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6.2 Automatic real-time detection and processing of regional seismic phases on the wide-aperture NORSAR array

6.2.1 Introduction

NORSAR has for a number of years carried out processing and analysis of seismic events in the European Arctic, using the regional array network in Fennoscandia and NW Russia. The regional processing system at the NORSAR Data Center comprises the following steps:

- Automatic single array processing, using a suite of bandpass filters in parallel and a beam deployment that covers both P and S type phases for the region of interest.
- An STA/LTA detector applied independently to each beam, with broadband f-k analysis for each detected phase in order to estimate azimuth and phase velocity.
- Single-array phase association for initial location of seismic events, and also for the purpose of chaining together phases belonging to the same event, so as to prepare for the subsequent multiarray processing.
- Multi-array event detection, using the Generalized Beamforming (GBF) approach (Ringdal and Kværna, 1989) to associate phases from all stations in the regional network
- Interactive analysis of selected events, resulting in a reviewed regional seismic bulletin, which includes hypocentral information, magnitudes and selected waveform plots.

Until recently, the large aperture NORSAR array in southern Norway has not been incorporated in this process, since a sufficiently reliable regional processing system has not been available for an array this size. The NORSAR array was designed in the late 1960s to detect low-yield underground nuclear explosions at teleseismic distances (Bungum et. al., 1971). The instruments, covering an aperture of approximately 100 km, were spaced to minimise the coherency of microseisms and thus provide an optimal SNR-gain for teleseismic signals between 0.5 and 2.0 Hz using classical beamforming with suitable steering parameters. After 1980, the focus in nuclear explosion monitoring turned towards the observation and interpretation of regional seismic phases and this motivated the development of the NORES regional seismic array and numerous subsequent arrays based upon this design (Mykkeltveit et. al., 1990). The GBF system provides fully automatic event locations by the association of phase detections made by the network of regional seismic arrays in Fennoscandia and Spitsbergen and the absence of detections from the NORES array (since June 2002) has led to a substantially worse detection and location capability for Southern and Western Norway.

A spatial reconfiguration of the NORSAR array to facilitate the processing of high-frequency regional phases using traditional regional array processing methods has been deemed undesirable because of the exciting possibilities which the large aperture NORSAR array represents in terms of detection of low-magnitude events using full waveform methods and because of the unique opportunity to study the variation of site effects over this large heterogeneous region. The vast majority of underground nuclear explosions occurred before the most of the regional arrays were built and the 35 year long database of high quality digital seismic data from the NORSAR array provides a unique and invaluble reference.

Traditional array processing methods are entirely inadequate to process high frequency regional phases over the NORSAR array due to the signal incoherence. The low attenuation in Fennoscandia means that many regional signals are best observed at high frequencies; signals become incoherent over the NORSAR subarrays (aperture of the order 10 km) above approximately 3 Hz. It was noted many years ago by Ringdal et. al., 1972, however, that high frequency signals could be detected with a high SNR over the NORSAR array despite the incoherence of the actual waveforms by forming incoherent beams with the envelopes of filtered waveforms. Attempts to estimate propagation parameters from such a procedure have subsequently failed due to the very different time-histories recorded at the different sites. Gibbons, Kværna and Ringdal (2003) discuss further the issues associated with the detection and identification of regional phases over the large aperture array, and present an algorithm for the detection of regional phases at sub-array level using incoherent beams and a subsequent association of estimated onset picks. Whilst the method worked demonstrably well for certain events, the output was never included in the standard GBF system due to an unacceptable number of false alarms. The following section outlines a method of phase detection and parameter estimation based upon continuous spectral estimates which has proved to be remarkably robust and, although still in an experimental phase, contributes to the online GBF.

6.2.2 Phase detection and parameter estimation using continuous spectral estimates

The multitaper method of Thomson (1982) facilitates the calculation of low-variance estimates for the amplitude density spectrum, $A(f)$, over relatively short time windows and recent improvements in CPU power mean that it is now trivial to compute running "spectrograms" (i.e. $A(f)$ as a continuous function of time) in real-time for the entire NORSAR array. In particular, the function

$$D(f,t) = \log_{10}(A(f)_{t+}) - \log_{10}(A(f)_{t-})$$

measures the ratio between the energy in a time-window immediately following time t and the energy in a time-window immediately prior to time t. Figure 6.2.1 shows the functions $A(f,t)$ and $D(f,t)$ for two channels of the NORSAR array for a regional event. The $D(f,t)$ function reaches a maximum value in the vicinity of the phase arrival time with variation determined by how emergent the signal is and how the amplitude at each site varies with time. However, the form of the $D(f,t)$ function is a far more stable indicator of the arrival of a phase than the SNR of a waveform filtered in a given frequency band. Under the traditional power detectors of the kind proposed by Freiburger (1963), frequency bands are chosen a priori and are not necessarily optimal for a given signal; the $D(f,t)$ function only attains significant values for the frequencies at which an SNR is observed. A time window length of 3.0 seconds was deemed ideal for the identification of regional phases at NORSAR; the sought after phases generally have a frequency content between 2.0 and 16.0 Hz and this length of time window is generally sufficient to ensure that the maximum value comes close to the phase onset time even for quite emergent signals.

These functions of time and frequency can be beamformed in the same way as seismograms using the plane wave delays appropriate for regional phases. Although the NORSAR array is too large for the true validity of such propagation models, the deviations from plane waves generally cancel out under the beamforming process resulting in a maximum value which typically fits the arrival time at the NB200 central array element with a surprising consistency. Eventually, the plane-wave time delays employed during the current experimental phase will be replaced by calibrated time delays. The detection process is executed by calculating a scalar function of time which is a mean of $D(f,t)$ in a frequency band appropriate for the aniticipated phase. Following a detection reduction algorithm, the slowness of the detected phase is estimated by beamforming the differentiated spectrograms on a dense grid; the slowness results for the northern Norway event displayed in Figure 6.2.1 are shown in Figure 6.2.2. For each of the phases shown, the slowness estimate is close to that anticipated from the reviewed event location.

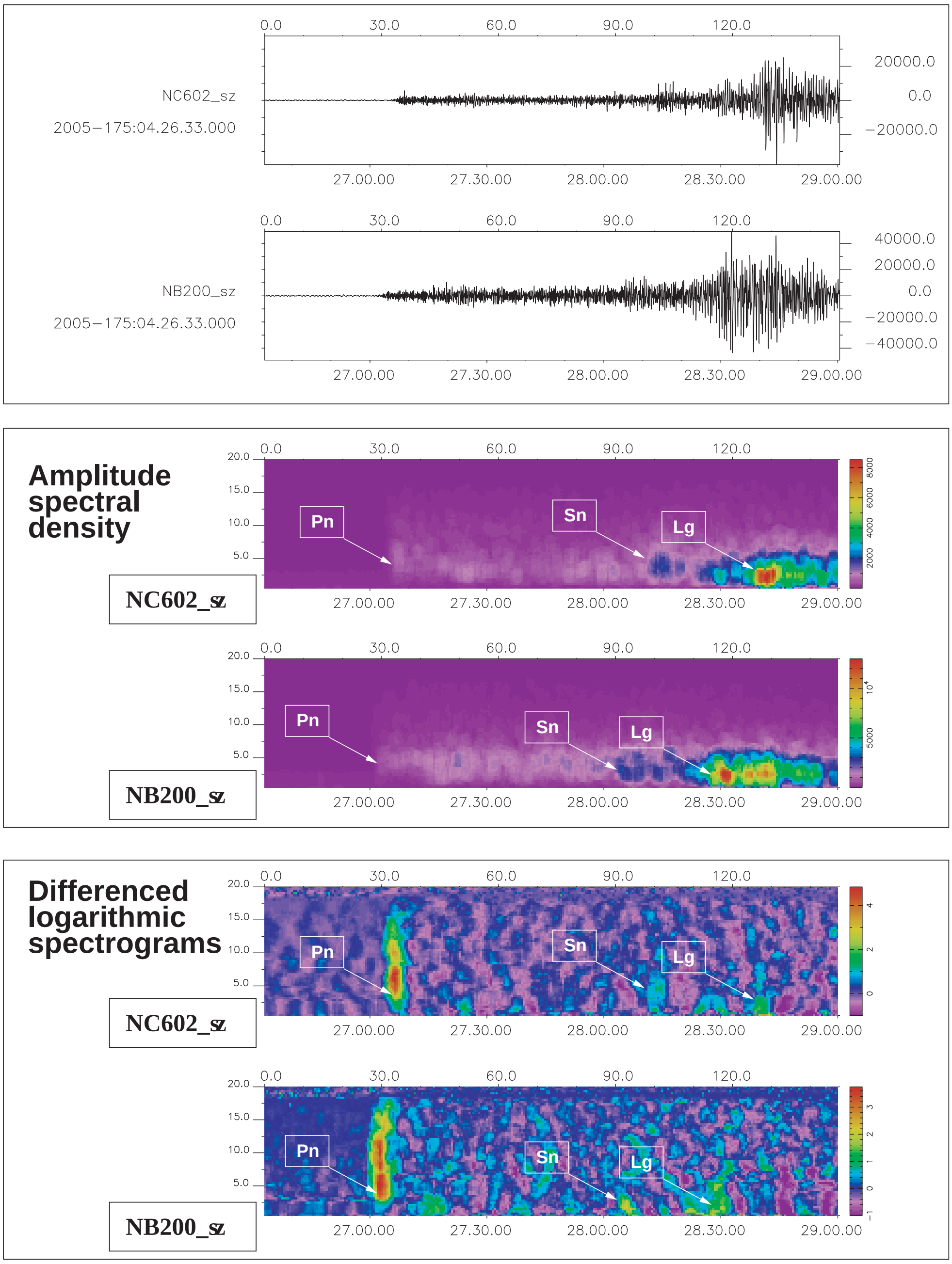

Fig. 6.2.1. Seismograms from two elements of the NORSAR array (top panel) for an earthquake in Northern Norway (distance approximately 610 km) with corresponding spectrograms, A(f,t), (center panel) and the function $D(f,t) = \log_{10}(A(f)_{t+}) - \log_{10}(A(f)_{t-})$ (lower panel). The secondary phases exhibit relatively poor spectral contrast on single channel spectrograms. This contrast is improved greatly by beamforming these functions using the appropriate delay times. The large number of array sites and large intersite distances mean that features which are not observed at a majority of sites at the appropriate times are rarely detected.

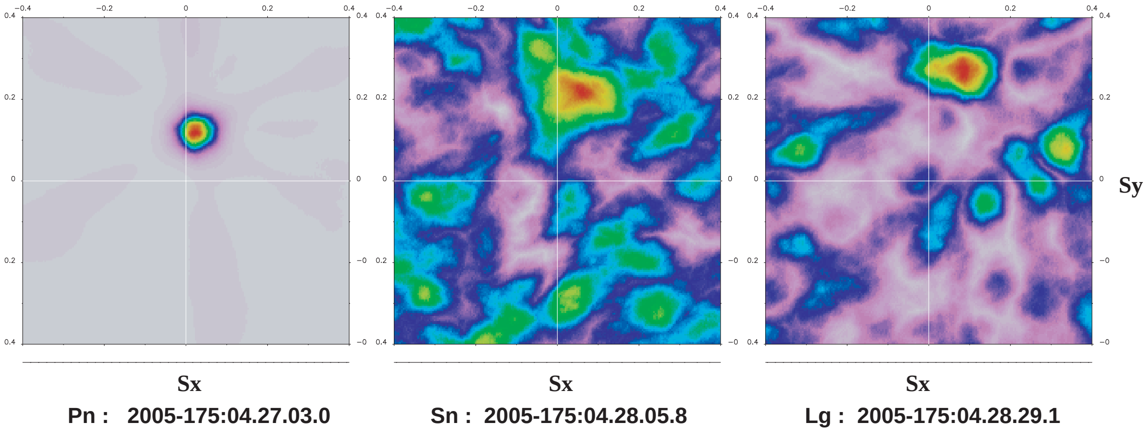

Fig. 6.2.2. Slowness estimates from the large aperture NORSAR array for the Pn, Sn, and Lg phases from the North Norway event on June 24th 2005 using spectrogram beamforming at the times indicated. The automatic location estimate incorporating these phase detections, together with detections from the regional arrays in Fennoscandia, is found on http://www.norsar.no/NDC/bulletins/gbf/2005/GBF05175.html

6.2.3 Inclusion of detections from the NORSAR array in the GBF automatic event location system

Detections from the NORSAR array have been incorporated in the GBF system since March 16, 2005, and, despite the unconventional method employed, have contributed significantly to the automatic detection capability in this region and have reduced considerably the analyst workload. Since operations began, an average of 40 detections per day have been registered for regional, far regional and some teleseismic events. Most teleseismic events are missed since the waveforms are bandpass filtered above 1.8 Hz; such signals are captured by the traditional processing of the NORSAR array. Although the number of detections made is far smaller than for the regional arrays, the large aperture of the array, combined with a conservative detection threshold, ensures that almost all detections are the result of genuine regional phases and the vast majority are subsequently associated with phases from the regional arrays.

Local Rg detections which can often dominate the detection lists from the other arrays are not made since such phases would not excite all seven subarrays at times consistent with regional body waves or Lg phases. Given that the energy contrast is so low for many coda phases, few are detected using this process; beamforming with the appropriate steering parameters on a coherent array is required to achieve a sufficient SNR for detection. This is regrettable in that the rich information available to a regional array is lost, but, for the multi-array phase association (GBF), the absence of many coda detections has meant that the NORSAR contributions have in many cases provided the best constraints on the solution since the detections made are almost inevitably the first P- and first S- phases at these sites.

Phase arrivals from weaker and more distant events than those currently detected can be observed using the spectrogram beamforming method. However, estimates of propagation parameters for these phases using spectrogram beampacking were frequently found to be spurious for the more marginal signals. The detection threshold has been set such that essentially all slowness estimates obtained are qualitatively correct, meaning that the azimuth error is small and that the phase classification (P, Pn/Pg, Sn, Lg) is correctly assigned. A reduction in the detection threshold would greatly increase the number of detections, but the proportion of phase detections with qualitatively incorrect propagation parameter estimates would increase dramatically. Conisderable research is required in order to characterise the spectral shapes which can be anticipated from low amplitude phases and to design algorithms which can estimate robustly slowness and azimuth. It may be that a source-specific spectrogram correlation algorithm (analogous to the waveform correlation detection and location algorithm of Withers et al., 1999) is the best procedure.

6.2.4 Concluding remarks

We have implemented a new, experimental, processing system for incorporating regional seismic phases detected by the large NORSAR (NOA) array into the Generalized Beamforming process currently in use at NORSAR for on-line automatic detection and location of seismic events in the European Arctic. The system represents a significant improvement over previous processing systems for large arrays, and we recommend that this method be further developed for improving automatic detection and location using local or regional networks.

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