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6.6 Some results derived from the seismic signals of the accident of the Russian submarine Kursk

Introduction

In several studies different authors have used the observed seismic signals from the accident of the Russian submarine Kursk to investigate in detail the concomitant circumstances of this tragedy. Especially the location capabilities of the seismic networks and the yield of explosions, which presumably destroyed the submarine, were investigated in detail (Ringdal *et al.*, 2000; Koper *et al.*, 2001a, b; Savage and Helmberger, 2001; Northrop, 2001). The results of these studies were used to launch different theories on the presumed cause and sequence of events of the accident. In this short note, focus is on some new aspects resulting from a study of the seismic signals.

Relative location of the two seismic events

From analysis of ARCES data it became very soon clear that two different seismic events occurred about 2 minutes and 16 seconds apart in the same area, which later was confirmed as the Kursk submarine accident area. The first of these two events (Kursk-1) was about two magnitude units smaller than the second one (Kursk-2), which had a local magnitude of about 3.5 (Ringdal *et al.*, 2000); for details see Table 6.6.1. To get a better understanding of the accident, the relative location between these two events is investigated.

We assume that the sources of both events were in the submarine or in the surrounding water. In this case, S-waves can only be generated from P energy converted at the bottom of the Barents Sea. Events occurring at different depths in the water will have approximately the same S-P time difference at recording stations. Our event locations can therefore only provide information on the horizontal positions as projected down to the sea bottom. By measuring with high accuracy the time difference between both events at many stations and for different phases we should in principle be able to provide information on the relative horizontal position between Kursk-1 and Kursk- 2. Therefore, we will calculate relative coordinates of Kursk-1 with respect to the well located Kursk-2 event by applying the master-event location technique.

The Kursk-1 was best observed at ARCES and correlation analysis between different onsets for the two events show correlation coefficients of up to 0.78 (see Table 6.6.2). This indicates similar but not identical propagation effects and source characteristics for Kursk-1 and Kursk-2. The correlation method was used to measure the travel-time differences between the two events accurately. The first event was less visible at other stations than at ARCES, but using the correlation method, signals from the first event could also be identified at the Apatity array, the FINES array, and at the 3C-broadband stations APZ9, KEV, and LVZ. For this analysis all data were resampled to a common digitalization rate of 400 samples per second and the time difference of all interpretable signals was measured with an assumed accuracy of 0.005 s (two samples). To take into account the inversion the different signal-to-noise ratios of the Kursk-1 signals, the measured time differences were weighted with the observed correlation coefficients. Both P-type and S-type onsets were used to measure the source-time difference. These time differences scatter around a mean value of 135.76 s, and details with respect to each station and phase are listed in Table 6.6.2.

Then the master-event location technique was applied and the deviations in the time differences were inverted for a relative horizontal location between the two events. For this the 12 measured time differences could be inverted by applying the generalized-matrix inversion. The data were weighted with the standard deviations calculated from the corresponding correlation coefficient. The inversion reduced the variance of the residuals by 42.7%. Table 6.6.3 shows the results of the inversion, where the horizontal distance between Kursk-1 and Kursk-2 was estimated at about 145 m.

Observations by analyzing the seismic signals of the Kursk events

As mentioned before, many authors have tried to estimate the yield of the explosions, which hit the Kursk submarine. Koper *et al*. (2001a, b) and Savage and Helmberger (2001) proposed a simple explosion-like source for Kursk-2. However, it was also observed that all readable first movements of the first P signals have a negative motion for this event (Koper et al. (2001a,b); Northrop (2001)). As an example, Fig. 6.6.1 shows the clear negative first motions on the array beams of ARCES and FINES. This does not fit with the idea of an explosion source. Koper *et al*. (2001a, b) rejected Northrop's (2001) argument against an explosion source mostly by pointing to the presence of a bubble signal as observed in the spectra of Kursk-2 in the frequency range between 1 and 6 Hz (Fig. 6.6.2, red curve). The wide amplitude maximum around 9 Hz is interpreted as the signal of the surface reflection and its reverberations in the water layer. For a water depth of about 115 m as in the Kursk accident area we can expect destructive interference for the frequencies 6.3 and 12.6 Hz and constructive interference for the frequencies 9.5 and 15.8 Hz. This is exactly what is seen in Fig. 6.6.2 (red curve), supporting our presumption that Kursk-2 happened close to the sea bottom. Fig. 6.6.2 also shows the spectra for Kursk-1 (blue curve) and an equally long noise sample observed just before the Kursk accident. It can easily be seen that the data of Kursk-1 are very close to the noise level. Any modulation due to a bubble pulse is not visible; maybe a slight amplitude increase for the frequency range of the surface reflection / water-layer reverberations signal can be seen.

As reported by Ringdal *et al.* (2000) and in several press reports, the Russian navy conducted a series of underwater explosions in the Kursk accident area during autumn and winter 2000/2001. For the largest of these explosions with a magnitude of about 2.5 (*i.e.* about one magnitude unit smaller than Kursk-2, see Table 6.6.1) we can clearly observe a positive first motion at ARCES and at FINES (Fig. 6.6.1). In addition, we cannot identify a bubble-pulse related modulation of the lower part of the spectrum (compare the green with the red curve in (Fig. 6.6.2). The signals from the surface reflection / water-layer reverberations at about 9 Hz are now more clearly visible than for Kursk-2 but we cannot see the outstanding amplitude minimum at about 6 Hz. We can also identify further amplitude maxima at about 11 and 15 Hz. By interpreting these frequency modulations as signals from the bubble pulse and assuming an identical explosion depth as for Kursk-2, we are led to a relatively small yield estimate of about 15 kg TNT equivalent for this explosion (after relations published in Gittermann et al. (1998)). This is far too small to produce a magnitude 2.5 event.

We observe these apparent discrepancies:

- clear negative first-motion onsets for Kursk-2 and spectral evidence of a bubble pulse for a proposed simple explosion inside of a submarine.
- clear positive first-motion onsets for an underwater explosion with no bubble pulse.

Because both signals came from the same source area, propagation effects can be excluded as cause for the observed discrepancies. This leads to the conclusion that the source history of Kursk-2 is quite complex. It also indicates that an explosion inside a closed steel container, possibly still in a gas volume, cannot be described with the standard model of an explosion source in water as done, e.g., for the Dead Sea explosions in 1999. Therefore, a source function with an initially implosive signal may be considered, as also proposed by Northrop (2001). In the following, the size of an imploding volume will be estimated, which would explain all observed seismic energy of this event (as an extreme case).

Following Müller (1973, 2001) the seismic moment M_0 of a volume change ΔV due to an explosion (or implosion) can be modeled by $M_0 = (\lambda + 2\mu) \cdot \Delta V$, with the Lamé's parameters λ and μ. From the observed local magnitude 3.5 of Kursk-2 a seismic moment can be deduced of about $M_0 = 9 \cdot 10^{13}$ Nm. The modeled implosion source can be described as the collapse of a gas volume at normal atmospheric pressure inside the submarine due to the sudden pressure change (about 100 m water column) after a leakage. For water and gas the shear modulus $\mu \equiv 0$. Then λ becomes identical to the bulk modulus κ and the seismic moment can be written as $M_0 = \kappa \cdot \Delta V$.

The change of the gas volume ΔV due to the pressure change from one atmosphere to the pressure at about 100 m water depth can be written after applying Boyle-Mariotte's law for ideal gasses as $\Delta V = V \cdot \frac{\Delta p}{p}$, with the relative pressure change $\frac{\Delta p}{p}$, and the original volume V. The equation for the volume to be collapsed to radiate a specific seismic moment is then:

$$V = \frac{M_0 \cdot p}{\kappa \cdot \Delta p}$$

For 100 m water depth, the relative pressure change is about a factor of 10 and the bulk modulus for sea water is about $\kappa = 2.14 \cdot 10^9$ N/m^2. Putting all results together, we get for the collapsed volume a value of approximately V = 4200 m^3. Following published specifications of the Kursk (*e.g.* Federation of American Scientists: http:www.fas.org/nuke/guide/russia/theater/949.htm), the 150 m long Kursk submarine had a submerged water displacement in the range 16 400 to 24 000 tons, which corresponds with a total volume of about 16 700 to 24 400 m^3. In the case that the energy from Kursk-2 was radiated only by one imploding volume, about 20 to 26% of the whole submarine must have been cataclysmically flooded during this event. This volume corresponds well with news reports that about the first third (bow) of the submarine was heavily damaged.

Discussion

The application of the master-event analysis between the two seismic events connected with the Kursk accident suggests that the submarine moved about 145 m to the north-west during the 135.8 s between the two events. The azimuth of this movement is about 302°. After the accident not only the exact position of the Kursk submarine became known but also the direction in which the submarine was lying on the sea bottom (Lind, 2002). This direction was reported as 288°. This is in good agreement with our results about the relative movement of the submarine during the time interval between Kursk-1 and Kursk-2. How much the corresponding change in depth was, cannot be resolved. Assuming a pure horizontal movement, the minimum average velocity of the submarine was about 1.1 m/s (or 2.2 knots). In case the first event occurred when the submarine was close to the surface and the second event occurred when the submarine was close to the bottom of the Barents Sea, the depth difference would be about 100 m. Then, the total change in position was about 180 m and we get a maximum average velocity of about 1.3 m/s (or 2.6 knots). Both extreme average values for the velocity of the submarine during the accident suggest that the submarine was already in a more or less motionless state when it was hit by the first event.

The observed differences between the explosion events during autumn and winter 2000/2001, and the proposed simple explosion-like source derived for Kursk-2 are obvious. The spectral analysis of the signals from Kursk-2 and the observed negative first motion of the onsets clearly indicate a very complex source function.

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Table 6.6.1. Source parameters for the analyzed events (three first lines). The depth of all events are unknown. The epicenter of Kursk-2 is assumed to coincide with the known location of the Kursk submarine on the sea bottom after the accident (provided in the fourth line).

Event	Date	Time	Latitude [º]	Longitude [º]	Depth [km]	Magnitude (NORSAR)	Reference
Kursk-1	12.08.2000	07.28.26.6	69.6160	37.5740	?	1.50	This study
Kursk-2	12.08.2000	07.30.42.4	69.6166	37.5708	?	3.50	This study
Explosion	15.11.2000	06.23.16.8	69.703	37.001	?	2.49	NORSAR
Submarine	12.08.2000	--	69.6166	37.5708	0.115	--	Lind (2002)

Table 6.6.2. The table shows the data used for the master-event inversion:
App.vel. is the applied apparent velocity for this observation,
Cor.coeff is the measured cross-correlation coefficient between Kursk-1 and Kursk-2 for the phases considered,
δt is the measured time difference,
δt-M is the measured time difference after removing the mean value,
Residuum is the time difference after the inversion, and
σ-δt is the assumed uncertainty of the measured time difference.

Station	Backazimuth	Phase	App. vel.	Cor. coeff.	δt	δt-M	Residuum	σ-δt
APA0	219.938	Pn	7.91	0.455	135.770	0.0088	0.0057	0.0110
APA0	219.938	Lg	3.56	0.407	135.755	-0.0063	0.0128	0.0123
APZ9	216.610	Lg	3.56	0.311	135.805	0.0438	0.0150	0.0161
ARCES	273.839	Pn	8.61	0.656	135.760	0.0188	0.0071	0.0119
ARCES	273.839	PnPn	8.14	0.755	135.757	-0.0013	-0.0098	0.0076
ARCES	273.839	Sn	5.72	0.780	135.743	-0.0043	-0.0103	0.0066
ARCES	273.839	Lg	4.12	0.774	135.740	-0.0183	-0.0147	0.0064
FIA0	214.939	Pn	8.07	0.421	135.780	-0.0213	-0.0204	0.0065
KEV	276.374	Pn	8.62	0.496	135.747	-0.0143	-0.0104	0.0101
KEV	276.374	Lg	3.07	0.734	135.731	-0.0303	-0.0291	0.0068
LVZ	210.569	Pn	7.74	0.675	135.769	0.0078	0.0087	0.0074
LVZ	210.569	Lg	3.71	0.770	135.778	0.0168	0.0181	0.0065

Table 6.6.3. Results of the master-event location between Kursk-1 and Kursk-2 and associated standard deviations σ. The distances are given relative to Kursk-1.

	Kursk-1 > Kursk-2 [km]	**σ [km]**
East-West	-0.123	0.021
North-South	0.076	0.013

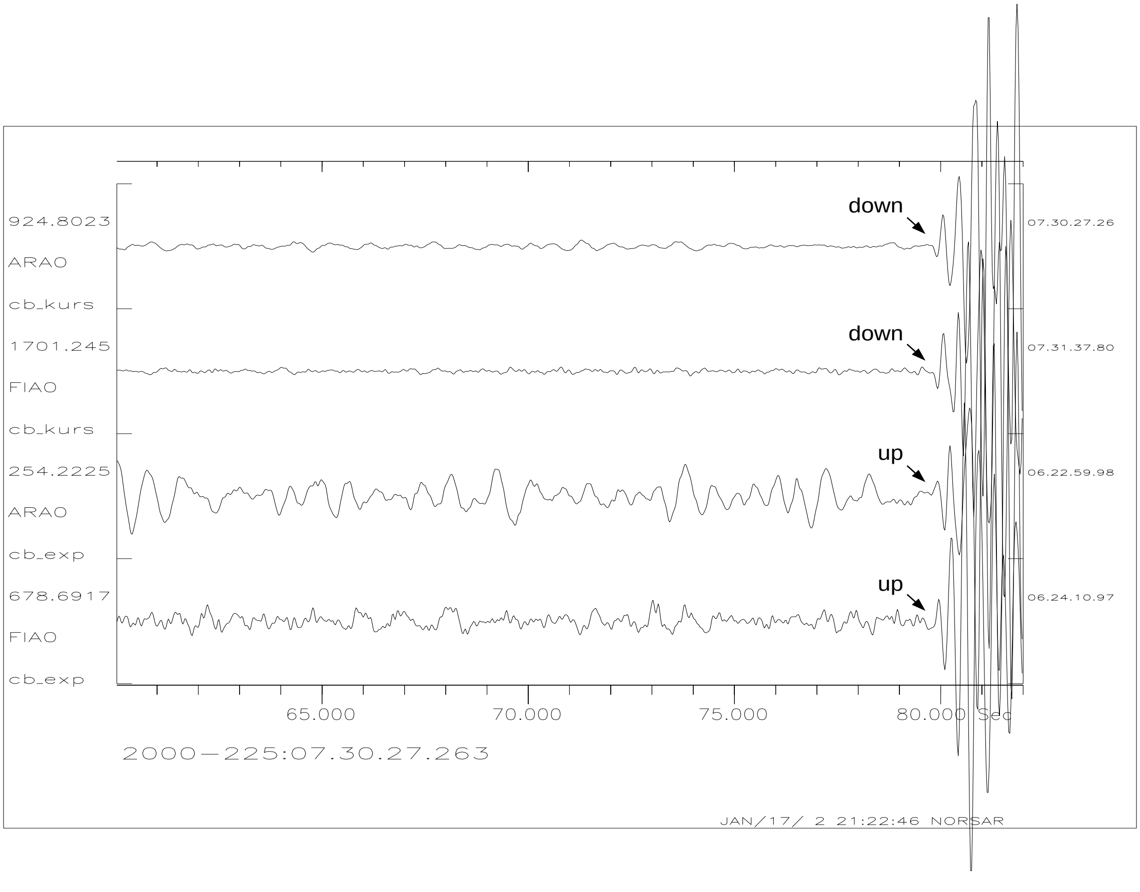

Fig. 6.6.1. Butterworth band-pass (1.5 - 8 Hz) filtered beams of Kursk-2 (_kurs) and the discussed explosion in the Barents Sea (_exp) as observed at the regional arrays ARCES and FINES. The source details are listed in Table 6.6.1.

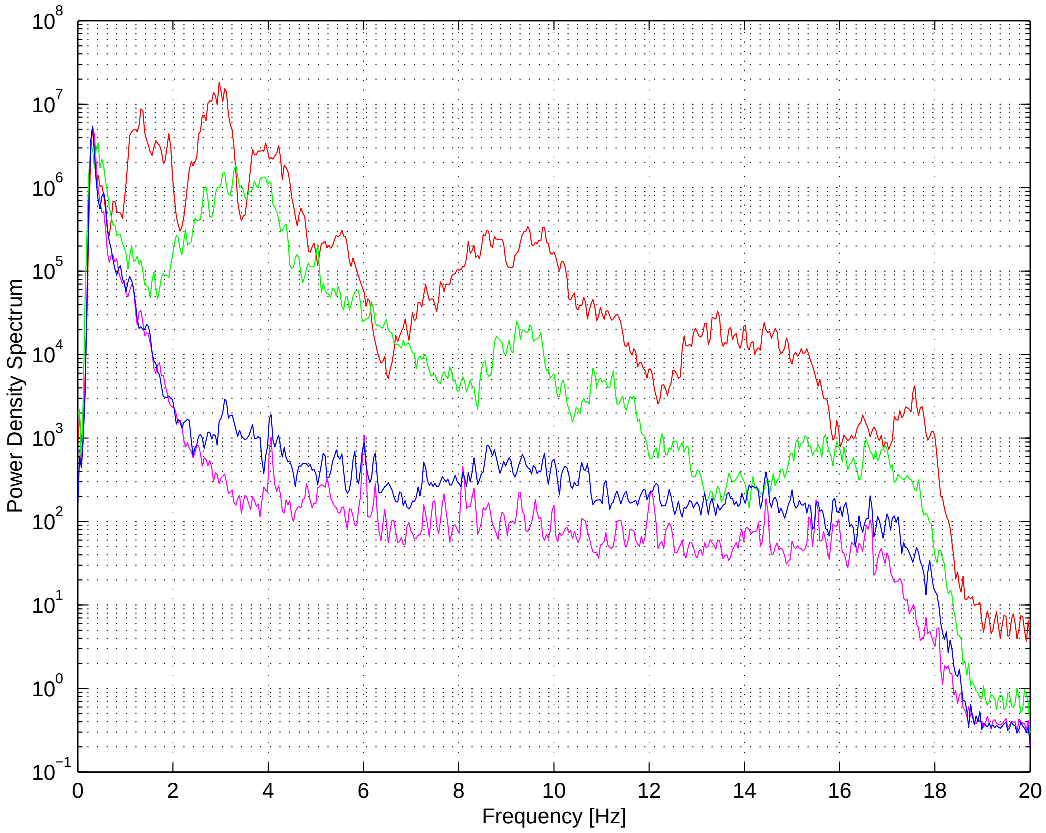

Fig. 6.6.2. Power density spectra from the Kursk main event (Kursk-2, red), the Kursk precursor event (Kursk-1, blue), the magnitude 2.5 explosion in the Barents Sea close to the Kursk site (green), and a noise sample measured just before the Kursk accident (magenta). All spectra are mean spectra of all three components of the central site ARA0 of the ARCES array. The time series were all 90 s long, starting with the P onset, and including most of the Lg wave train. The data were not filtered or processed before calculating the power density spectra using the Welch method.