NORSAR Scientific Report No. 2-2006

Semiannual Technical Summary

1 January - 30 June 2006

Frode Ringdal (ed.)

Kjeller, August 2006

6.4 The exploitation of repeating seismic events to measure and correct erroneous timing at the KBS station, Spitsbergen, during February and March 2006

6.4.1 Introduction

The IRIS/GEOFON/AWI seismic station KBS is situated near to Ny Ålesund, King's Bay, on the arctic island of Spitsbergen (Figure 6.4.1). The location is important in the context of nuclear explosion monitoring due to the relative proximity of the Russian island of Novaya Zemlya which was the site of numerous Soviet-era nuclear tests, the last known event being on October 24, 1990. Also on Spitsbergen, a highly sensitive small-aperture seismic array, SPITS, became operational in 1992 and is now a designated Auxiliary Seismic Array (AS72) of the International Monitoring System (IMS) of the Comprehensive nuclear Test-Ban-Treaty Organization (CTBTO). However, the KBS station is still of great importance given both the high quality of the continuous seismic data and the availability of the historical data recorded at that site. Crucially, all the known nuclear tests preceded the installation of the SPITS array whereas many were recorded at the KBS site providing an essential basis for comparison (see, for example, Hartse 1998).

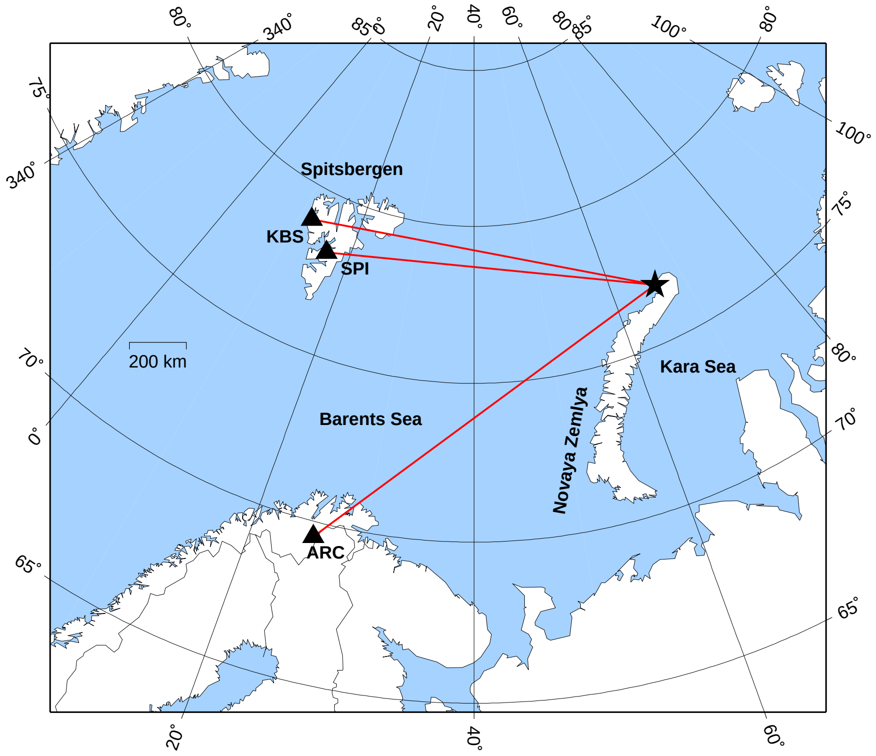

Fig. 6.4.1. Location of the IRIS/GEOFON/AWI station KBS, the IMS auxiliary seismic array SPITS, and the island of Spitsbergen in relation to Novaya Zemlya, the Barents Sea, the Kara Sea, and the IMS primary seismic array station ARCES. The black star at the northern tip of Novaya Zemlya indicates the fully-automatic location estimate for the March 5, 2006, event using the GBF algorithm (Ringdal and Kværna, 1989). Note that this location estimate is a trial epicenter location on a predetermined grid.

On March 5, 2006, an event on or close to Novaya Zemlya was detected using automatic phase determinations at the ARCES and SPITS seismic arrays. The fully-automatic Generalized Beamforming (GBF) phase-association and event location procedure (described by Ringdal and Kværna, 1989) provided the event with coordinates 76.80° N, 66.04° E, an origin time 2006-064:23.17.35.0, and a network magnitude estimate of 2.65[1]. Seismic events occurring in the vicinity of Novaya Zemlya are few and far between and consequently always examined very closely (see, for example, Ringdal, 1997; Richards and Kim, 1997; Bowers et al., 2001; Bowers, 2002). Although the event was reasonably well recorded by the ARCES array, and very well recorded by the SPITS array, it is desirable to utilize all available recordings in order to apply the best possible constraints on the event location and source type. P- and S- arrivals from this event are seen clearly on the KBS data.

Using *Pn* and *Sn* arrivals from SPITS and ARCES, with both arrival time, slowness, and back-azimuth estimates, an analyst location of the event was obtained with a well-constrained hypocenter and small traveltime and azimuth residuals. Location attempts which include the phase picks from KBS correspond to far larger error ellipses and time-residuals. The routine employed to locate the event was the HYPOSAT program (Schweitzer, 2001a) which is equipped with features that allow such discrepancies to be investigated. Most usefully, a flag can be set such that, for specified stations, the absolute arrival times are ignored and only the S-P traveltime difference is used in the inversion. Using absolute arrival times from SPITS and ARCES, but only the difference $t_S - t_P$ for KBS, a well constrained location estimate was obtained with large but self-consistent time-residuals for both P- and S- arrivals at KBS. It was first at this time that analysts and researchers at NORSAR became aware of a possible timing disparity at KBS. Following contact with GEOFON staff at GFZ-Potsdam, it transpired that in February 2006 a technical malfunction had occurred at the KBS station such that high quality broadband seismic data continued to be recorded and transmitted, albeit with an incorrect and varying time-stamp. The fault had been identified rapidly, replacement parts were dispatched, and the station was repaired on March 22, 2006. In the meantime, we are in possession of a recording of an event of interest, without an authentic time-stamp, and we would like to evaluate whether or not it is possible to measure (and therefore correct) the timing anomaly in order that phase readings from the data can be used in any subsequent event locations.

Problems of instrument synchronization present formidable challenges to a seismologist attempting to obtain accurate location estimates for seismic events. Koch and Stammler (2003) realized that many poor parameter estimates using the IMS seismic array GERESS in Germany were the result of one or several channels being unsynchronized. They developed an ingenious system for the detection and measurement of timing anomalies whereby the continuous and highly coherent microseismic background noise was correlated between the different sites of the array. They point out that such a procedure is not possible for a single-site station, such as KBS. A different approach is required.

There is a source of seismicity close to both the KBS and SPITS stations from which subsequent seismic events have been demonstrated to produce very similar signals. The mining-induced seismicity is generated at the Barentsburg coal mine, approximately 50 km from SPITS and 120 km from KBS. Gibbons and Ringdal (2005, 2006) describe how the signal from a single rockburst at Barentsburg could be used as a waveform template to detect many far weaker subsequent rockbursts using multichannel waveform correlation. The continuous corre-

---

[1] See http://www.norsar.no/NDC/bulletins/gbf/2006/GBF06064.html

lation coefficient traces between the master-event waveform template and the incoming data at each of the seismometer sites were demonstrated by Gibbons and Ringdal (2006) to be coherent over an arbitrary array or network even when the actual waveforms are not: provided that the two events considered are essentially co-located. If the correlation maxima from two co-located events are not aligned at two different stations, this is essentially a guaranteed indicator of a timing irregularity. This is demonstrated pictorially in Figure 6.4.2. The clear disadvantage of this method, compared with that of Koch and Stammler (2003), is that it requires the occurrence of fortuitous seismic events. Gibbons and Ringdal (2005) showed that a vast number of similar signals were generated by events at Barentsburg between January and August 2004; it is by no means guaranteed that the same regularity of repeating events will be observed in February and March 2006. Whereas the goal of Gibbons and Ringdal (2005, 2006) was to detect events with as low a magnitude as possible, our goal now is to detect events as similar as possible. We require that all events used occurred very close to each other such that differences in traveltimes can be neglected. We have the additional constraint that the events must be large enough to be well recorded at both SPITS and the more distant KBS station.

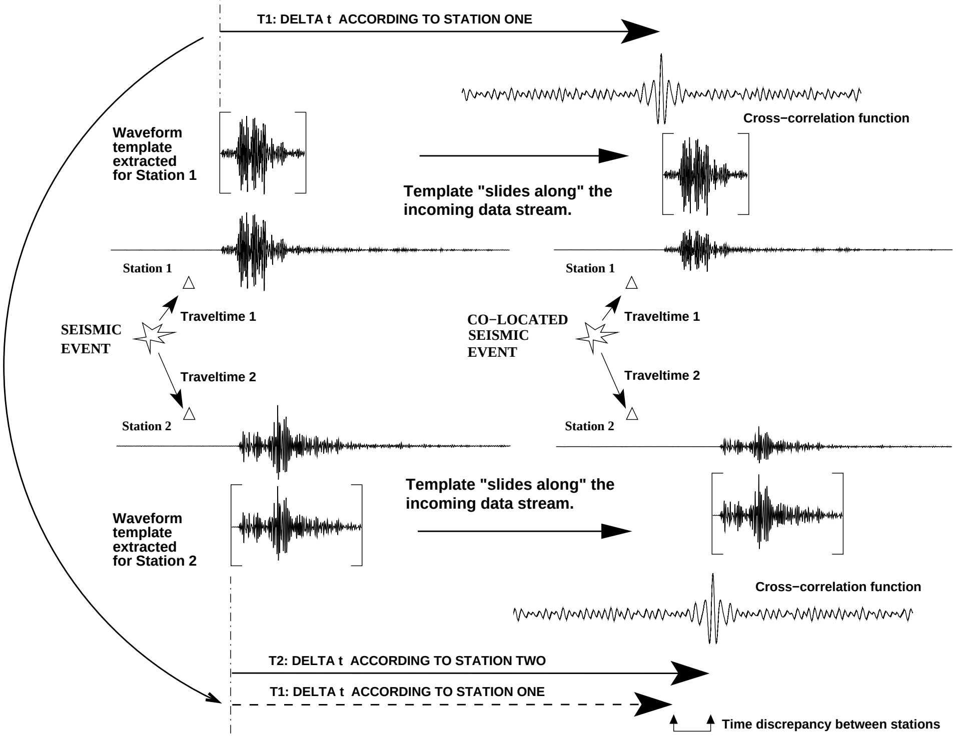

Fig. 6.4.2. A schematic illustration of how two successive events from almost identical seismic sources can be exploited to reveal anomalies in the timing at a given station. Assuming that no measurable changes occur to the velocity structure between source and receivers, seismic waves from two co-located events will take the same length of time to reach any given sensor. The cross-correlation function for a given signal at a given station measures how similar the subsequent portion of the seismogram is to the waveform template. The time separating the start of the template and the maximum of the cross-correlation function should equal the time separating the two event origin times for all stations. Any discrepancy in the separation times measured at two different stations, which is not attributable to source differences or a poor SNR, must be the result of a timing anomaly at one, or both, of the instruments.

It transpired that a large number of events at Barentsburg did indeed produce similar signals during the period of interest. In the following section, I will describe the observations of the March 5, 2006, event on Novaya Zemlya and I will proceed by discussing the results of various attempts to locate the event. I will then present an overview of the timing anomaly at the KBS station as is discernible using the repeating events from the Barentsburg mine. I will conclude by making a few suggestions about strategies we ought to consider for known timing discrepancies at seismic stations.

6.4.2 Observations of the March 5, 2006, Novaya Zemlya event

Of the recordings of this event which are available to the international seismological community, by far the best is that from the SPITS array (Figure 6.4.3). The array was upgraded in the summer of 2004, with 3-component instruments being installed at 6 of the 9 seismometer sites. This has made an enormous improvement to the signal-to-noise ratio (SNR), and therefore the detection capability, for S-phases since beamforming is now possible using the horizontal components. Both the *Pn* and *Sn* phases are dominated by quite high frequencies and, due to the characteristic high amplitude microseismic background noise in the 1-2 Hz band, the best SNR for both phases is observed above 3 Hz. The *Lg*-phase is characteristically absent. (The blockage of *Lg* propagation by sediments in the Barents Sea Basin and elsewhere is discussed in depth by Baumgardt, 2001.)

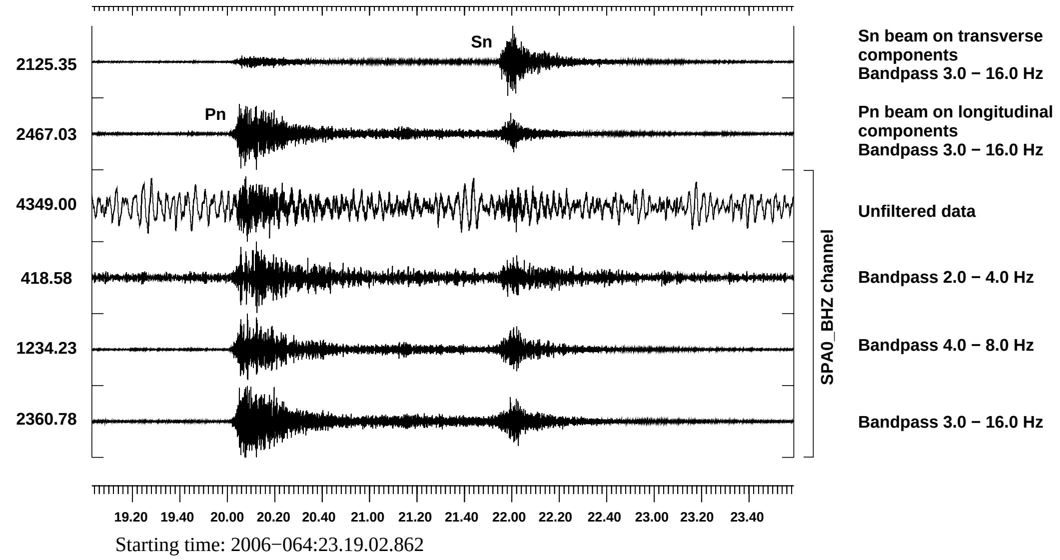

Fig. 6.4.3. Waveform data from the SPITS array for the March 5, 2006, Novaya Zemlya event. The longitudinal and transverse channels are rotated from the 3-component instruments assuming a backazimuth of 80^o *and an incidence angle of* 45^o*. The Pn- and Sn- beams are formed assuming apparent velocities of* $8.5\ kms^{-1}$ *and* $4.5\ kms^{-1}$ *with elevation corrections imposed assuming P- and S- velocities of* $4.75\ kms^{-1}$ *and* $3.0\ kms^{-1}$*.*

Figure 6.4.4 shows waveforms from ARCES for the March 5, 2006, event. The SNR is substantially worse at ARCES than at SPITS in spite of the fact that the ARCES array is not much further from the assumed event location. (The last event on Novaya Zemlya prior to 2006 to be detected by the NORSAR-operated seismic arrays was on October 8, 2003, quite close to the presumed location of the March 5, 2006, event[2]. This event registered a reasonable SNR on SPITS but failed to produce a detection at ARCES.) Due to the diminished signal to noise ratio, the accuracy with which the phase onset times can be read is significantly poorer. However,

---

[2] See http://www.norsar.no/NDC/bulletins/regional/2003/10/5705.html

considering the SNR, directional estimates for both *Pn* and *Sn* using broadband f-k analysis are surprisingly well-determined and robust.

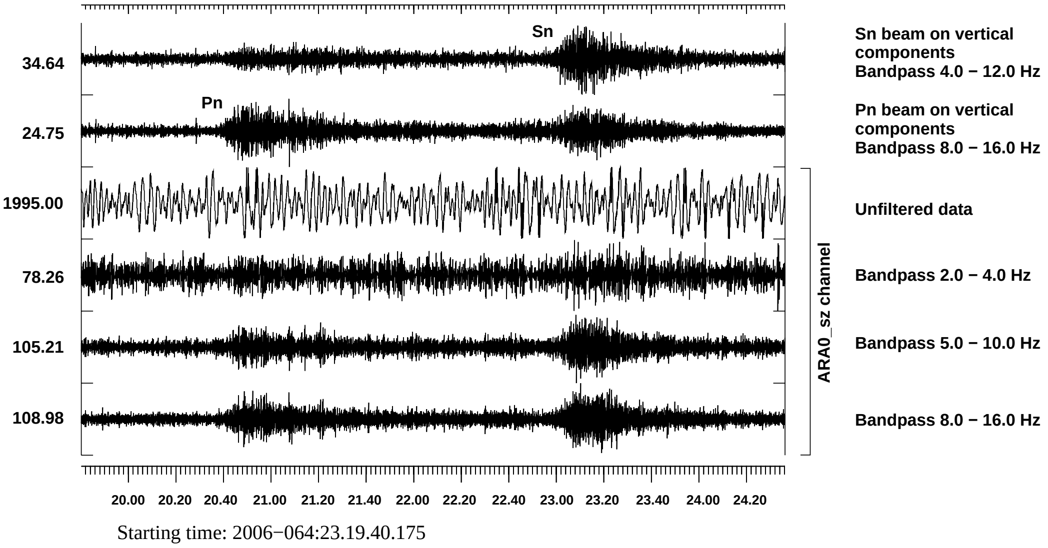

Fig. 6.4.4. Waveform data from the ARCES array for the March 5, 2006, Novaya Zemlya event. Since ARCES has 25 vertical component sensors and only 4 3-component sensors, the SNR gain is often better on the vertical component beams even though the signal is stronger on the horizontal components.

The KBS recording of the Novaya Zemlya event is displayed in Figure 6.4.5. The SNR is poorer than for the single channels at SPITS, possibly a result of higher background noise (particularly at the lower frequencies). However, the *Pn* and *Sn* arrivals are at least as discernible as at the ARCES array. The absence of recordings at distinct sites precludes the determination of direction using f-k analysis, although a reasonably stable backazimuth and incidence angle for the P-arrival may be estimated using polarization analysis. An excellent introduction to both methods of direction estimation is provided in Chapter 23 of Kennett (2002).

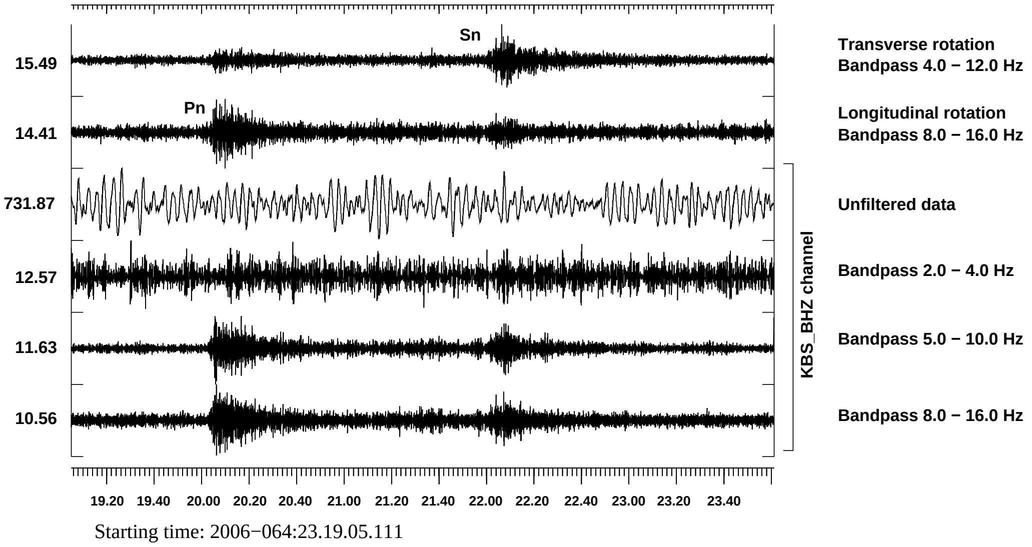

Fig. 6.4.5. Waveform data from the KBS 3-component station for the March 5, 2006, Novaya Zemlya event. With channels from only a single site, we are unable to perform beamforming. However, we are able to improve the SNR for the Sn phase by rotating the horizontal components.

The results of all of the phase arrival determinations are displayed in Table 6.4.1. In principle, all of these time picks and slowness/azimuth estimates can be input into a location routine (such as HYPOSAT) to obtain an event location estimate. We discuss a number of attempts to locate the event in the following section.

Table 6.4.1. Phase determinations for the March 5, 2006, Novaya Zemlya seismic event estimated for the central sites of the SPITS and ARCES arrays and the KBS 3-component station. Azimuth and apparent velocity are measured using broadband f-k analysis for all phases at the array stations and using 3-component polarization analysis for the Pn-phase at KBS.

Station	Phase	Arrival time	Estimated error (s)	Backazimuth (°)	Apparent velocity (km/s)
SPA0	Pn	23.20.00.863	±0.5	76.4 ± 5.0	7.79 ± 1.0
SPA0	Sn	23.21.53.416	±1.2	82.5± 10.0	4.60 ± 1.0
ARA0	Pn	23.20.38.414	±1.5	55.1± 7.0	9.65 ± 1.0
ARA0	Sn	23.22.57.704	±2.0	51.0± 8.0	4.98 ± 1.0
KBS	Pn	23.20.01.526	±1.5	73.0±12.0	7.40 ± 2.0
KBS	Sn	23.21.59.289	±2.0	Not available	Not available

6.4.3 Location estimates for the March 5, 2006, Novaya Zemlya event

Whilst the phase picks and parameter estimates listed in Table 6.4.1 are not the only observations of this Novaya Zemlya event, they are by far the best that researchers at NORSAR have access to. Other phase picks from more distant stations are unlikely to lead to a more accurate location estimate. All location estimates discussed here are consequently limited to the information provided in Table 6.4.1. The routine used to locate the event is the HYPOSAT program (Schweitzer, 2001a) and the 1-dimensional velocity model used is the *barey* model, as tabulated in Hicks et al. (2004). A number of different location attempts are tabulated in Table 6.4.2 and mapped out in Figure 6.4.6. The location estimates differ only by the use of different subsets of the arrivals listed in Table 6.4.1, and by the use or otherwise of the option in the HYPOSAT program which allows the inclusion of only the travel time difference (t_S-t_P) in the location inversion for a given station, rather than the absolute arrival times t_P and t_S.

The most natural approach when locating a seismic event is to constrain the location by using as many high quality onset estimates as possible. Solution A in Table 6.4.2 includes all of the phase arrival determinations listed in Table 6.4.1 with both absolute arrival times and travel-time differences being used in the inversion. This location estimate lies approximately 50 km West of the GBF solution and has an origin time within one second of the GBF estimate. However, the RMS time-residual of 3.65 seconds is completely unacceptable and immediately alerts an analyst to the possibility of a qualitative error in the list of phase determinations.

Table 6.4.2. Summary of location estimates for the March 5, 2006, Novaya Zemlya event using HYPOSAT and various subsets of the phase determinations listed in Table 6.4.1. Table cells which contain only a dash (-) indicate that the value in question was not used in the inversion. An asterisk (*) against a time residual indicates that only the S-P traveltime difference was used in the inversion, and not the actual phase arrival times. The depth is fixed to zero for all estimates. Note that no RMS time residuals are given for the single station location estimates since, with only two defining phases, the times can essentially be fitted exactly with the dimensions of the error ellipse being determined by the time uncertainty and azimuth values. Note that RMS time residuals are provided for solutions F and G but that these values are misleadingly low since the differential time constraint for the second station is far weaker than the absolute time constraint.

Location estimate	A	B	C	D	E	F	G	H
Latitude	76.8390	76.6528	76.1376	73.7171	77.2153	74.0465	76.2267	76.6613
Longitude	64.4691	64.4518	63.1573	65.1605	64.3826	65.2217	63.4022	64.4094
Origin time: seconds after 2006-064:23.17.00.000	34.299	34.313	33.736	36.558	31.998	36.310	33.732	34.281
Origin time uncertainty (s)	4.388	2.470	1.622	7.762	4.722	7.178	1.592	2.135
RMS onset time residual	3.656	0.469	N/A	N/A	1.200	0.084	0.001	0.432
Err. ellipse major axis (km)	38.66	21.06	83.58	209.72	38.92	186.64	77.26	18.50
Err. ellipse minor axis (km)	36.23	20.11	18.47	63.47	25.02	56.91	18.28	17.81
Err. ellipse azimuth	85.7	99.3	26.6	2.3	98.4	2.4	26.5	95.4
Err. ellipse area (km^2)	4400.0	1330.9	4849.78	41818.0	3059.4	33371.0	4436.08	1034.75
SPITS Pn time residual (s)	2.946	-0.333	N/A	-	-	-	0.000	-0.352
SPITS Sn time residual (s)	4.088	-0.144	N/A	-	-	-	-0.001	-0.031
ARCES Pn time residual (s)	2.244	0.801	-	N/A	1.552	0.058	-	0.715
ARCES Sn time residual (s)	0.656	-0.324	-	N/A	-0.777	-0.103	-	-0.332
KBS Pn time residual (s)	-4.872	-	-	-	-1.505	-35.348*	-8.592*	-8.360*
KBS Sn time residual (s)	-5.062	-	-	-	0.692	-55.898*	-10.521*	-9.516*
SPITS Pn azimuth residual	3.04	2.13	-1.22	-	-	-	-0.62	2.14
SPITS Sn azimuth residual	9.14	8.23	4.88	-	-	-	5.48	8.24
ARCES Pn azimuth residual	15.72	14.92	-	1.78	17.36	3.25	-	14.97
ARCES Sn azimuth residual	11.62	10.82	-	-2.32	13.26	-0.85	-	10.87
KBS Pn azimuth residual	-1.21	-	-	-	0.39	-10.94	-4.59	-2.02

The first exploratory step is to repeat the location procedure but only using phase arrivals from the array stations (i.e. ignoring the KBS phase determinations). This solution is labelled B and, whilst located quite close to the previous estimate, has a far smaller RMS onset time residual. The time residuals for the SPITS and ARCES arrays are all smaller than one second without the inclusion of the KBS station. This however does not prove that the KBS phase picks are to blame for the poor fit of solution A; other combinations need to be tried in order to eliminate other sources of error.

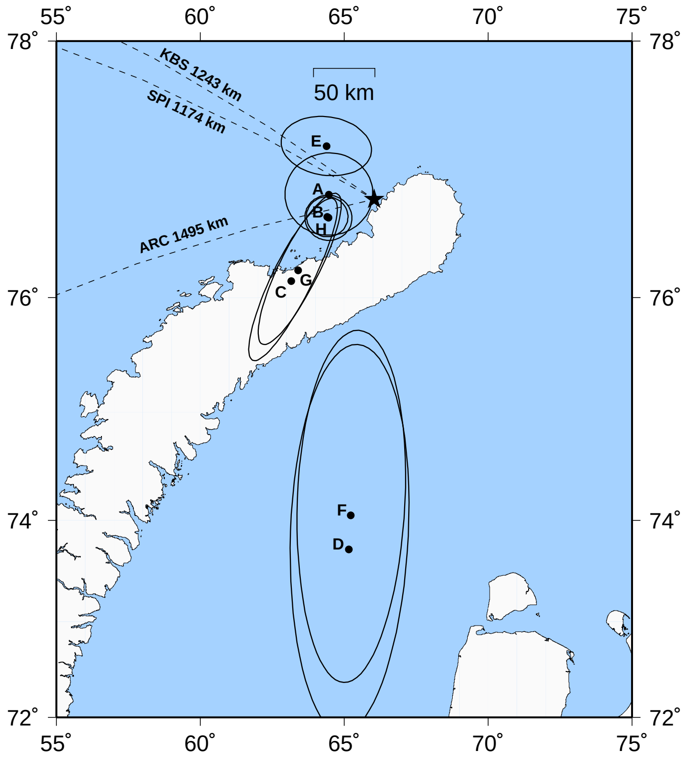

Fig. 6.4.6. Location estimates and associated error ellipses for the March 5, 2006, Novaya Zemlya event. The letters adjacent to each of the epicenter locations correspond to the solutions listed in Table 6.4.2. The asterisk indicates the GBF fully-automatic location for the event and the dashed lines indicate the great circles joining this location to the marked stations

A single array location, using only *Pn* and *Sn* from SPITS, is labelled C in Table 6.4.2. The corresponding error-ellipse is elongated perpendicular to the great circle linking the epicenter solution and the array. This reflects the fact that the epicentral distance can be determined to fit the two arrival times perfectly and the minor axis of the error-ellipse only reflects the uncertainty in the arrival time estimates; the major axis of the error-ellipse accounts for both the uncertainty in the azimuth estimates and the conflict inherent in the azimuth estimates for the two phases. The corresponding single array solution for ARCES (labelled D) has a somewhat larger error-ellipse as a result of the larger parameter uncertainties but, more worryingly, exhibits a large offset from all the solutions so far obtained which include phases from the stations on Spitsbergen. This is because the solution is dominated by the backazimuth estimates obtained using broadband f-k analysis, and these indicate an apparent direction of arrival which is quite different to that anticipated geographically. Whilst very accurate single array solutions can be obtained (see, for example, Gibbons et al., 2005) we cannot use azimuth estimates from regional arrays uncritically, especially when these values are paramount in determining the location. We must follow the counsel of Schweitzer (2001b) and apply a slowness correction based upon calibration studies prior to locating the event.

In solution E, the *Pn* and *Sn* phase determinations from the KBS station are added to the ARCES phases (whilst ignoring SPITS) bringing the location estimate back to the North East tip of Novaya Zemlya. The solution is equivalent to B, except with KBS phase readings in place of those from SPITS. The RMS time residuals, the origin time uncertainty, and the corresponding error ellipse are all far larger for solution E than for solution B, indicating that phase determinations from SPITS fit the solution better. Solution F has an almost identical input to that for solution E except that HYPOSAT is now instructed to consider only the S-P traveltime difference for the KBS station. The phase determinations from ARCES now completely dominate the solution and location estimate F is little different from that in D. A location attempt using phase readings (with both absolute and differential times) from SPITS and KBS only is not possible; the inversion fails. This indicates that an inconsistency between the absolute arrival times recorded for SPITS and those recorded for KBS is pivotal to the location failure. Again, instructing HYPOSAT to ignore the absolute arrival times for KBS allows for a solution (labelled G) which falls close to the SPITS-only solution (C) but which indicates quite consistent traveltime residuals of approximately -9 seconds for both *Pn* and *Sn* from KBS.

A final solution, H, is proposed whereby phase readings from all three stations are included but with only the S-P traveltime difference (and the *Pn* azimuth estimate) for the KBS station. This location estimate is almost identical to estimate B which ignored the KBS station completely. Solution H corresponds to the smallest time-residuals and the smallest error ellipse. The *Pn* and *Sn* traveltime residuals from the KBS station are consistent in the sense that, if a timing error of approximately 9 seconds at KBS were to be assumed, all constituent phase arrival times would correspond to an error less than one second. In the following section, we investigate a strategy for measuring a timing error at the KBS station.

6.4.4 Overview of the KBS timing error based upon correlation analysis of repeating events at the Barentsburg coal mine

Scientists at NORSAR and at the Kola Regional Seismological Center (KRSC) in Apatity, Russia, have observed mining-induced seismicity at the Barentsburg coal mine over many years (see, for example, Kremenetskaya et al., 2001). Following a fatal rockburst on July 26, 2004, a special effort was launched to detect with a high level of confidence all seismic events which had occurred in the immediate vicinity of this event. It was decided that the most effective method was to extract a waveform template from the July 26 event and to identify subsequent (or previous) events by running a multi-channel matched filter detector on continuous SPITS data (see Gibbons and Ringdal; 2005, 2006). This procedure identified over 1500 Barentsburg events within an eight month period in 2004, approximately an order of magnitude more events than could be detected using traditional STA/LTA detectors. Provided that the source mechanisms for the different events do not vary too much, the signal recorded at a given station is like a fingerprint for a given source location. Since correlation detectors work by comparing a sample waveform with a given segment of arriving data, they are exquisitely sensitive detectors for events from a specific source location which are seldom triggered by signals from different locations.

Not only is the correlation detector for the July 26, 2004, Barentsburg event still running on incoming SPITS data, but the pool of master-events has been expanded continually to include an ever greater number of waveform templates. Every signal identified by the correlation detector is subjected to an automatic post-processing system which measures the SNR on the P- and S- arrivals anticipated for events at Barentsburg. If this indicates a high-SNR event from our site of interest, the event is marked for analyst review. An event detected because of sufficient similarity to a current Barentsburg master event, but which is dissimilar enough to indicate a source at a slightly different location within the mine, is earmarked for possible inclusion as a new master event. In this way, a pool of over 100 master event signals has now been accumulated which are all correlated in quasi real-time with the latest SPITS array data. It is not yet known what proportion of seismicity at the mine is covered by the given master event pool, or the degree of degeneracy which exists within the event pool with respect to the detectability of new events.

We assume an origin location of 77.9375^o N and 14.0703^o E for events at Barentsburg. If an event at this site occurs with an origin time, t_0, the barey velocity model predicts a first arrival at SPITS at a time $t_0 + 8.55$ seconds and a first arrival at KBS at a time $t_0 + 18.41$ s. It must however be emphasized that neither the precise location of the event nor the velocity model assumed is important. As illustrated in Figure 6.4.2, the only measurement made is the time separating the start of the waveform template and the maximum of the correlation coefficient function. As a result, the only real prerequisite is that the two events being compared are essentially co-located; if this is not the case, the measured time difference will include a component due to traveltime differences which may not be possible to quantify.

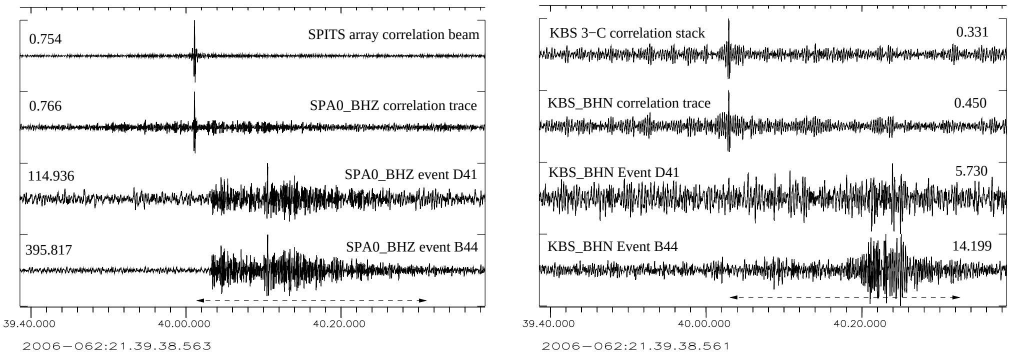

Fig. 6.4.7. Correlation between a master event with assumed origin time 2006-037:23.14.08.413 and a detected event with assumed origin time 2006-062:21.39.53.563 on the SPITS array (left) and on the KBS 3-component station (right). For each panel, the lowermost trace is the master event waveform for a single channel (with the template duration indicated by the arrow), the second trace up is the detected waveform for the same channel aligned according to the maximum correlation coefficient, the third trace up is the corresponding single channel correlation coefficient trace, and the top channel is the correlation coefficient beam. The SPITS waveform template begins at a time 2006-037:23.14.15.96250 and the interpolated correlation coefficient maximum at SPITS occurs at a time 2006-062:21.40.01.11667. The KBS waveform template begins at a time 2006-037:23.14.25.82310 and the interpolated correlation coefficient maximum at KBS occurs at a time 2006-062:21.40.02.93727. All waveforms were bandpass filtered between 3.0 and 6.0 Hz prior to resampling, and all correlation coefficient maxima times were estimated using spline interpolation. Note that the correlation maxima can be very well-defined even when the signal SNR is low.

For each master event used, waveform templates were prepared for both the SPITS and KBS stations. For each channel (3 components for KBS and up to 21 components on the SPITS array) a long segment of waveform data was bandpass filtered between 3.0 and 6.0 Hz, resampled to 200 samples per second, and a 30.0 second long window was cut starting at the assumed first arrival time. Due to the distances involved, a 30.0 second long segment includes both P- and S- phases for both receiver sites. Master Events were restricted to periods in which no known timing problems occurred. This is easier said than done since it has been demonstrated that single channels on the SPITS array have displayed synchronization problems analogous to those demonstrated by Koch and Stammler (2003) on the GERESS array. In order to identify any master events which are subject to single channel synchronization errors, all master events were cross-correlated with all other master events and, for each event-pair, the alignment of the correlation coefficient traces was verified using the Multi-Channel Cross-Correlation (MCCC) and Least Squares method of VanDecar and Crosson (1990). This method is employed by Gibbons et al. (2006) to identify and measure synchronization problems between sites on the NORSAR and SPITS arrays. Figure 6.4.7 shows the detection of a Barentsburg event using a template from a master event at both KBS and SPITS.

If t always denotes a UTC time then we can define a correction function $C_{KBS}(t)$ which allows the apparent time according to the KBS station to be calculated using

$$t_{KBS}^{app} = t - C_{KBS}(t)$$

The time separating the origin times of the two events is equal to the time separating the start of the waveform template and the maximum correlation coefficient for all stations.

Assuming that the SPITS array recorded both master and detected events with the correct time, and that the KBS station recorded the master event with the correct time, we can calculate $C_{KBS}(t)$ using

$$C_{KBS}(t) = \left[t_{KBS}^{ccm} - t_{KBS}^{wft}\right] - \left[t_{SPI}^{ccm} - t_{SPI}^{wft}\right]$$

where t_x^{wft} is the start of the waveform template for station x and t_x^{ccm} is the apparent time of the maximum of the correlation coefficient maximum for station x. For the example displayed in Figure 6.4.7, replacing the terms in the formula above with the times quoted in the figure caption gives a $C_{KBS}(t)$ value of 8.040 seconds. Since this implies that the time stamp indicated by the KBS station was 8.040 seconds earlier than the actual UTC time, this would be consistent with the time-residuals obtained for the March 5 Novaya Zemlya event. There were no usable, well-correlating, Barentsburg events on March 5 (Julian day 064). If we repeat the procedure for the first Barentsburg event following the Novaya Zemlya event (using the same master event), we obtain a $C_{KBS}(t)$ value of 8.089 seconds. The similarity of these time correction estimates provides the basis for a cautious optimism that a similar correction would apply at the time of the March 5 event. The following Barentsburg event results in a $C_{KBS}(t)$ value of -19.108 seconds, when the same master event is used. This is a substantial apparent leap in time which demands closer scrutiny.

We must be aware of the fact that the values for $C_{KBS}(t)$ vary slightly depending upon which master event is used. This is due to the fact that signals from subsequent events are not identical and any waveform dissimilarity will always lead to a degree of ambiguity in the time of best correlation. Whether the signal dissimilarity is due to reduced SNR, a difference in event location, or most likely a combination of both, the correlation coefficient will provide a reasonable indication of the quality of a $C_{KBS}(t)$ estimate and we need to evaluate the variability observed for a large number of master events. Figure 6.4.8 shows $C_{KBS}(t)$ evaluated at the times of a number of Barentsburg events as a function of the correlation coefficient. In the right hand panel, where both master and detected events occurred after the station was repaired, the time-correction term estimates clearly tend towards a zero mean value, with a standard deviation which increases as the correlation coefficient decreases. In the left hand panel, where the detected events occurred during the period of uncertain timing, not only is $C_{KBS}(t)$ clearly non-zero for these events, it also appears to be increasing steadily with time. The time-correction term evaluated on March 6, 2006, is approximately 0.2 seconds greater than that measured on February 26. One conclusion which can be drawn from Figure 6.4.8 is that it is essential to have as many reference events as possible in order to maximize the likelihood of including a master event which correlates well with the detected event.

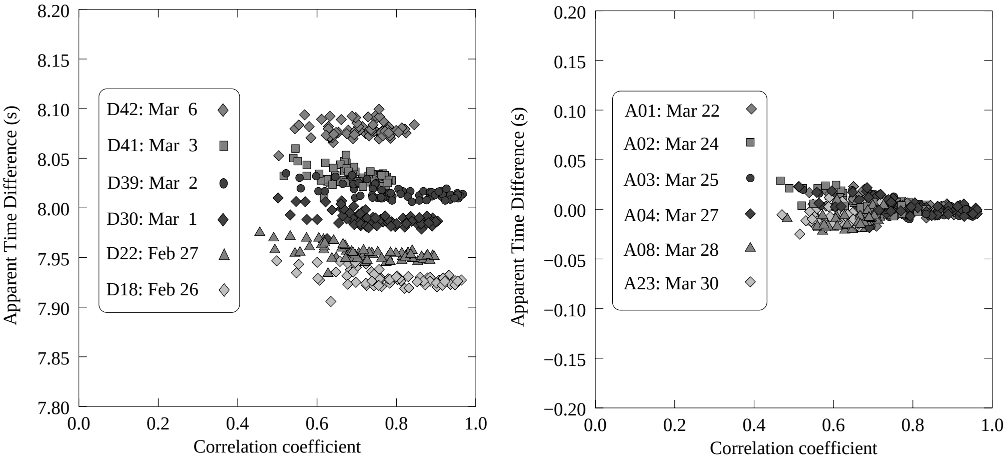

Fig. 6.4.8. Variability of the time-correction function $C_{KBS}(t)$ for a number of detected Barentsburg events. Each point indicates the time-difference calculated for the indicated event using a certain master event with the SPITS array correlation coefficient displayed on the x-axis. All master events are taken from March 22, 2006, or later after the KBS station was repaired. The detected events in the left hand panel all occurred during the time-period without an authentic time-stamp and the events in the right hand panel occurred after the station was repaired. All autocorrelations are trivial and have not been included in the right hand panel.

Figure 6.4.9 shows the time-correction term evaluated for every instant at which we have a repeating event from the Barentsburg mine. There are four clear time intervals, separated by data gaps, over which the time according to KBS is associated with a steady drift and a different offset term of up to 20 seconds. The drift appears to be the same for each interval, indicating that it is probably associated with the digitizer. Under normal operation, this drift is corrected at regular intervals. The times of the data gaps were observed easily by differentiating long segments of waveform data. Whilst there are several periods of several days in which no Barentsburg events were detected, each new occurrence of Barentsburg events appears to be consistent with the pattern previously observed.

6.4.5 Conclusions and Discussion

A timing error at the KBS station between February 17, 2006, and March 22, 2006, resulted from a temporary technical fault. The operators of the station were alerted to the problem rapidly and took the necessary corrective steps. Scientists at NORSAR only became aware of a synchronization problem when attempting to locate an interesting seismic event using KBS phase determinations. Successive, strategic attempts to locate the event using a fixed set of phase determinations indicated that anomalous P- and S- arrival times at KBS were almost certainly to blame for the large residuals in the location estimates. It was demonstrated that if both P- and S- phases had arrived at KBS approximately 8 seconds later than indicated on the seismograms, the phase determinations would be consistent with P- and S- arrivals from the SPITS and ARCES seismic arrays. Mining-induced seismicity at the Barentsburg coal mine, close to the SPITS and KBS stations, results in signals at both sites which are very similar from event to event. Many such events occurred during the period in which the timing at KBS was erroneous. The frequency of these repeating events was sufficiently high during this period for the KBS timing error to be measured by comparing the time separating the correlating patterns in the subsequent waveforms at the two different stations. Based upon numerous waveform correlation calculations, we can state with a high level of confidence that the time-stamp on the KBS data at the time of the March 5, 2006, seismic event at Novaya Zemlya was approximately 8.07 seconds earlier than real-time. The corrected arrival time estimates allow for a very well-defined location estimate for the Novaya Zemlya event.

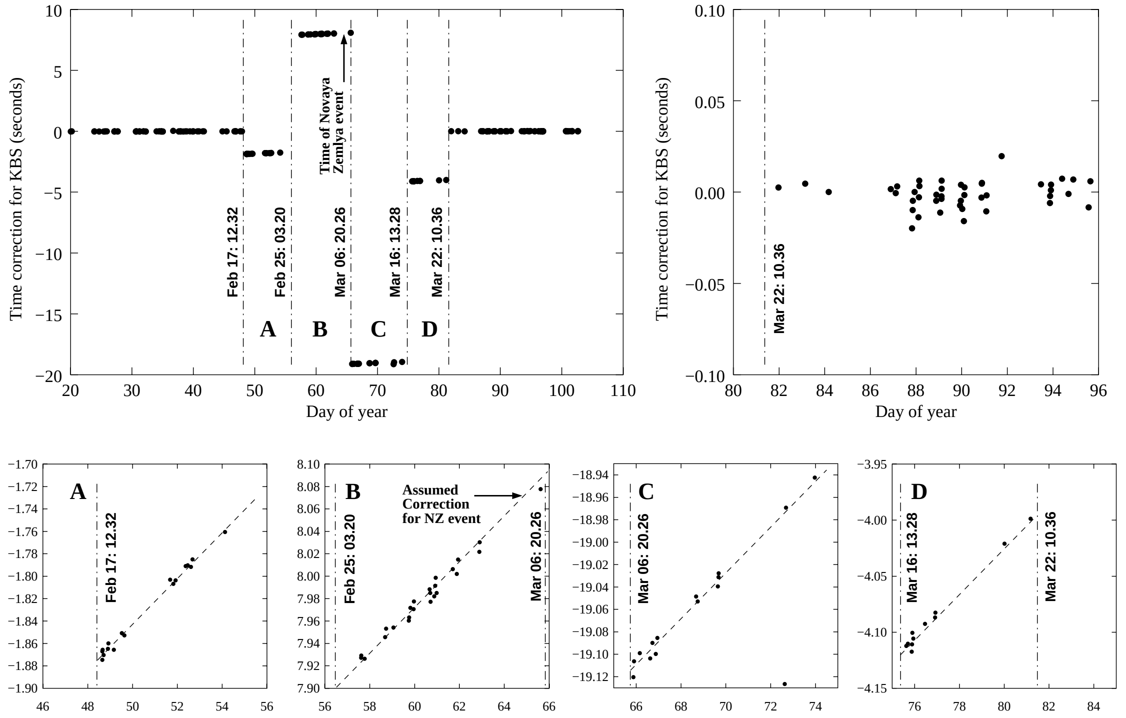

Fig. 6.4.9. The largest panel shows variation of CKBS(t) with time for all Barentsburg events in the interval shown. Each of the vertical dashed lines indicates the time at which a data gap is observed. The remaining panels each show a zoom-in of the indicated time-windows. The four unlabeled plots for windows A, B, C, and D are all drawn to the same scale and the diagonal lines are fitted by eye to the scatter plots and have the same gradient in each panel.

At least five gaps appear in the KBS data stream between February 22 and March 22, 2006. In between each of these discontinuities, the apparent time-stamp on KBS data appears to drift by approximately 0.021 seconds (i.e. slightly less than one sample) per day. Whilst this drift is small, this amounts to 0.2 seconds over 10 days which is measured clearly in these correlation calculations. Whilst scatter is observed in the data due to failings of our identical-event assumption, the uncertainty is far smaller than the uncertainty associated with phase onset time readings.

Whilst it is desirable to simply eliminate such timing errors, the fact is that they do occur and we must become better equipped to detect, identify, document, and (if possible) correct them. With regard to the detection and identification of timing errors, both station operators and observatory analysts have an important role to play. In the example presented here, the station operators were aware that the time-stamp for a given station over a given period could not be relied upon but had no mechanism by which to make current and future users of the data aware of the fact. One solution would of course be to simply cease to archive data which were known to be subject to a time uncertainty. However, waveform data is precious and, once lost, cannot be replaced. It may be possible to calculate a high-level-of-confidence timing correction at a later date (as we have done here) in which case, with careful processing, the data can be used as if no error existed. It may be deemed impossible to correct for a given timing error. In such a case, we need to accept that the data cannot be used for location purposes (or used to a limited degree only) but we may be able to extract other useful information from the data (for instance spectral properties for source discrimination).

The observatory analyst has a responsibility to react to phase determinations that would appear to preclude a well-determined solution. In the current example, the removal of the KBS station led immediately to dramatically reduced residuals; the temptation in such circumstances is to accept the first solution with small residuals without questioning why the inversion fails with all data present. In the CTBT context, where accurate locations for small seismic events are sought using a fairly sparse global network of 3-component stations and arrays, large residuals (particularly in azimuth) can be observed frequently due to insufficient calibration studies. Location routines generally attempt to minimize some form of residual norm; uncertainties should be weighted appropriately and deviations due to demonstrable and calibrated geophysical anomalies should be corrected for prior to the inversion. An unidentified case of erroneous timing provides an additional deviation which is not corrected for or weighted accordingly in the input, but which may be capitalized on by the inversion routine to produce a plausible but erroneous location estimate. Had the Novaya Zemlya event occurred at a time when the KBS offset was 2 seconds rather than 8 seconds, the erroneous timing could have been completely absorbed by the phase-pick uncertainties in our location estimate. However, the world of earthquake location procedures is changing rapidly as has been reviewed recently by Richards et al. (2006), with highly accurate cross-correlation relative times becoming increasingly important. Never before has it been so important to have complete control on instrumental timing. (A differential traveltime measurement in a double difference location calculation will in general determine the spatial separation of event hypocenters; it is essential to ensure that such measurements are not the result of instrumental anomalies.)

Whilst the rockbursts at the Barentsburg mine are a convenient source of repeating signals for our timing verification, they are by no means unique and there are most likely such sources in the vicinity of many seismic stations. Their identification could provide us with a wide range of means with which to verify or control instrumental timing. There are probably many more on the island of Spitsbergen; they have simply yet to be identified. In situations where seismologists discover sources of repeating seismic signals, I would advocate the documentation and publication of these sources (preferably with reference to specific events and with details about the signal repetition) such that the signals can subsequently be exploited to verify instrumental timing.

The time-stamp on seismograms, once made, is irreversible. It has to be this way since data is downloaded by different users at different times and stored in different formats; the circulation of waveform data with a multitude of different time-stamps would lead to chaos. I would like to throw down the gauntlet to the seismological community to reach a consensus on a standardized information center for seismic stations. My suggestion would comprise a single website with an information retrieval page whereby a user would input a station name and a UTC epoch time and could expect to receive a status report for the specified channel at that time. Such a report could contain the information “status not known”, “station not in operation”, “timing certified OK”, “questionable time stamp”, or “8.0674 seconds to be added to timestamp to provide true UTC”. It would provide the necessary mechanism for station operators to provide information of known uncertainties and for analysts to raise questions of data authenticity. The single site would be preferable since an institute-based system would be de facto very heterogeneous and seismologists often have many different sources of the same seismic data. It would remain to be seen how such a project would be administrated or financed. Is there a need for such an information repository?

6.4.6 Acknowledgements

NORSAR obtains data from the KBS station via GEOFON at GeoForschungsZentrum, Potsdam, Germany and gratefully acknowledges the GEOFON Program of GFZ Potsdam.

I would like to thank Dr. Winfried Hanka at GFZ Potsdam for providing me with status reports on the KBS station during this period and for confirming the time when the station was repaired. I am also grateful to Dr. Johannes Schweitzer for useful discussions.

Maps were created using GMT software (Wessel and Smith, 1995).

An edited version of this report has been accepted for publication in Seismological Research Letters.

S. J. Gibbons

References

Baumgardt, D. R. (2001). Sedimentary Basins and the Blockage of Lg Wave Propagation in the Continents, *Pure Appl. Geophys.*, **158**, 1207-1250.

Bowers, D. (2002). Was the 16 August 1997 Seismic Disturbance near Novaya Zemlya an Earthquake?, *Bull. Seism. Soc. Am.*, **92**, 2400-2409.

Bowers, D., Marshall, P. D. and Douglas, A. (2001). The level of deterrence provided by data from the SPITS seismometer array to possible violations of the Comprehensive Test Ban in the Novaya Zemlya region, *Geophys. J. Int.*, **146**, 425-438.

Gibbons, S. J., Bøttger-Sørensen, M., Harris, D. B. and Ringdal F. (2006). The detection and location of low magnitude earthquakes in Northern Norway using multi-channel waveform correlation. *Manuscript submitted to Phys. Earth Planet. Inter. Under review.*

Gibbons, S. J., Kværna, T. and Ringdal, F. (2005). Monitoring of seismic events from a specific source region using a single regional array: a case study. *J. Seismol.*, **9**, 277-294.

Gibbons, S. J. and Ringdal, F. (2005). “The detection of rockbursts at the Barentsburg coal mine, Spitsbergen, using waveform correlation on SPITS array data”, In *NORSAR Scientific Report: Semiannual Technical Summary No. 1 - 2005*. NORSAR, Kjeller, Norway. 35-48.

Gibbons, S. J. and Ringdal, F. (2006). The detection of low magnitude seismic events using array-based waveform correlation, *Geophys. J. Int.*, **165**, 149-166.

Hartse, H. (1998). The 16 August 1997 Novaya Zemlya Seismic Event as Viewed From GSN Stations KEV and KBS, *Seism. Res. Lett.*, **69**, 206-215.

Hicks, E. C., Kværna, T., Mykkeltveit, S., Schweitzer, J. and Ringdal, F. (2004). Traveltimes and Attenuation Relations for Regional Phases in the Barents Sea Region, *Pure Appl. Geophys.*, **161**, 1-19.

Kennett, B. L. N. (2002). The Seismic Wavefield. Volume II: Interpretations of Seismograms on Regional and Global Scales, Cambridge University Press, Cambridge, United Kingdom.

Koch, K. and Stammler, K. (2003). Detection and Elimination of Time Synchronization Problems for the GERESS Array by Correlating Microseismic Noise, *Seism. Res. Lett.*, **74**, 803-816.

Kremenetskaya, E., Baranov, S., Filatov, F., Asming, V. E., and Ringdal, F. (2001). “Study of seismic activity near the Barentsburg mine (Spitsbergen)”, In *NORSAR Scientific Report: Semiannual Technical Summary No. 1 - 2001*. NORSAR, Kjeller, Norway. 114-121.

Richards, P. G. and Kim, W. Y. (1997). Testing the nuclear test-ban treaty, *Nature*, **389**, 781-782.

Richards, P. G., Waldhauser, F., Schaff, D. and Kim, W.-Y. (2006). The Applicability of Modern Methods of Earthquake Location, *Pure Appl. Geophys.*, **163**, 351-372.

Ringdal, F. (1997). Study of low-magnitude seismic events near the Novaya Zemlya nuclear test site, *Bull. Seism. Soc. Am.*, **87**, 1563-1575.

Ringdal, F. and Kværna, T. (1989). A multi-channel processing approach to real time network detection, phase association, and threshold monitoring, *Bull. Seism. Soc. Am.*, **79**, 1927-1940.

Schweitzer, J. (2001a). HYPOSAT - An enhanced routine to locate seismic events, *Pure Appl. Geophys.*, **158**, 277-289.

Schweitzer, J. (2001b). Slowness Corrections - One Way to Improve IDC Products, *Pure Appl. Geophys.*, **158**, 375-396.

VanDecar, J. C. and Crosson, R. S. (1990). Determination of teleseismic relative phase arrival times using multi-channel cross-correlation and least squares, *Bull. Seism. Soc. Am.*, **80**, 150-169.

Wessel, P. and Smith, W. H. F. (1995). New version of the Generic Mapping Tools, *EOS Trans. Am. Geophys. Union*, **76**, 329.