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Technical Summary

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6.2 Experimental threshold monitoring of the area surrounding the site of the Kursk submarine accident

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6.2.1 Introduction

On 12 August 2000, signals from two presumed underwater explosions in the Barents Sea were recorded by Norwegian seismic stations. The first of these, at 07.28.27 GMT, was relatively small, measuring 1.5 on the Richter scale. The second explosion, 2 minutes and 15 seconds later, was much more powerful, with a Richter magnitude of 3.5. These explosions were associated with the accident of the Russian submarine “Kursk”, although the exact sequence of events leading to this disaster is still unknown.

The area in the Barents Sea where the Kursk accident occurred has no known history of significant earthquake activity. Beginning in September 2000, a number of small seismic events were detected in this area (Ringdal et. al. 2000). According to an official Russian announcement in November, these signals were generated by underwater explosions near the Kursk accident area, carried out by the Russian Navy. At the time of this report, this explosion activity is still continuing.

This explosion sequence, with numerous explosions ranging in magnitude from very small (about 1.0 on the Richter scale) to fairly large (about magnitude 3.0) provides a unique opportunity to investigate the performance of the threshold monitoring technique. We have implemented an experimental site-specific threshold monitoring procedure to monitor the Kursk accident area in the Barents Sea, and present some of the results in this report

We first note that the timing patterns of the explosions show some single explosions and some compressed sequences with explosion intervals of 1-2 minutes. The waveforms have similar characteristics, although they are not identical. These explosions, although their magnitudes were only about 2.0 on the Richter scale, were well recorded by the ARCES array (distance 500 km), but the FINES, SPITS and NORES array also detected several of the events. In addition, the Apatity array station on the Kola Peninsula (not an IMS station) provided useful recordings.

6.2.2 Automatic processing

In developing the site-specific parameters for optimized monitoring of the Kursk accident area, we have built on previous efforts to develop a fully automated tool for monitoring of a given target area. We have included additional functionality to facilitate the review of the computed threshold traces, and examples of this new functionality are shown below.

As outlined in reports under previous contracts, we have already available a robust method for detecting peaks on the threshold traces. The next step is to identify the peaks that are caused by events located outside the actual target area. We will in the following describe the procedure developed for monitoring of the Kursk accident area using data from the SPITS, ARCES, FINES, APATITY and NORES arrays.

6.2.3 Automatic explanation facility

The automatic explanation facility for threshold peaks builds on an integration of traditional detector and event information with the results of continuous Threshold Monitoring.

The first step in the automatic analysis of threshold traces is to identify significant threshold peaks. Our approach has been to develop a peak detection method based on estimates of the noise variance and the long term trend of the threshold trace. From experiments with various data sets, we have developed a method which comprises the following steps:

- Calculate the long-term-median (LTM) of the threshold trace with a typical window length of 60 minutes and a sampling interval of 5 minutes.
- Calculate the overall standard deviation (SIGMA) of the threshold trace around the long-term-median after removing the upper 5% of the data values. The removal of the upper 5% of the data values is done to reduce the influence of the threshold peaks on the estimate of the standard deviation.
- Define the peak detection limit as LTM + n * SIGMA. Optionally, the peak detection limit can be set by the user, and in this study the limit is set to approximately 0.4 m_b units above the LTM.

Fig. 6.2.1 shows a panel with threshold traces for 20 November 2000 (day 325) with the peak detection limits superimposed. Notice that several peaks are identified on the network threshold trace which we have to investigate in more detail.

In order to relate the peaks of the network threshold trace to information obtained by traditional signal processing at each array, we have to determine the time intervals associated with each network threshold peak as well as the expected azimuths and velocities from the site to be monitored (**Table 6.2.1**). The following procedure has been established:

- Detect peaks on the threshold traces calculated for each individual phase.
- For each phase considered, find the peak detection intervals overlapping the peak detection intervals of the network threshold trace, and use the union as the time interval of interest.
- The X-axes of the threshold traces show hypothetical origin times at the Kursk accident area. When searching the detection lists for signals associated with the threshold peaks, we need to shift the detection times in accordance with the expected phase travel time from the Kursk accident area to the actual array.
- We define for each phase a critical azimuth and slowness range for events in the vicinity of the Kursk accident area. Detected signals with azimuth and slowness estimates falling outside the critical ranges are assumed to be caused by events located outside the Kursk area.
- For all panels, green peaks indicate that none of the associated detections were considered critical. Yellow peaks indicate that there were no associated detections whatsoever (see the FINES-P panel in **Fig. 6.2.1** between 7:00 and 9:00). All peaks are flagged on the X-axis for easy identification.

- Each individual phase is given a weight (0 or 1) based on the sensitivity of the array and the usefulness of the phase. The P-phases from Apatity, ARCES, and FINES are given a weight of 1; all other phases have a weight of 0. Critical detections and their associated peaks will be either orange (phase weight 0) or red (phase weight 1).
- Critical peaks on the network trace are assigned a weight which is the sum of the phase weights of the corresponding individual phase peaks. These network peak weights are shown on the top of the panel. Critical peaks with a total weight of at least 2 are red (see **Fig. 6.2.1**, 7:00-9:00); otherwise they are orange (see **Fig. 6.2.1** at about 3:00 and just after midnight). The orange network peak at about 18:20 has an associated critical Lg phase at ARCES. The individual threshold traces for ARCES Lg, Apatity Lg, FINES Lg, and NORES Lg are not shown in **Fig. 6.2.1**, but these phases are all included in the calculation of the network thresholds.
- The causes of the red threshold peaks have to be investigated in more detail, e.g. by comparing to existing event bulletins or by offline analysis of the raw seismic data.

6.2.4 Comments on the Kursk TM case study (day 325/2000)

The plot in **Fig. 6.2.1** shows seven consecutive red color peaks on the network (top) trace. These peaks all correspond to real explosions from the Kursk accident area, as has been verified by interactive waveform analysis. The explosions occur between 7 and 9 GMT, and are almost equidistant in time (15 minute intervals). The software tool has the functionality to provide a higher resolution of the plot, if so desired by the analyst. **Fig. 6.2.2** shows a plot of the one-hour interval 07.00-08.00 for the same day, and it is possible to analyze the peaks in somewhat more detail.

Another new feature is the option to focus on one particular phase, and compare the results with the network trace. **Fig. 6.2.3** shows an example, focusing on the ARCES Pg phase for the day 325/2000. Together with **Fig. 6.2.4**, which is a blow-up of **Fig. 6.2.3** covering the time interval 07.00-08.00, these figures show (from top to bottom);

- The network Threshold Monitoring trace
- The TM trace using the ARCES Pg phase only
- The SNR (in dB) for the ARCES Pg detections
- The ray parameter (s/deg) for the ARCES Pg phase, with the critical interval for the Kursk accident area marked in yellow
- The calculated azimuth for the ARCES Pg phase, with the critical interval for the Kursk accident area marked in yellow
- The slowness difference (absolute value) compared to the expected ray parameter for Pg.

We note from **Fig. 6.2.3** that one red peak in the ARCES plot (at around 03 GMT) is only orange on the network trace. A closer investigation reveals that this peak corresponds to a small mining explosion near the Norway-Russia Border (The Zapolyarnyi/Nikel mine). The azimuth of this mining site from ARCES is almost exactly the same as for the Kursk accident area, and the slowness resolution is not sufficient to distinguish this phase from the Kursk phases using ARCES alone.

It is important to note that the availability of additional array data in this case provide some important contributions to the threshold monitoring results:

- They reduce the size of this “false” peak on the network trace
- They ensure that the peak is not marked in red on the network trace, because the azimuths from the other arrays do not correspond to events at the Kursk accident area.

The development of the automatic explanation facility for analysis of the threshold monitoring results is at an early stage. Our approach is to gain experience through processing of numerous different time intervals, such that as a final product we can present a tool for continuous monitoring of a given target region that requires very little human interaction.

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Table 6.2.1. Definition of critical azimuth and slowness ranges for phases from events near the Kursk accident area

Array	Phase	Expected Azimuth (degrees)	Lower Azimuth (degrees)	Higher Azimuth (degrees)	Expected Slowness (sec/deg)	Lower Slowness (sec/deg)	Higher Slowness (sec/deg)
APA	Pg	50.65	25.0	65.0	13.97	10.1	22.2
APA	Lg	46.57	20.0	60.0	25.78	18.5	37.1
ARCES	Pg	88.1	75.0	100.0	13.7	10.6	15.9
ARCES	Lg	88.4	70.0	100.0	26.2	22.2	37.1
FINES	P	23.15	10.0	40.0	13.28	10.11	18.53
FINES	Lg	21.75	5.00	35.0	28.88	22.24	44.48
SPITS	P	142.70	135.0	155.0	15.27	11.12	24.71
NORES	P	33.38	20.0	45.0	12.47	9.27	15.88
NORES	Lg	29.75	20.0	45.0	32.42	22.24	55.60

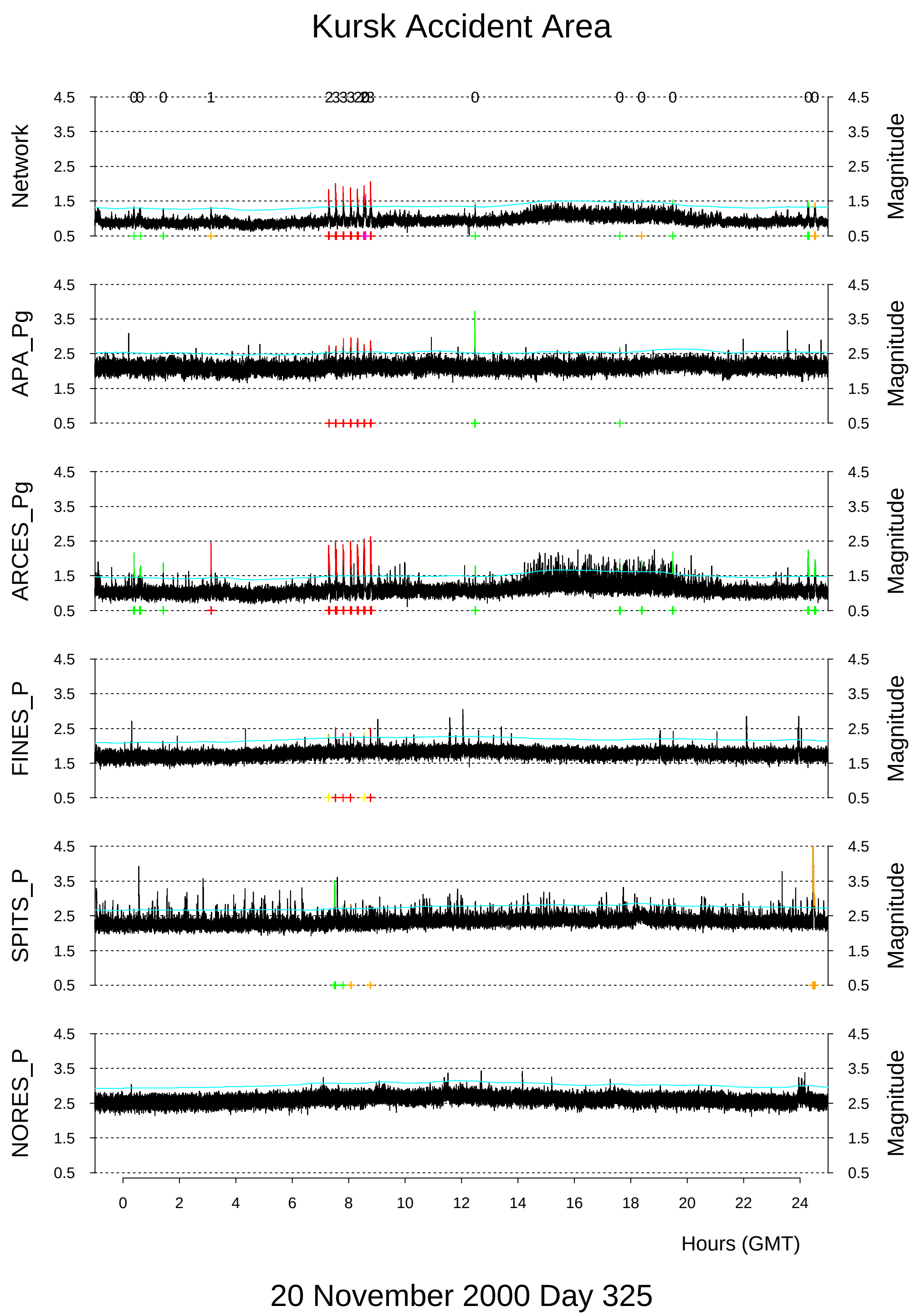

Fig. 6.2.1. *Site-specific Threshold Monitoring of the Kursk accident area for 20 November 2000 (day 325). The plot shows the 5 individual station thresholds (P-phases), with the combined threshold trace on top. Peaks which are likely to be caused by events near the Kursk accident area are shown in red.*

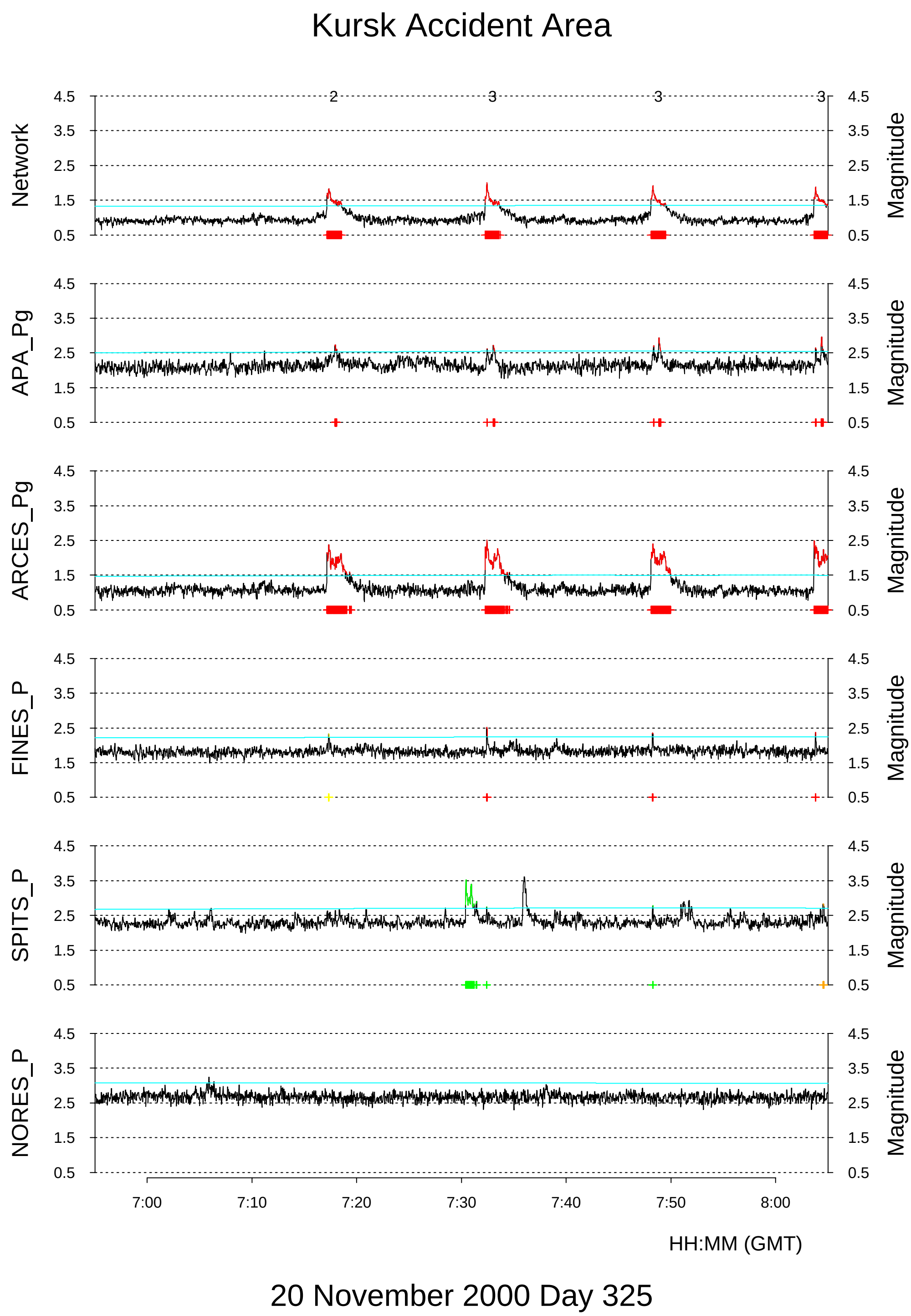

Fig. 6.2.2. *Same as Fig. 6.2.1, but covering only the one-hour interval 07.00-08.00 on day 325/2000. Note that the detailed plot for ARCES shows two peaks for each event. This corresponds to the P and S phases, and these two peaks are merged into one for each event on the network trace.*

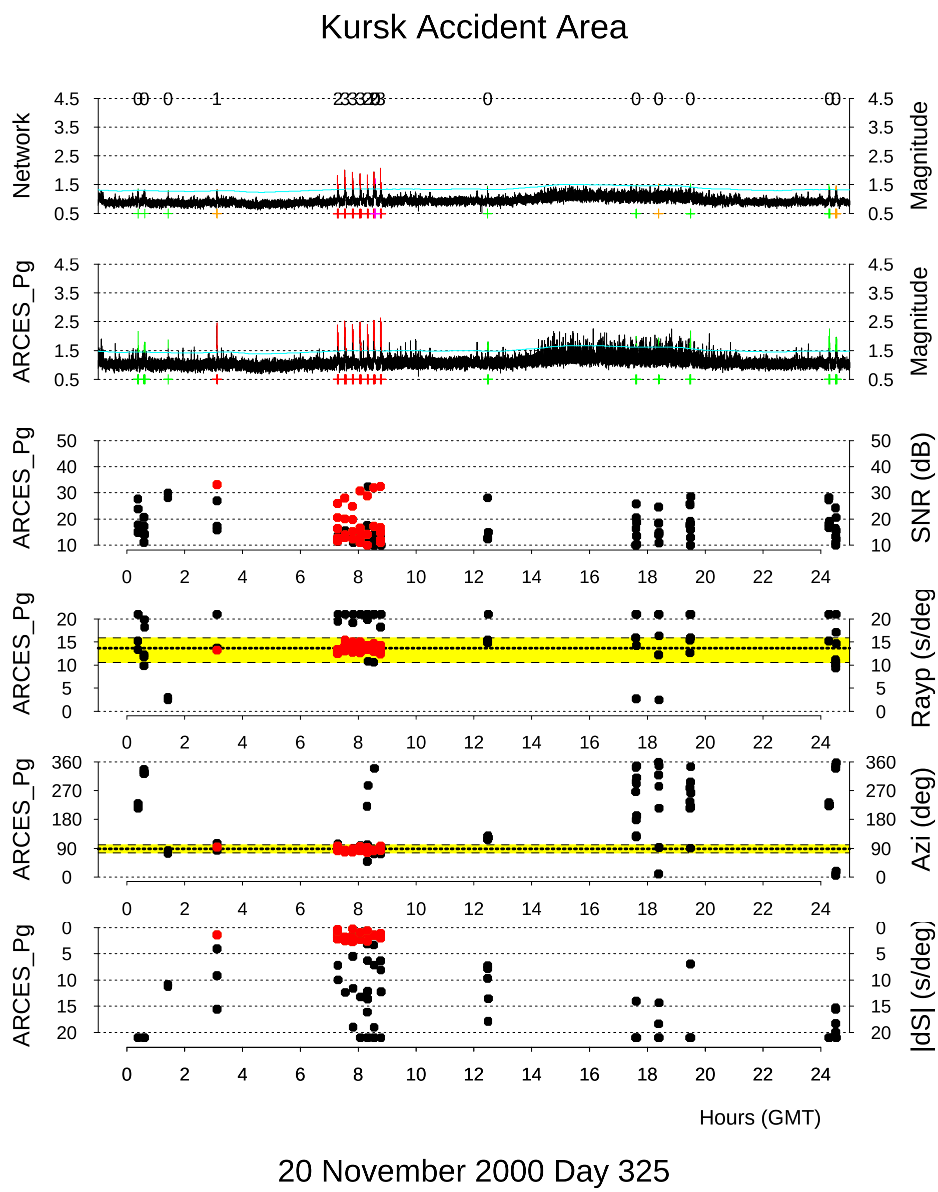

__Fig. 6.2.3.__ Site-specific Threshold Monitoring of the Kursk accident area for 20 November 2000 (day 325) with information from the signal detector at ARCES. The two upper panels show the threshold traces for the network and for the ARCES Pg-phase. Peaks which are likely to be caused by events near the Kursk accident area are shown in red.
Information about the signal detections associated with the network threshold peaks is displayed in the four lower panels. The critical ranges of slowness (ray parameter) and azimuth are indicated in yellow in panels 4 and 5, and the bold dashed lines indicate the expected values of Pg-phases from the Kursk accident area.
The panel at the bottom indicates the differences in horizontal slowness estimates between the detected signals and the expected value for P-phases from the Kursk accident area (in s/deg). Signals satisfying both the azimuth and slowness criteria are shown in red.

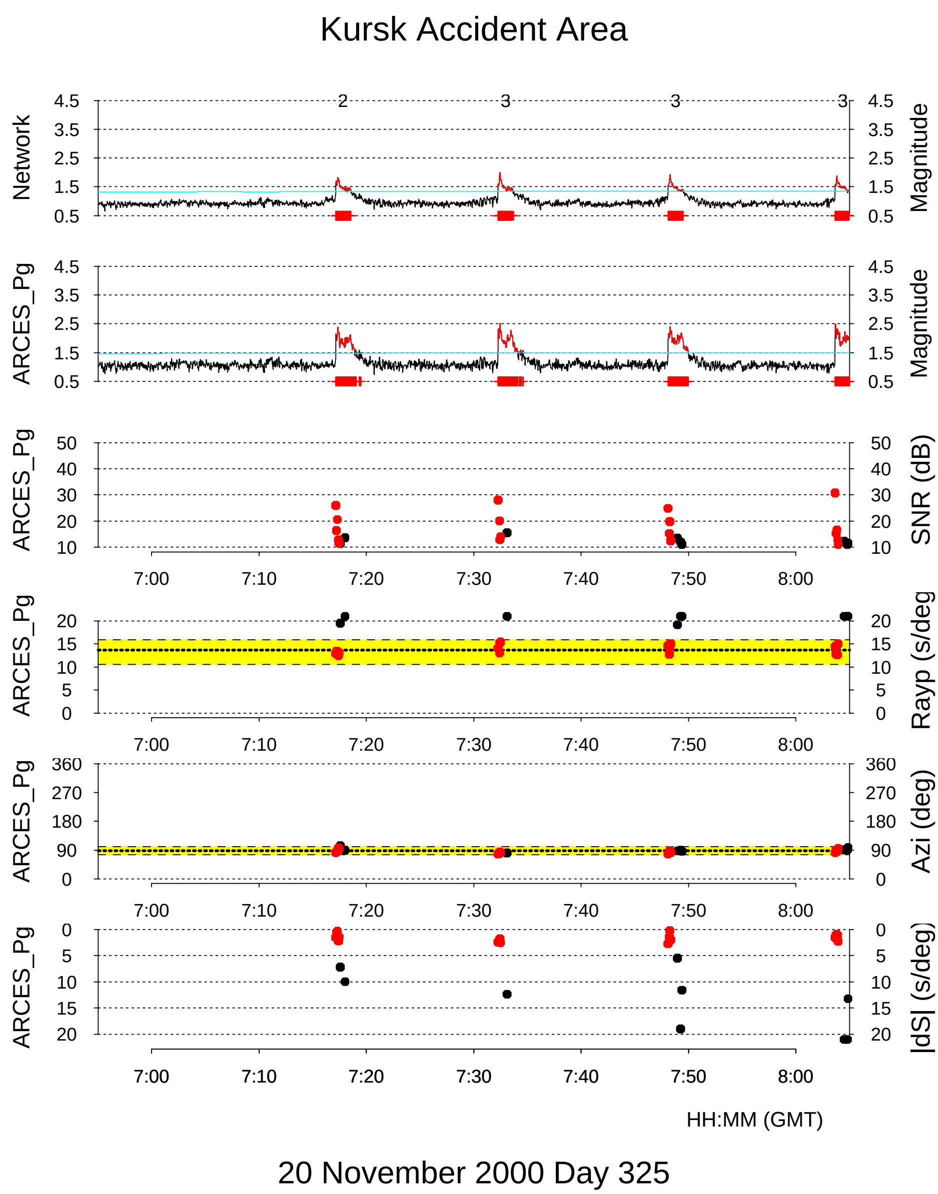

Fig. 6.2.4. *Same as Fig. 6.2.3, but covering only the one-hour interval 07.00-08.00 on day 325/2000. The red dots on the four lower panels correspond to Pg detections from events at the Kursk accident area, whereas the other (black) detections on these plots actually correspond to S-phases from the same events. Their azimuths are consistent with the Kursk accident area, while their slownesses are outside the critical area.*