CHARACTERISTICS OF INFRASOUND PRODUCED BY LARGE MINING EXPLOSIONS IN KAZAKSTAN

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ABSTRACT

Since October, 1997, we have recorded infrasonic signals at the Kurchatov Observatory in Kazakstan from large mining blasts in Kazakstan and Siberia. The Kurchatov Observatory is an ideal site for research on infrasound and application of synergistic (seismic and acoustic) methods of event discrimination as it operates a 21-element short-period seismic cross-array and a three-component broadband seismographic station, and because of its close proximity to several large (100+ton) mining operations.

In September, 1998, we installed two additional infrasound sensors to form a three-element triangular array with 2-4 km spacing. Two of the elements consist of Globe microphones connected to noise reduction hose and pipe arrays, while the third is actually a small array comprised of several Soviet built, low-frequency microphones (K-301A) connected to various noise-reducing pipe configurations. We have compiled and analyzed infrasound signals from mine blasts for 1997 and 1998 in order to understand the character of infrasound signals produced by regional mine blasts and the nature of infrasound propagation at high latitudes. We are currently analyzing signals from 1999 recorded by the new large array.

Several large mines in the region routinely generate explosions that are detected seismically and with infrasound. The mines range in distance from 80 to 750 km from the infrasound array. The Ekibastuz mine, 250 km west of the array, regularly produces 4-6 seismic detections per day. The corresponding number of infrasound detections is found to be dependent upon the season and the local winds. During the winter months, when the direction of the zonal component of the stratospheric wind is from west to east, a strong stratospheric duct develops between Ekibastuz and Kurchatov and the number of infrasound detections is high. During this period the infrasound signal consists of two arrivals separated by about 60 s.

A preliminary interpretation of these signals, based on ray-tracing through an atmospheric model that includes a mean zonal wind model for mid-latitude, northern hemisphere winter and is modified below 15 km to account for an observed tropospheric duct, is that the first arrival at 250 km distance propagates through the troposphere and is followed 60 s later by a stratospheric arrival. During the summer months, when the zonal winds reverse direction, the number of infrasound detections is low.

Preliminary analysis of signals recorded during spring, 1999, by the larger aperture array suggests that the larger array results in improved infrasound detection of Ekibastuz mine blasts and improved discrimination of non-acoustic noise. During this period the second infrasound arrival follows the first by 90 s and is found to consist of two pulses separated by about 10 s. The larger array also confirms identification of infrasound signals believed to be produced by events in the Kuzbass mining region of Siberia, over 700 km away.

Key Words: Infrasound, ray-tracing, mine explosion, atmosphere, Kazakstan

OBJECTIVE

In order to meet the monitoring requirements of the Comprehensive Nuclear-Test-Ban Treaty (CTBT), three technologies - seismic, hydroacoustic, and infrasonic - will be relied upon to detect acoustic waves produced by nuclear explosions detonated on land, in the sea, and in the air. While seismic and hydroacoustic technologies are sufficiently evolved to meet the monitoring needs of the CTBT, in its current state, infrasonic technology, is not. There are several reasons why development of the infrasound component lags behind the other two. Temperatures in the atmosphere vary on time scales of hours to months, and wind speeds (up to 100 m/s) are a significant fraction of the average sound speed (~330 m/s). The result is that the acoustic propagation channels in the atmosphere are highly variable. This variability must be quantified for infrasonic monitoring to meet the needs of the CTBT.

There is currently an acute lack of reliable infrasonic observations that can be utilized to examine the effects of time-dependent variations in atmospheric properties on the delectability and characteristics of infrasound signals. This is particularly true for infrasound generated from smaller explosions, which the CTBT aims to monitor, but which are likely to be recorded by only a few (1-3) of the nearest IMS stations. We are constructing a database of infrasound waveforms from the mine explosions in order to examine the variability of observed infrasound characteristics (delectability, arrival time, waveform) throughout the year. In addition, we are evaluating the performance of several adaptive filtering techniques designed to suppress wind noise and enhance infrasound detection.

RESEARCH ACCOMPLISHED

Installation of Kurchatov Infrasound System

Since October, 1997, we have conducted infrasound observations at the Kurchatov Geophysical Observatory in Kazakstan using available microphones coupled with existing noise reduction systems in order to address some of the infrasound monitoring issues outlined above. The Kurchatov Observatory (Figure 1) is an ideal site for research on infrasound and on the application of synergistic (seismic and acoustic) methods of event discrimination as it operates both a 21-element short-period seismic cross-array (Figure 2) and a three-component broadband seismic station, and because of its close proximity to several large (100+ton) mining operations (Figure 1). In addition, conditions appear to be favorable for long-range infrasound propagation in Kazakstan, where infrasound signals have been detected out to 2,000 km distance [Al'Perovich et al., 1985].

Three types of noise reduction configuration are utilized in this study from fall of 1997 through January 1998 at the central recording site Figure 2: 1) six, 70 m long underground pipes extending radially from a central chamber and referred to as "East-" and "West-" spiders; 2) a single, 30 m long pipe with an outlet at the center of the length; and 3) an "H-pipe" array consisting of two, 300 m long pipes joined at their centers by a 100 m long pipe. The 300 m long pipes are raised 1 m above the ground and have sampling nozzles spaced at 3 m intervals located on their undersides, facing the ground. The internal diameter of the 300 m long pipes varies from 1/2 inch at the ends to 2 inches in the middle. The 30 m long pipe is raised 0.5 m above the ground and has sampling nozzles spaced at 0.5 m intervals. We presume that these systems, which were constructed during the Soviet era, were designed to be functional during the severe local winters, when snow covers the ground for five months each year and prohibits the use of conventional plastic hoses.

Two types of capacitor microphone - Globe and Soviet K301 - have been utilized with the pipe arrays described above. The K301s were originally installed at Kurchatov in the early 1970's by the Russian Ministry of Defense and recorded on paper. Since February, 1995, the analog signal from a K301 sensor has been digitized and recorded by a 16-bit A/D system together with the seismic channels from the cross array. Since October, 1997, 4-8 microphones connected to the various noise reduction systems have been simultaneously recorded, forming a small aperture acoustic array.

Fall 1997, Winter 1998 Small Array Infasound Observations

Between October, 1997 and January, 1998, we detected infrasound signals generated by 26 Ekibastuz mine events. The location and origin time of each event were determined from the seismic cross-array and are

listed in Table 1. Ekibastuz comprises a number of coal mines centered about (51.67N, 75.40E) as determined by satellite

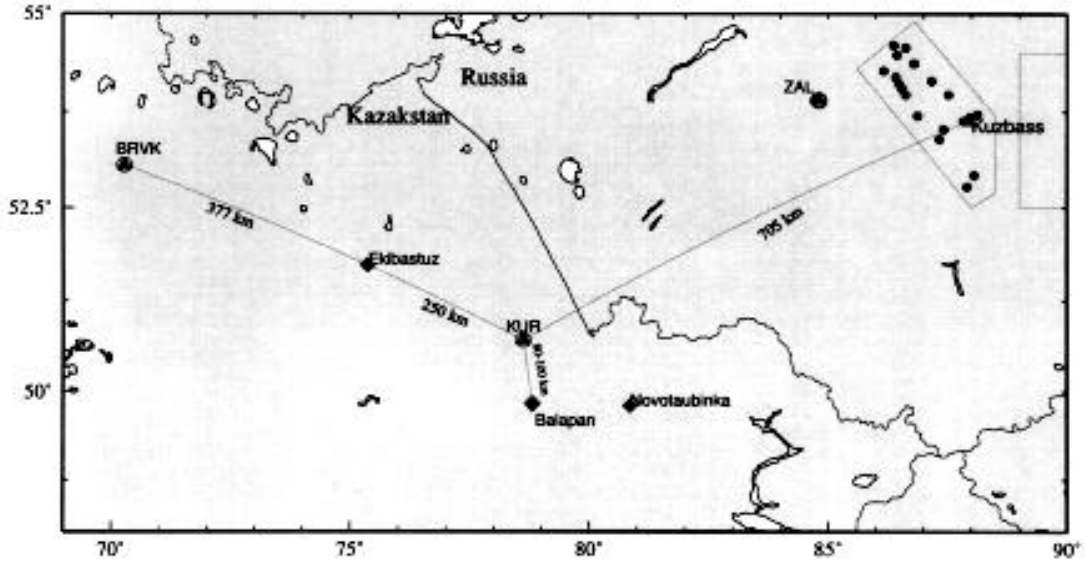


Figure 1: Map of Kazakstan and southwestern Siberia showing locations of broadband seismic stations in Kazakstan (solid triangles), active mining areas (diamonds), Kuzbass and Abakan mining areas (shaded squares), the Balapan nuclear test site, and the Kurchatov Geophysical Observatory (KUR), where the seismic and infrasonic observations were made.

Figure 2: Plan view of the 21-element seismic borehole array (cross array) at Kurchatov and location of infrasound sensors. All are located within the Kurchatov Geophysical Observatory compound, which also houses the central recording unit for the cross array and a three-component broadband seismometer installed in a 25m shaft. Infrasound noise reduction systems (pipe arrays) utilized in this study are located at the central recording site (circled triangle).

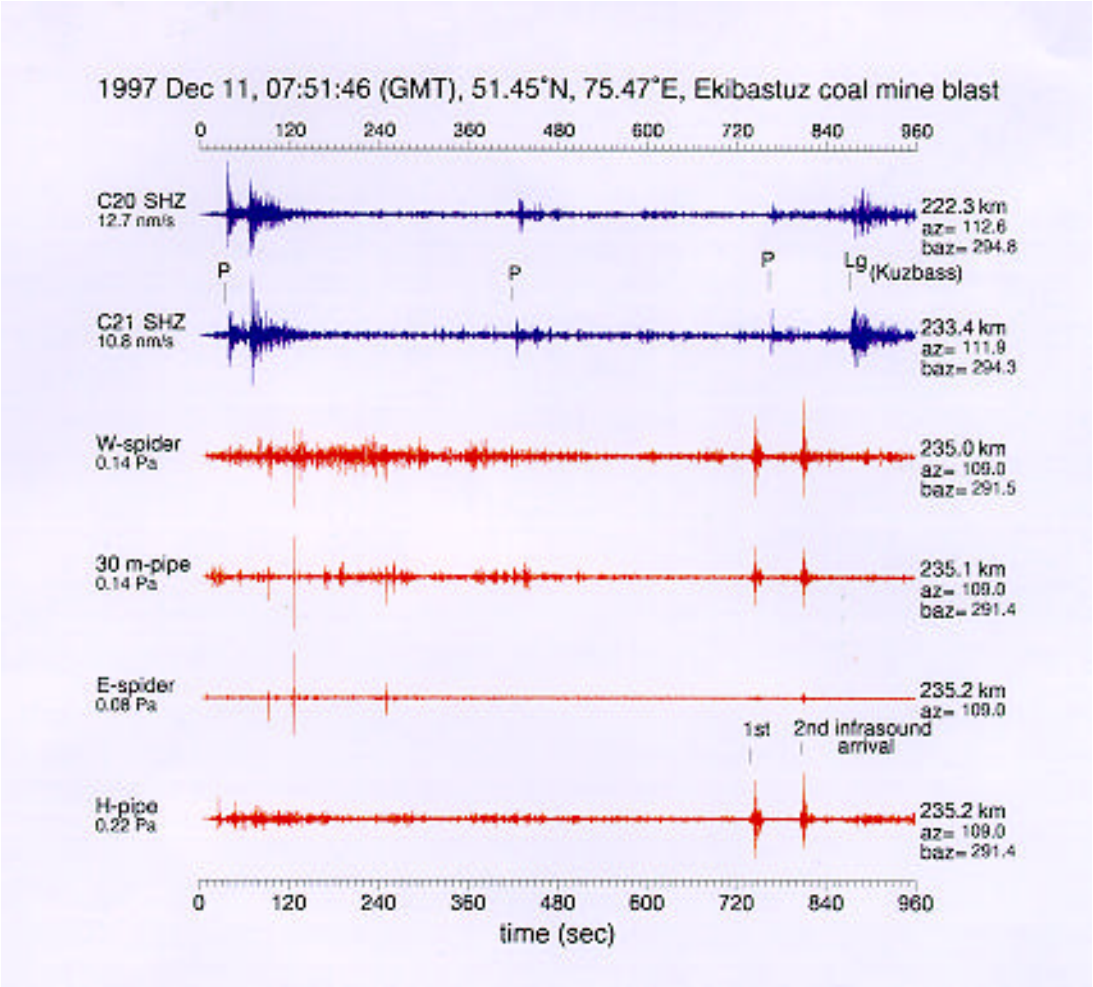


Figure 3: Selected cross-array seismic channels (top two traces) and infrasound signals recorded with four different noise reduction systems (Figure 2) for an Ekibastuz coal mine blast on Dec. 11, 1997. The first infrasound arrivals show phase velocity=0.38 km/s and back-azimuth=267º.

photographs [Thurber et al., 1990].

The infrasound wavetrain generated by Ekibastuz explosions during this period can be classified into two categories. The first, shown in Figure 3, consists of 1 or 2 simple pulses, with travel times of approximately 740 and 810s with respect to the seismically estimated origin time. The second arrival is observed in about 60% of the events (18) from Ekibastuz; when present, it generally follows the first by 50-70 s, though this can range anywhere from 24 to 85 s (Table 1). The travel time of the first arrival exhibits great variation and probably reflects varying atmospheric conditions such as transient propagation ducts.

We applied a beamforming procedure to the acoustic traces to estimate the apparent phase velocity (0.38 km/s) and back-azimuth (2670). The estimated back-azimuth is 30'off that predicted from the seismic location (2970). The large discrepancy likely reflects the small aperture of the small infrasound array; the back-azimuth estimated by the large aperture array, discussed below, is extremely close to the predicted value.

The second type of infrasonic wavetrain associated with Ekibastuz events, shown in Figure 4, consists of a series of pulses of growing amplitude lasting some 20-30 s. The event shown in Figure 4 is actually two

explosions closely spaced in time. While the seismic waves from the two explosions overlap, making it difficult to resolve two events, the lower phase velocities and shorter durations of the infrasonic waves allow the two events to be distinguished (Figure 4). For this reason, infrasound observations may be crucial for detecting a shallow nuclear test hidden in the seismic coda of an earlier event.

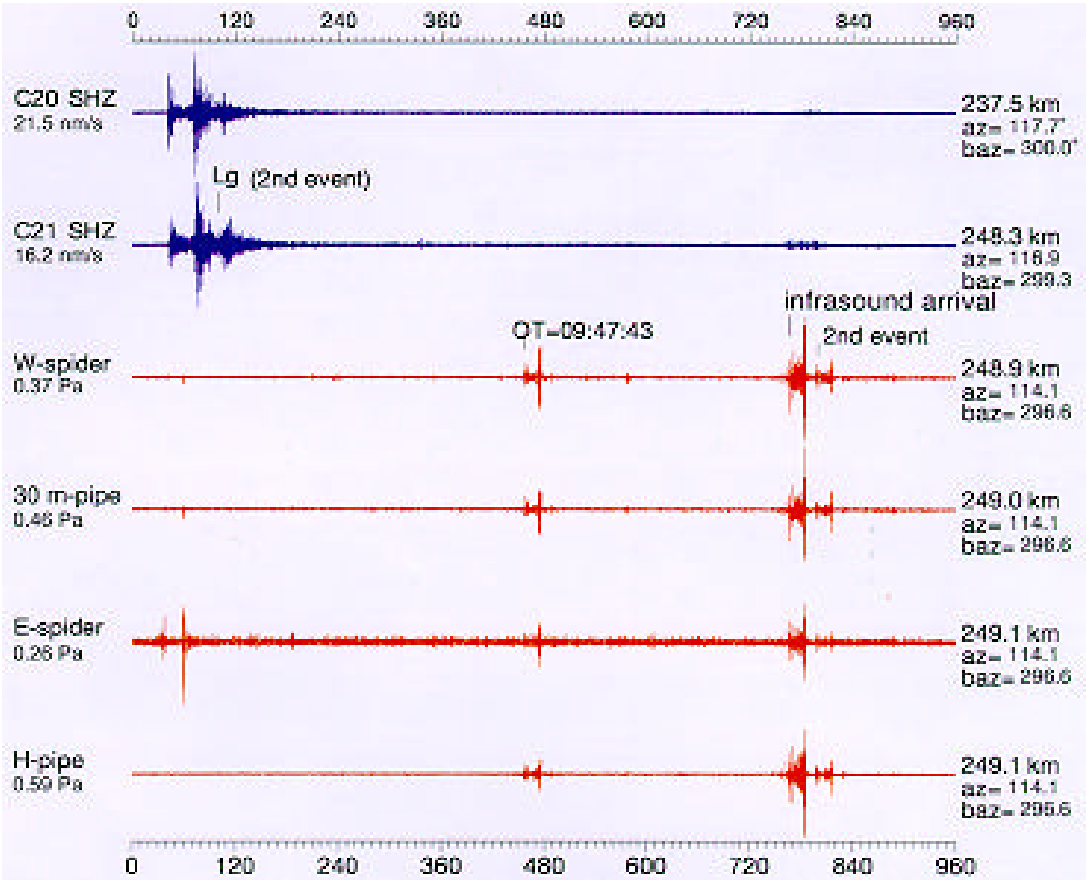
Table 1: **List of infrasound signals from mining blasts at Ekibastuz, Kazakstan**

Id	Origin time		Magnitude	Phase	Travel time	Group velocity	Amplitude
no.	mm/dd/yy	hh:mm:sec		id	(s)	(m/s)	(Pa)
01	10/16/97	08:16:13	2.1	S1	820	303	0.22
02	10/16/97	08:28:43	2.6	S1	810	307	0.23
03	10/16/97	08:34:39	2.3	S1	825	301	0.11
04	10/17/97*	11:39:14	2.2	S1	646	325	0.13
				S2	731	287	0.06
05	11/19/97	09:37:57	2.2	S1	730	341	0.09
06	11/19/97	10:20:07	2.5	S1	793	313	0.13
07	11/27/97	07:43:17	2.2	S1	763	326	0.29
08	11/27/97	09:47:45	1.9	S1	788	315	0.16
09	11/27/97	09:53:18	2.4	S1	765	325	0.54
10	11/28/97	08:34:14	2.5	S1	763	326	0.13
11	11/28/97	08:58:06	2.4	S1	761	327	0.19
12	11/28/97	09:30:49	2.3	S1	757	328	0.45
13	12/02/97	08:48:11	1.9	S1	734	339	0.29
				S2	793	313	0.17
14	12/02/97	09:23:38	1.6	S1	756	329	0.08
				S2	794	313	0.05
15	12/02/97	09:27:25	2.0	S1	746	333	0.41
				S2	786	316	0.22
16	12/02/97	10:29:01	2.1	S1	743	335	0.13
				S2	779	319	0.08
17	12/11/97	07:51:46	2.4	S1	739	336	0.23
				S2	809	307	0.29
18	12/11/97	07:57:43	1.9	S1	718	346	0.04
				S2	799	311	0.03
19	12/11/97	08:36:50	2.8	S1	747	333	0.09
				S2	809	307	0.05
20	12/11/97	08:58:22	2.5	S1	750	332	0.19
				S2	812	306	0.17
21	12/11/97	10:49:47	2.2	S1	737	337	0.09
				S2	798	312	0.06
22	01/14/98	07:02:34	2.0	S1	796	312	0.26
				S2	827	301	0.49
23	01/14/98	08:13:40	2.4	S1	795	313	0.26
				S2	829	300	0.31
24	01/14/98	09:16:47	2.6	S1	815	305	0.17
				S2	839	296	0.25
25	01/28/98	07:31:04	3.0	S1	753	330	0.15
				S2	777	320	0.08
26	01/28/98	08:15:21	2.4	S1	764	325	0.25
				S2	788	315	0.27

There is no evidence for multiple cast firing within either of the two seismic events, hence, the multiple phases observed in the infrasound data must be produced by propagation effects.

During the observation period, three infrasound signals from events in the Kara-Zhyra coal mine in the Balapan former Soviet nuclear test site were identified (Table 2); their detection at such short range (Δ=80 km) suggests that a favorable tropospheric duct exists.

1997 Nov 27, 09:53:16 (GMT), 51.67ºN, 75.40ºE, Ekibastuz mine blasts



time (sec)

Figure 4: Same as Figure 3 for Ekibastuz mine blast on Nov. 27, 1997. This event is actually two closely spaced explosions which produce overlapping Lg phases in the seismic channels but produces separate infrasound arrivals. An additional infrasound arrival at t~460 s is from an earlier Ekibastuz event. Each event is seen to consist of a sequence of pulses of increasing amplitude lasting 20-30 s.

Modeling of winter infrasound signals

In order to identify the infrasound arrivals, we ray traced through various suitable atmospheric models. Figure 5 shows the sound speed (c) as a function of height in the atmosphere derived from mid-latitude (45N) temperature profiles for January and July [Valley, 1965] and the well-known theoretical relation $c(T) = 20.1\sqrt{(TK)}$, where T is the temperature in degrees Kelvin. In Figure 5 a mid-latitude zonal wind models for winter adapted from Georges and Beasley [1977] is shown. Ray tracing through the winter temperature model alone confirms that in the absence of wind, no rays are predicted return to the Earth's surface at distances less than 280 km. Beyond 280 km, the first arrivals turn in the thermosphere, at altitudes of ~150 km, followed by secondary arrivals that turn at ~125 km; no energy is returned from the stratosphere (40-80 km). Thus, in the absence of wind, no favorable propagation paths are predicted to exist between Ekibastuz and Kurchatov (Δ=250 km).

Figure 5 shows ray paths for the winter model including the winter zonal winds. The first rays arriving at 220-250 km have turned in the stratosphere (h~38 km). The predicted travel time and phase velocity match the observed values at Ekibastuz reasonably well, however, the second observed arrival is not predicted by this model. In order to produce two arrivals with the observed time separation (~70 s) at Δ=250 km, a tropospheric duct must exist between Ekibastuz and Kurchatov. This is supported by the observation of a direct (tropospheric) arrival from Kara-Zhyra explosions, 80 km away and well within the shadow zone

Table 2: **List of infrasound signals from other mining blasts**

Id	Origin time mm/dd/yy	Origin time hh:mm:sec	Lat. (°N)	Long. (°E)	Magnitude	Phase id	Travel time (s)	Group velocity (m/s)	Amp (Pa)
				Novotaubinka near Semipalatinsk					
1	11/19/97	09:24:38	49.80	80.85	0.5	D	624	302	0.10
				Kara-Zhyra mine in Balapan					
1	11/19/97	10:28:27	50.01	78.80	3.7	D	252	317	0.58
2	12/11/97	11:58:10	49.99	78.59	1.8	D	232	234	0.39

predicted by models with no tropospheric duct. The existence of a tropospheric duct implies an increase in the effective sound speed between the surface and the tropopause (0-15 km); we cannot distinguish whether this is caused by a temperature inversion or a westerly jet, however, we prefer the former as the duct must exist in both the easterly and northerly directions. Support for a winter temperature inversion can be found in a study on infrasound reception of explosions detonated at 1 km height in the atmosphere in southern Kazakstan [A1'Perovich et al., 1985]; direct arrivals observed out to distances of 200 km were linked with meteorological measurements in the troposphere that confirmed a temperature inversion between the surface and 2-4 km.

Spring 1999 Large Array Observations

Preliminary analysis of signals recorded during spring, 1999, by the large aperture acoustic array indicate an improved ability to detect mine events and to reject non-acoustic "noise" compared with use of the small array alone. An example 1 hour window of data recorded during peak mining hours (07:00-10:00 GMT) is shown in Figure 6. During this hour we are able to identify 7 Ekibastuz events in the seismic channels; for all but one of these we can also identify associated infrasound signals. The first infrasound arrival for each event has a travel time of 760 s and is followed 90 s later by a second arrival that consists of two pulses separated by 10 s. The estimated back-azimuth for these arrivals is 302°, close to the expected value. The character of the infrasound arrivals is so regular on this day, that we are able to identify two Ekibastuz events (one of these is indicated by the "?" in Figure 6), for which no seismic detection was made, solely on the basis of the infrasound detections. During this period we are also able to identify infrasound signals generated by mine explosions near the Kuzbass region in Siberia (Figure 1), over 700 km away. Since August, 1998, we have operated a broadband seismometer near the town of Eltsovka, close to the Kuzbass region, in order to aid identification of Kuzbass events.

CONCLUSIONS AND RECOMMENDATIONS

We have presented here an initial interpretation of the characteristics of infrasound propagation observed in northern Kazakstan and Siberia. During the winter, the infrasound signals associated with Ekibastuz events can be classified into two types. The first type consists of two pulses spaced 50-70 s apart, while the second type consists of multiple pulses arriving within about a 20-30 s window. Infrasound arrivals from both Ekibastuz (Δ=250 km) and Kara-Zhyra(Δ=80 km) explosions support the existence of a tropospheric duct, produced by a temperature inversion and/or a westerly jet in the troposphere. The multiple arrivals characteristic of the second type of infrasound wavetrains likely result from strong positive sound speed gradients in the troposphere and, especially, in the upper stratosphere. The large variability in the character of infrasound signals generated by Ekibastuz events over short time scales (hours to days) is indicative of the rapidity of atmospheric fluctuations.

Measurements of the back-azimuth of different infrasound arrivals have the potential to resolve some of the ambiguity that exists in using infrasound to infer the horizontal wind structure in the atmosphere. However, much more accurate back-azimuth estimates than can be obtained by a small aperture array are required. For this reason, we have extended the small array at Kurchatov into a larger triangular array with 2-4 km sides. In addition, we intend to install a second three-element infrasound array at Borovoye, 377 km NW of Ekibastuz (Figure 1), in order to examine the seasonal effects of the stratospheric winds both upwind and downwind from the source. These improved infrasound arrays will provide unique data that may be used to advance the infrasound technology used for CTBT monitoring.

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January sound speed & zonal wind

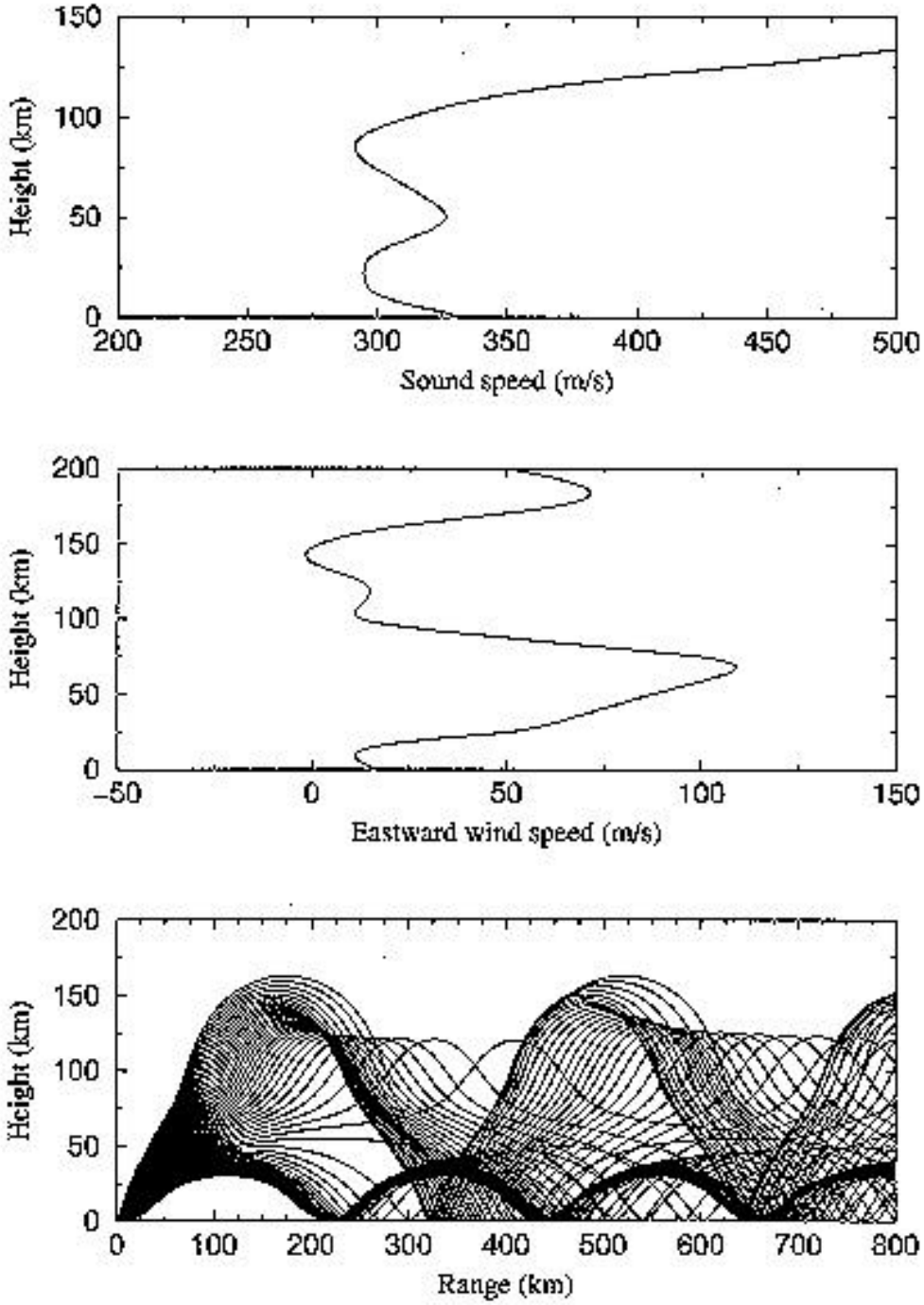

Figure 5: (a) January and July sound-speed profiles derived from the 1962 U.S. Standard Atmosphere midlatitude (45N) temperature profiles [Valley, 1965]. (b) January and July midlatitude zonal winds taken from Georges and Beasley [1977]. Also shown for comparison are zonal winds measured by the high-resolution doppler imager aboard the Upper Atmosphere Research Satellite (UARS) [Fleming et al., 1996]. (c) Results of ray tracing through a sound speed profile given by the 1962 U.S. Standard Atmosphere midlatitude temperature profile and the January zonal wind model. Ray paths computed for the exact method.

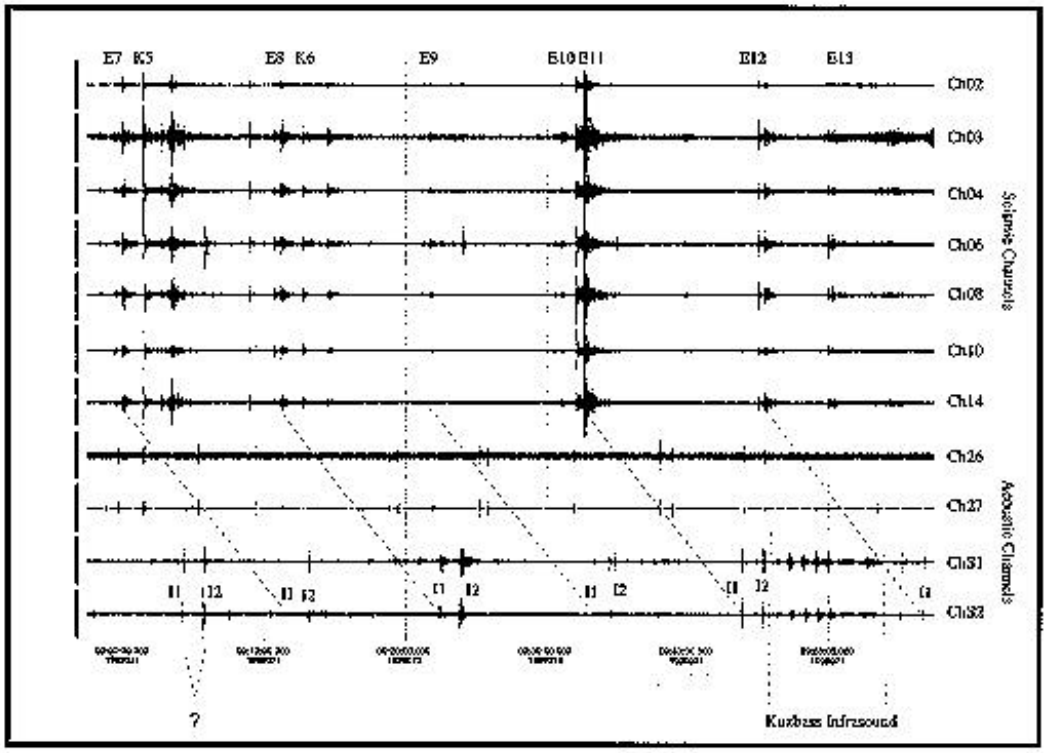

Figure 6: Example data from the Kurchatov seismic cross-array and acoustic triangle array for spring, 1999. During the one hour period shown are 7 Ekibastuz events with associated infrasound arrivals (?) believed to be produced by an Ekibastuz event that did not generate a seismic signal, and infrasound arrivals from a Kuzbass mine event, 700 km away.