p. comm. J. Havskov) use a 1-D detector tied to the vertical component and just one filter band of 2 - 8 Hz. In other words, our detector has a superior performance to that of the standard ASK station. Up to now station operation has been smooth the only nuisances being extensive testing of air guns in nearby fjords. These signals can cause triggerings every 10 - 15 sec for many hours at a time but easily recognized as such via the trigger counter. The detection parameter "apparent angle of incidence" is observationally limited to the interval $10° - 60°$ for earthquakes and chemical explosions. This implies that horizontal components record parts of the P-wave field even for teleseismic events making 2-D detectors superior to those based on vertical components only. For arrays where vertical sensors are dominant (only four 3-Comp. stations in ARCESS) 2-D detectors are of less interest unless the latter ones are used for detecting Lg and Rg-waves. The conservative threshold setting of 4.0 ensure no false alarms due to noise triggering. To lower threshold value, for Gaussian noise a threshold of 2.4 would be acceptable, we would produce many more detections of air gun signals and nearby human activity signals. Such events are of no scientific interest so better removed in this manner that is by a conservative threshold setting.

CONCLUSIONS AND RECOMMENDATIONS

Based on the results presented above our conclusions are:

- It is feasible to build and deploy low cost seismograph stations providing short period seismic record quality comparable if not better than that stemming from conventional, relative high-cost stations.
- Controlling your own station sitings and operations give clear research advantages regarding signal detector research and event location experiments.
- Our novel 2-D signal detector has a performance clearly superior to that of 1-D STA/LTA detectors. For array where most sensors are vertical only the advantages of 2-D detectors are likely to be marginal. Only exception is using the few 3-comp. array stations (only 4 in the ARCESS array) for detecting Lg- and Rg-waves.

Our recommendations are:

- 2-D type detectors should be installed in all 3-comp. stations in the seismic part of the IMS/CTBTO global monitoring system due to its superiority relative to 1-D detectors. For array stations 2-D detectors would be of limit usefulness.
- For event location research local network data are a must. We have demonstrated here that such networks are affordable even for low cost research budgets. Main design elements in our novel stations is replacing costly seismometers with low-cost geophones but retaining in the latter case seismometer response characteristics.
- Event locations; with many stations recordings at hand from dense networks envelope waveform inversion for retrieving source parameters should be feasible. With the above signal and instrumentation accomplishments we would focus our future research on these problems.

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