Forensic Seismology and the Sinking of the Kursk

On August 10, 2000, Russia’s Northern Fleet began its largest naval exercise in more than a decade. Among the vessels taking part was the heavily-armed Kursk, an Oscar class submarine that was the most modern cruise-missile sub in the fleet. Beginning on August 14, a series of reports in the press indicated that the Kursk had been severely damaged during the exercise and that the crew were likely dead. By August 17, news agencies were reporting that seismic networks in the Baltic area had detected two seismic events which appeared to correspond to the Kursk disaster in time and space (Figure 1). Specifically, the seismic events were consistent with reports from the British Broadcasting Corporation on the location of ongoing rescue efforts. The fact that this section of the Barents Sea is essentially seismically active lends credibility to the assertion that the seismic events were directly related to the sinking of the Kursk.

The basic facts about the Kursk incident that can be determined seismically are similar to the information that is routinely generated for earthquakes: the geographical location of the event, the origin time, the character of the source, and the amount of energy released. Figure 2 shows examples of the seismic waveforms associated with the Kursk incident. There are two distinct events separated by 135 s. The first event (2.2 $M_L$) is approximately 250 times smaller than the second event (4.2 $M_L$) and was clearly recorded at only a handful of nearby stations. The second event released energy equivalent to 3–7 tons of TNT and was recorded at distances of up to 5000 km. The Kursk data also possess features that are unique to underwater explosions and rule out the possibility of collision or impact as a source mechanism.

Underwater explosions are highly efficient at generating seismic signals [e.g., Bougandt and Der, 1989; Gitterman et al., 1998] and so it is not surprising that there is a seismic signal associated with the sudden sinking of the Kursk. In fact, the Soviet submarine Komsomolets sank to the northeast of Norway and produced signals on land-based seismometers. The region is well-instrumented in part because of its proximity to the Russian nuclear test site at Novaya Zemlya; however, the station density is not abnormally high compared to other regions in the world such as North America, Japan, Taiwan, and Western Europe. In general, the seismic data are open and electronically available to any seismologist. The forensic seismology analysis of the Kursk disaster illustrates the power of the open seismic data, and its importance in providing timely information to constrain the details of man-made seismic events. This type of analysis is expected to grow dramatically in the near future.

Seismic Recordings of the Kursk Events

The larger of the two Kursk events on August 12 was detected and automatically located by at least four independent monitoring groups. Table 1 gives these preliminary locations and the corresponding magnitudes that were calculated. The locations are quite similar, and the small discrepancies can be attributed to the use of different subsets of recording stations and different Earth models. All four locations were determined with the event depth constrained to be zero. This accounts for the small variations in origin time, which is presumed to be very accurate. We relocated the main event using a superset of arrival time data.

Fig. 1. Locations of regional distance seismic stations which recorded the Kursk events. The stations are a combination of short-period arrays, vertical short-period instruments, three component short-period instruments, and three component broadband instruments. The inset shows our locations and error ellipses for the precursory event (E1) and the main event (E2). The actual position (GT) of the downed sub is indicated by the star.

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and determined a location similar to those in Table 1 (37.160°N, 69.628°E) with a formal error ellipse of 370 km² (Figure 1).

The seismic signals from the first, relatively small Kursk event are extremely faint and we used a Waveform Correlation Detector (WCD) to identify and enhance the signals [Wiechcki Ver- gara, 2000]. The WCD cross-correlates the waveform of a large "master event" with a raw time series. Peaks in the resulting cross-correlograms correspond to sources that are similar to the "master event" both in character and location. We define a window bracketing the full waveform (P, P, S, and L) of the main Kursk event as the master event, and apply the WCD to the seismic beams of three array stations (ARCES, APA, and FINES) and the vertical component of the broadband station KEV. A statistically significant peak is observed with a lag of 135.75 s that corresponds to the precursor event. The waveform similarity is high enough that the precursor event cannot be located to a substantially different position than the main Kursk event. A relocation of the smaller event gives a position of 36.957°N, 69.604°E with an error ellipse of 1.745 km (Figure 1). Application of the WCD to a time span of 24 hours relative to the main event failed to find any other events.

Characterization of the Kursk Source

The high quality and abundance of regional distance seismic recordings of the larger Kursk event make it possible to use discrimination analysis to provide some constraints on the nature of the source. Owing to the lack of previous seismicity in the area, and the similarity of the seismic location with the position of the downed sub, it is extremely unlikely that either Kursk signal was created by an earthquake. However, we would like to determine if the data from the main Kursk event are consistent with a single explosion source, or if other mechanisms, such as multiple small explosions or impact with the sea floor are required.

There are two seismic observations that suggest a complex source process. The first is the emergent, possibly dilatational (downward), first motion on several radial and vertical components (Center for Monitoring Research, 2000). Explosions typically are impulsive and have compressive (upward) first motions at all ranges and azimuths. The second is the considerable variation in the relative excitation of P, P, S, and L. In general, explosions produce a higher ratio of P to S wave energy especially at high frequencies, which is inconsistent with the high level of Ls shown in Figure 2. In particular, application of a standard discrimination metric (P/S at 5-7 Hz) to the KEV data indicates that at this station the Kursk event appears more earthquake-like than explosion-like (Figure 3).

It may be that the explosion occurred as the Kursk was resting on the sea floor and that this caused asymmetries, which resulted in enhanced shear wave generation. It is also possible that the source phenomenology for underwater explosions is substantially different than that of underground explosions, and that pre-existing discriminants based on buried sources are not directly applicable to underwater sources.

An additional factor that may contribute to the source complexity of the main Kursk event is that the energy generated from an impact with the sea floor. In 1994, a large oil drilling platform capsized, filled with water and suddenly sank in the North Sea, producing a seismic event with a magnitude of 3.0 M. (H. Burgum, written communication, 2000). The platform was 50-70 times more massive than the Kursk, and if the Kursk hit the sea floor at a comparable speed, then the equivalent of a magnitude ~1.5 M event would have been generated. However, the energy release could have been significantly greater if the impact speed of the Kursk were higher. It is interesting to note that the sinking of the oil drilling platform also resulted in large shear wave generation (H. Burgum, written communication, 2000).

The most definitive seismic evidence that the main Kursk event was dominated by an explosion source is the observation of a "bubble pulse". Explosions that occur underwater generate a bubble of hot gases that quickly rises to the surface. This gas bubble oscillates in response to the confined hydrostatic pressure, and this oscillation has a dominant frequency that is related to the type of explosion, the yield of the explosive, and the depth of detonation. The oscillation of the bubble is called the bubble pulse, and it produces a distinctive signature on seismic records. In particular, waveforms from underwater explosions have a scalloped amplitude spectrum, similar to that produced by ripple-fired mining blasts.

We illustrate stacked amplitude spectra for the main Kursk event in Figure 4. A scalloped spectral pattern is consistently observed, with adjacent troughs (peaks) separated by ~1.45 Hz. The fact that the same pattern is observed at stations located at varying distances and azimuths implies that the scalloping is a source effect and is unrelated to propagation effects. Furthermore, the same spectral pattern is observed when the time window is chosen to single out a specific phase or the entire waveform is selected. Spectra of comparably sized time windows of seismic noise do not demonstrate the pattern of peaks and troughs illustrated in Figure 4.

A second phenomenon associated with underwater explosions that causes distinct peaks and troughs in the amplitude spectra is the reverberation of seismic energy in the water column. The reverberations come about
because the ocean-atmosphere Interface is an excellent reflector of acoustic energy: Observations of these "water multiples" are very common in seismic exploration experiments and even for shallow earthquakes. The broad spectral peak centered at 9 Hz is probably due to water multiples. Assuming that the wavespeed in the ocean is ~1500 m/s, this frequency gives a water depth of ~85 m, which is similar to the reports from the sinking site of ~100 m. Note that the water depth is much too shallow for reverberations to cause spectral peaks at the lower frequencies where the bubble pulse peaks are prominent.

A relationship between bubble pulse frequency, explosive yield, and detonation depth has been developed and verified using a large population of chemical explosions (Cole, 1948). The tradeoff between detonation depth and explosion size makes it impossible to determine a unique yield estimate. However, if we assume a detonation depth of 85–100 m, the bubble pulse frequency of 1.45 Hz results in yields of 3100–4500 kg equivalent TNT.

The spectral scalloping can be used to address another important question about the Kursk explosion: Was the main shock due to a single large explosion or to several small explosions detonated sequentially? The stacked spectra are very clean and only the fundamental scalloping at 1.4–1.5 Hz stands out sharply. This is much too low a frequency to be associated with explosions detonated over a fraction of a second. The simplest explanation from the seismic data is that the larger Kursk event resulted from a single, large explosion.

The Energy Released by the Kursk Events

Conversion of seismic observations to equivalent explosive yield is a complex exercise that dominated much of the research for monitoring the 1974 Threshold Test Ban Treaty. The most common seismic metric is a magnitude, usually based on P wave amplitude. However, there can be considerable scatter in the magnitude determinations at various stations due to variations in Earth structure or measurement practice. The most common yield-magnitude relations have the form magnitude = a x log((Yield) + b), where a is a constant that scales with the source and b is a constant that depends on the efficiency of seismic wave propagation. Values for b show large variability, which usually require a region to be calibrated with an explosion of known characteristics. On the other hand, a values tend to be very similar, nearly independent of region. Furthermore, a is not particularly dependent on the type of explosive, whether nuclear or chemical.

Owing to the constancy of a values, it is possible to calculate the relative energy release between the two Kursk events independently of the absolute yield of either event. The array stations in ARCES recorded both Kursk events and reported magnitudes of 2.2 M and 4.0 M. Using a = 0.75 (Rodenk, 1971), this implies that the main Kursk event released ~250 times as much energy as the precursory event.

To determine an absolute yield for the main Kursk event, it is desirable to use observations of comparably sized underwater explosions. Although seismic observations of large underwater explosions are rare, detailed records exist for a series of calibration explosions carried out in the Dead Sea in November 1993. Three explosions, with yields of 500 kg, 2000 kg, and 3500 kg of high explosive, were detonated at a depth of 70 m and were well recorded by the Israeli Seismic Network (ISN). Magnitudes of 3.1, 3.6, and 3.9 (M) were determined using ISN data, which is consistent with an a value of 0.80.

The largest of the Israeli shots was recorded by stations of the International Monitoring System (IMS), and the IMS assigned a magnitude of 4.0 M. This is quite similar to the IMS magnitude of 4.2 M, for the Kursk event. In addition, a station in southern Germany, the GERES array recorded both events. GERES is at remarkably similar distances from Kursk events and the Dead Sea shots; 23.86° from the Israeli shots and 23.88° from the Kursk events. Body wave magnitudes calculated at GERES were virtually identical as well; 3.3 and 3.4 (M), respectively. Since the detonation depth was probably similar for the two events, the equivalence of the two independent magnitude types implies that the yield of the Kursk event was on the order of 5 tons equivalent TNT.

This estimate is in excellent agreement with the bubble pulse analysis, although this is probably somewhat fortuitous. The uncertainty in absolute yield is likely to be ±50%, because of several unaccounted factors. These include uncertainty in precise depth of detonation, the difference in density (density) between the Dead Sea and the Barents Sea, and the difference in seismic attenuation along the ray paths to GERES, the influence of the sea floor topography and sediments on seismic coupling, and uncertainty in the importance of the energy released in sea floor impact. Nevertheless, the similarity of the two yield estimates implies that the second Kursk event was consistent with an explosion with an equivalent TNT yield of 5–7 tons.

Scenarios for the Sinking of the Kursk

The seismic signals from the Kursk Incident can only provide soft constraints on plausible sinking scenarios when considered by themselves. The main shock is consistent with the explosion of approximately 5 tons equivalent TNT detonated near, or on, the sea floor. The seismic waveforms contain a strong bubble pulse signature implying that the main event was mostly due to an explosion and not an impact. Furthermore, the waveform correlation between the two Kursk events implies similar source mechanisms and so favors the dual explosion hypothesis. The first explosion presumably disabled the Kursk and caused it to sink to the sea floor where, 2 minutes and 15 seconds later, the main explosion occurred. There is no clear evidence of source multiplicity for the main event and it resulted from either one large explosion or a number of virtually simultaneous smaller explosions.

A more complete scenario for the sinking of the Kursk can be inferred by combining the seismic observations with other evidence. When the Kursk was filmed on the ocean floor, it was observed that the periscope was in the up position, implying that the submarine was near the surface when the initial explosion occurred. It has also been reported that the Kursk radioed for permission to fire ordnance just before the first explosion. Jane's Defence Weekly reports that most modern torpedoes...
have warheads that are equivalent to 250 kg of High Explosive (HE). This is easily large enough to accommodate the size of the first explosion, suggesting a misfire or premature detonation of a torpedo in which a large fraction of the energy was absorbed by the submarine.

The second, larger explosion may have been triggered by impact with the sea floor. However, 135 s is much longer than necessary for a dense object to free-fall 80–100 m in the sea, and so the Krusk would have had to retain buoyancy for a significant period of time after the initial explosion. Alternatively, the main explosion may have been caused as fire from the initial explosion finally reached the other HE warheads on the submarine. The SS-N-19 ship-to-ship missiles carried by the Oscar class submarines have a 750-kg conventional HE warhead. The main event is consistent with the simultaneous detonation of 4–8 such missiles or the detonation of a single cruise missile tipped with conventional HE warheads. The size of the second explosion was so great that it is unlikely any submarines could have survived the corresponding pressure pulse.

It may seem surprising that the Krusk incident was so well recorded seismically, especially since it occurred in a remote corner of the globe and was small by seismic standards. However, the recording of exotic sources has become increasingly common in recent years, owing to the proliferation of open, high-quality seismologic stations. Tragedies such as terrorist bombings [Holzer et al., 1996; Koper et al., 1999] of gas pipeline explosions, and firework factory detonations are just some of the recent incidents in which forensic seismologists have made significant contributions to investigative agencies and the general public.

There are approximately 15,000 seismometers that are permanently installed around the world, and this number is often augmented by temporary deployments of seismometers for activities such as PASSCAL experiments and aftershock studies. Furthermore, there is the prospect of a deployment of unprecedented numbers of high-quality seismometers throughout the U.S. in the next decade [Levander et al., 1999]. Coupled with the growing access to open, near-real-time data from around the globe, these facts ensure that numerous opportunities for forensic seismology will exist in the near future.

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