Tornado Detection Based on Seismic Signal

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ABSTRACT

At the present time the only generally accepted method for detecting when a tornado is on the ground is human observation. Based on theoretical considerations combined with eyewitness testimony, there is strong reason to believe that a tornado in contact with the ground transfers a significant amount of energy into the ground. The amount of energy transferred depends upon the intensity of the tornado and the characteristics of the surface. Some portion of this energy takes the form of seismic waves, both body and surface waves. Surface waves (Rayleigh and possibly Love) represent the most likely type of seismic signal to be detected. Based on the existence of such a signal, a seismic tornado detector appears conceptually possible. The major concerns for designing such a detector are range of detection and discrimination between the tornadic signal and other types of surface waves generated by ground transportation equipment, high winds, or other nontornadic sources.

1. Introduction

Tornadoes represent the most violent of all forms of atmospheric storms, resulting in hundreds of millions of dollars in property damage and approximately 50–100 fatalities each year. In recent years, by means of Doppler radar, considerable success has been achieved in detecting tornadic storms. Such radar systems, however, cannot determine when a tornado is actually in contact with the ground.[1] At the present time the only generally accepted method for detecting when a tornado is on the ground is human observation. There is strong evidence to indicate that a tornado in contact with the ground produces a significant seismic signal. The existence of this tornadic seismic signal (TSS) suggests a totally new way of detecting when a tornado is on the ground.

2. Background

a. Nature of the physical process

The considerable kinetic energy contained within a tornado is a generally accepted fact. The magnitude of this energy may vary depending on the intensity of the tornado. According to one source, the rate of production of kinetic energy in a tornado with a swath of 200 m and wind speeds of 100 m s^{-1} is on the order of 10^3 MW (Davies-Jones 1982). Whenever in contact with the ground, a tornado encounters considerable frictional resistance. In overcoming such resistance and in interacting with the ground through turbulent pressure fluctuations, as depicted in Fig. 1, the tornado transfers a considerable amount of energy into the ground. A significant portion of the energy absorbed by the ground takes the form of seismic vibrations with the remainder being transformed into thermal energy. In effect, the ground acts as a filter, characterized by an impulse response function, with the pressure fluctuation as an input and the particle velocity as an output. The characteristics of the filter are functions of both the position of the source and the position of the receiver.

Seismic waves in the earth exist as either body waves or surface waves, depending on the region through which they propagate. Such waves may also be classified according to the direction of displacement relative to the direction of propagation. Waves whose displacement is parallel to the direction of propagation are classified as longitudinal, compressional, or P (for primary) waves. Waves whose displacement is perpendicular to the direction of propagation are classified as

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[1] A tornado is generally considered to be in contact with the ground when destructive winds are encountered at ground level.

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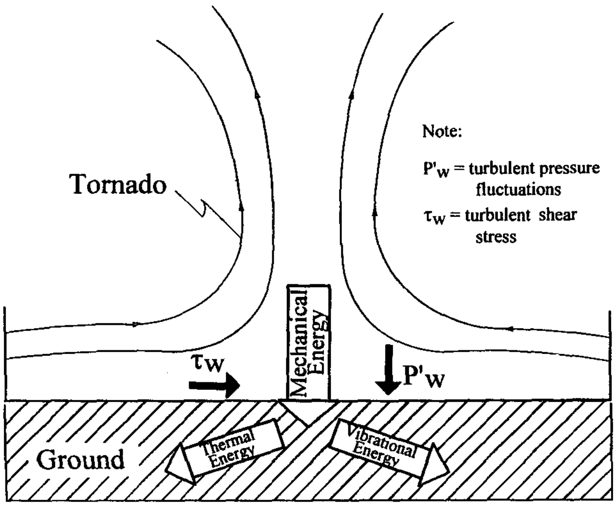

FIG. 1. Tornado–ground interaction.

transverse or S (for secondary or shear) waves. The S waves are further divided into SV (for vertical shear) waves and SH (for horizontal shear) waves (Ben-Menahem and Singh 1981).

For the problem at hand the seismic source is located on the interface and only surface waves appear to be of interest (Ben-Menahem and Singh 1981). Surface waves generally are divided into Love waves, which exhibit SH wave motion, and Rayleigh waves, which are a combination of P- and SV-type waves. At a fluid–solid interface for a semi-infinite homogeneous medium, the Love waves should not exist (Ben-Menahem and Singh 1981) and only Rayleigh waves are present. Because the earth's surface is not homogeneous, however, for the problem under consideration, Love waves may occur and could be significant.

b. Seismic signal and noise sources

A number of different sources of seismic waves are generally recognized as follows: 1) earthquakes, 2) volcanic eruptions, 3) nuclear explosions, 4) conventional blasting operations, and 5) ground transportation equipment. To most investigators, with the possible exception of the fifth type, these types of sources produce seismic signals as opposed to noise.

In addition to the preceding well-known categories, certain other sources can be identified (Ben-Menahem and Singh 1981; Asten and Henstridge 1984; Bernard 1990; Kværna 1990) including 1) coastal wave action, 2) ocean storms, 3) atmospheric disturbances, 4) river flow, and 5) high winds in general.

It is noteworthy that these last five sources, which are considered to produce noise, generally involve turbulent fluid dynamic processes. Each noise source generates a seismic signal that is characterized by a time series from which a power spectrum can be derived. The process of filtering out unwanted signals is a well-developed, albeit complex, field of technology that has received considerable attention in seismic analysis. Although the last five sources are considered to produce noise, in the case of ocean storms seismographic measurements were used by the U.S. Navy to track hurricanes and typhoons more than 50 years ago (Gilmore 1947).

c. Existing tornado detection techniques

The use of Doppler radar to detect wind patterns characteristic of tornadoes is fairly well established (Davies-Jones 1982; Darkow 1976; Burgess 1991). Such a technique can detect wind patterns at distances in excess of 100 miles, but it cannot determine whether or not a tornado has touched down, except possibly at very short ranges.

Another device used in the remote detection of tornadoes is the sferics detector (Davies-Jones 1982) based on the correlation between storm severity and the rate of high-frequency electromagnetic emissions. Such a system has been shown capable of detecting 80% of the tornadoes within a 70-km radius, but unfortunately it is characterized by an unacceptably high false-alarm rate.

At least two devices have been developed for use by the homeowner for short-range tornado detection. The first is a battery-powered tornado alarm designed to sense the rapid drop in atmospheric pressure, which is generally characteristic of tornadoes (Davies-Jones 1982). The current availability of this device is unknown. Furthermore, such a detection device is considered "inadequate, because only a few seconds elapse between the alarm and tornado passage" (Davies-Jones 1982). The second device, which is called Final Alert, is designed to detect the characteristic roaring sound transmitted through the atmosphere by a tornado (H. Bass 1993, personal communication). This device is due to be introduced in the near future. Notice should be taken that it is not clear whether Final Alert can distinguish between a tornado on the ground and a funnel cloud passing overhead.

d. Evidence of the existence of tornadic seismic waves

The idea of using seismic signals for detecting meteorological phenomena is certainly not new. As already noted, more than 50 years ago (Gilmore 1947) the U.S. Navy used seismographic readings to track typhoons and hurricanes. However, a review of available literature, both meteorological and seismological, as well as extensive contact with the United States Geological Survey (USGS) National Earthquake Information Center (NEIC) and the National Oceanic and Atmospheric Administration (NOAA) National Severe Storm Laboratory (NSSL), revealed no pub-

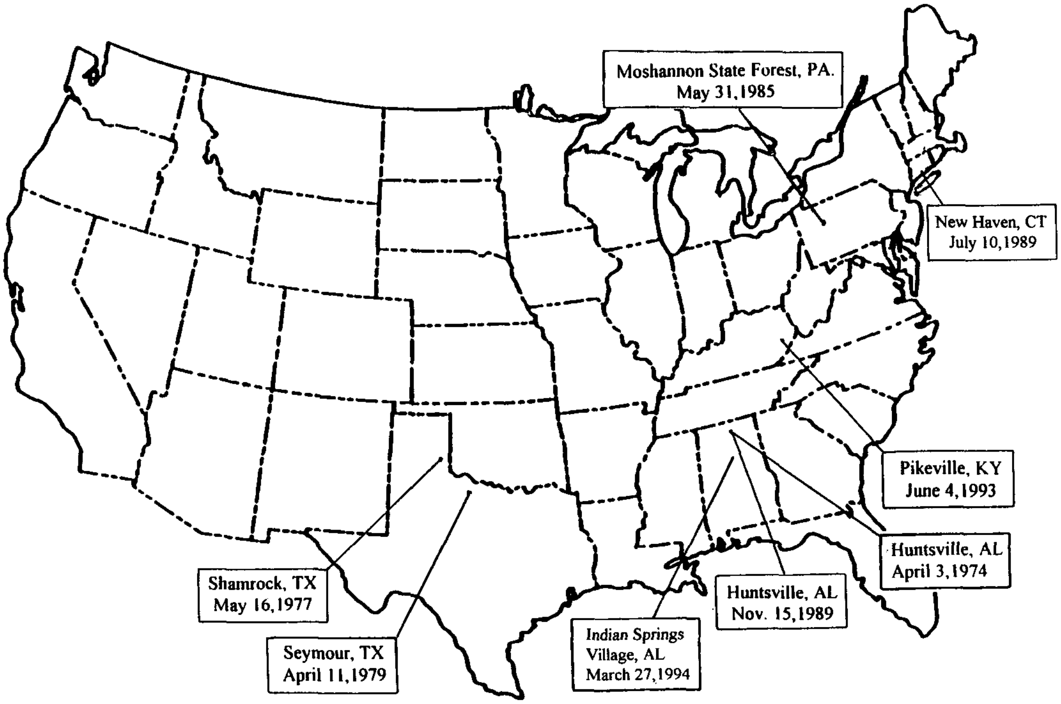

FIG. 2. Eyewitnesses of tornadic seismic vibrations (TSV).

lished accounts of seismic signals produced by tornadoes or any concept concerned with the seismic detection of tornadoes. For this reason, a preliminary collection of eyewitness accounts concerning tornadic seismic vibrations (TSV[2]) was obtained based on interviews with witnesses living in Alabama, Texas, Kentucky, Pennsylvania, and Connecticut, as indicated in Fig. 2. The subsections that follow summarize the accounts of nine eyewitnesses that are especially relevant.

1) EYEWITNESS ACCOUNT BY A CHIEF SCIENTIST (R. Watson 1994, personal communication)

On 3 April 1974, at approximately 1800 CST in Huntsville, Alabama, the chief scientist of a large engineering firm was outside in the backyard of his residence, near the intersection of Inspiration Lane and Panorama Drive on Monte Sano Mountain. There was light rain and moderate wind. He was aware that a tornado warning was in effect and observed a greenish glowing cloud with its base about 1 mile away, near the foot of the mountain. He heard a very low frequency rumble and at the same time felt a vibration. At this point he sought safety inside his home. Approximately 30 s later, an F5 tornado passed within approximately 500–1000 ft of his property.

2) EYEWITNESS ACCOUNT BY AN AIR FORCE METEOROLOGIST (G. Moore 1993, personal communication)

On 16 May 1977, near Shamrock, Texas, an air force meteorologist, who has pursued tornadoes as a hobby, managed to position himself within 1 mile of a powerful tornado with winds probably in excess of 200 mph. He heard a roaring noise and also felt vibrations through the ground where he was standing. This tornado was classified as an F3 by the National Weather Service (NWS) based on the destruction produced.

The same meteorologist on 11 April 1979, near Seymour, Texas, was again able to approach within 1 mile of another large powerful tornado with winds in excess of 200 mph. As before, he experienced ground vibrations and also heard a roaring sound. There appeared to be some correlation between the vibrations he felt and the tornado's destruction of numerous mesquite bushes found in that area. Such bushes are known to have extensive root systems that extend deep beneath the ground surface. Based on the degree of destruction, this tornado was classified as an F2 by the NWS.

3) EYEWITNESS ACCOUNT BY A PARK RANGER (G. Forbes 1993, personal communication)

On 31 May 1985, at approximately 1900 EST, a park ranger was inside a cabin in Parker Dam State

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[2] The term *tornadic seismic vibration*, or TSV, is used to refer to seismic waves felt by humans as opposed to the term "tornadic seismic signal," or TSS, which is used to refer to seismic waves detected by seismic instrumentation.

Park adjacent to Moshannon State Forest, Pennsylvania. As a tornado passed through the state forest approximately 1 mile from his location, he heard a rumble and felt the cabin shake. The tornado was classified as an F4 by the NWS.

4) EYEWITNESS ACCOUNT BY A MEDICAL ADMINISTRATOR (A. Stoddard 1994, personal communication; C. MacClintock 1994, personal communication)

On 10 July 1989, at approximately 1715 EST, a Yale University medical administrator was walking on a concrete sidewalk near a parking garage in New Haven, Connecticut. The winds were gusty and it was beginning to rain. She looked up and saw a tornado funnel cloud. The tornado was classified as an F4 by the NWS. She heard no sound, but the ground shook for a period of about 10 s. At the time of the vibration the tornado was approximately 2.5 miles from her location.

5) EYEWITNESS ACCOUNT BY A POLICE OFFICER (J. Hudson 1993, personal communication)

On 15 November 1989, in Huntsville, Alabama, an officer assigned to the Huntsville Police Academy was sitting in his car near a drainage culvert observing a tornado as it approached from the southwest. His car was positioned so that he could observe the tornado through the windshield, and the car's engine was turned off. He had opened the driver's door so that he could escape into the drainage culvert if necessary, and he had his left foot on the ground, which had a covering of grass. As the tornado approached, he heard the roar and then felt ground vibrations through his left foot. There was no wind or rain at this time. Both the sound and the vibrations reminded him of a freight train passing by. The tornado passed in front of him, approximately 1800 ft to the south. The total elapsed time during his observation was 1–2 min. The vibrations persisted until he raised his foot to close the car door. This tornado was classified as an F4 by the NWS.

6) EYEWITNESS ACCOUNT BY A CHURCH MUSIC MINISTER (V. Thompson 1993, personal communication)

On 15 November 1989, in Huntsville, Alabama, the minister of music for a church was in the midst of a handbell choir rehearsal when he was advised of the possibility of a tornado in the area. He escorted the choir into the church basement furnace room where they remained until all danger was past. As the tornado approached, he became aware of a roaring sound and at the same time began to feel vibrations through the basement floor. For a period of up to 1 min both the sound and the vibration continued until the tornado struck the church. At this point he heard other sounds related to the breakup of the church building itself, and he also began to experience an extreme headache, apparently due to the reduction in static pressure. As noted previously, this tornado was classified as an F4 by the NWS.

7) EYEWITNESS ACCOUNT BY A SERVICE STATION MANAGER (W. Elmore 1993, personal communication)

On 15 November 1989, in Huntsville, Alabama, a service station manager was working on replacing the headlight in an automobile in front of his service station, which faced to the east, with the car hood raised and the engine turned off. As he was working, he began to notice strange vibrations in his feet, and he also noticed the engine within the car was shaking. Although he heard no sound and the wind was not blowing, he observed the peculiar color of the sky, and he realized something unusual was about to happen. He urged the driver of the car to go with him inside the station office. When she declined, he pulled her from the car and escorted her into the station office where they huddled behind the counter. During this time he noticed that the office windows were vibrating, although there was still no wind. No more than 1 min after initially sensing the vibrations he heard the roar of the tornado, and shortly thereafter it struck the service station. The tornado winds demolished the station and swept him out of the building into the middle of the street. This tornado was classified as an F4 by the NWS, as previously described.

8) EYEWITNESS ACCOUNT BY COAL YARD WORKERS (V. Robinson 1993, personal communication)

On 4 June 1993, at approximately 1500 EST, near Pikeville, Kentucky, a crew of workers were in a coal loading facility building situated in a natural hollow. On the other side of a small mountain, a tornado was approaching from the southwest. As the tornado progressed up the west slope of the mountain, about one mile away, the entire building shook. The tornado passed over the hollow without touching down near the building. This tornado has not been classified by the NWS.

9) EYEWITNESS ACCOUNT BY AN NWS METEOROLOGIST (B. Kilduff 1994, personal communication)

On 27 March 1994, at approximately 1740 EST in Indian Springs Village, Shelby County, Alabama, a meteorologist employed by the National Weather Service was inside his residence. A tornado warning had been in effect for approximately 10–15 min and a power failure had just occurred. There was no wind or rain, but he heard the sound of a tornado approaching through a wooded area to the southwest of his home.

He sought shelter by sitting on the concrete floor in a closet in the basement of his home. When he sat down he felt vibrations that continued to build up for 30 s as the tornado approached his residence. The time from the power failure to the arrival of the tornado was approximately 4 min. When the tornado reached his home he felt a pressure drop in his ears. The tornado appeared to pass over his neighborhood with the resulting damage corresponding to an F0 or F1. The vibrations persisted but died out as the tornado continued to move to the northeast, away from his residence.

3. Tornado seismic signal (TSS) characteristics

The preceding eyewitness accounts are clearly consistent with the concept of TSV and provide reasonable motivation for further research into the existence of such vibrations. The next step is to develop a better understanding of the nature and magnitude of TSS resulting from TSV.

a. Magnitude of TSS energy source

The kinetic energy within the tornado is reduced due to the frictional resistance by the ground surface to the passage of the tornadic winds. Some amount of this mechanical energy is transferred into the ground as described in the subsections that follow. The fraction that is transformed into vibrational energy, as opposed to thermal energy, depends upon the surface impedance (Massarsch 1993).

1) SEISMIC NOISE/VIBRATIONS PRODUCED BY PRESSURE FLUCTUATIONS INDUCED BY TURBULENCE

For high Reynolds numbers ($>10^5$) the flow over a flat surface will generally be turbulent. Immediately adjacent to the surface, however, there exists a viscous sublayer within which the turbulence is greatly reduced. On the surface itself, pressure fluctuations occur primarily as a result of the turbulence outside the viscous sublayer. The magnitude of these pressure fluctuations P'_w for a flat surface has been empirically correlated with the shear stress τ_w on the surface according to the relation (Blake 1970)

$$P'_w \approx 3.6\tau_w. \tag{1}$$

The shear stress can be related to the ambient dynamic pressure q_∞ according to the relation

$$\tau_w = C_f q_\infty, \tag{2}$$

where C_f is the friction coefficient and $q_\infty = \rho_\infty U_\infty^2/2$. In the case of flow over the smooth surface of an aerospace vehicle, the pressure fluctuations are a significant source of vibration and acoustic noise (Crandall 1963; Blevins 1977).

Because of the stochastic nature of turbulence, the pressure fluctuations are characterized by a power spectrum such as that shown in Fig. 3 (Hodgson 1962). The frequency corresponding to the maximum point on the spectrum is referred as the frequency of the energy-containing eddies. This frequency can also be related to the correlation length of the turbulent pressure fluctuations. The larger the correlation length, relative to the characteristic dimension of the surface, the greater the amount of vibration energy produced (Blevins 1977).

All energy not converted into vibration energy must be transformed into thermal energy, unless such energy can be stored as some type of potential energy associated with an elastic or viscoelastic deformation.

If the pressure fluctuations produced by turbulent flow over the smooth surface of an aerospace vehicle can be a source of internal vibration, by analogy, there is reason to believe that the turbulent flow generated by a tornado passing over the surface of the earth should likewise be the source of a seismic signal. With the assumption of atmospheric density (1.22 kg m^{-3}), a wind speed of 112 m s^{-1}, and a friction coefficient of 0.028, characteristic of a rough surface (Blevins 1984), the resulting rms surface pressure fluctuations would be 760 Pa.

Although the total energy transferred to the ground cannot be readily calculated, some idea of its magnitude

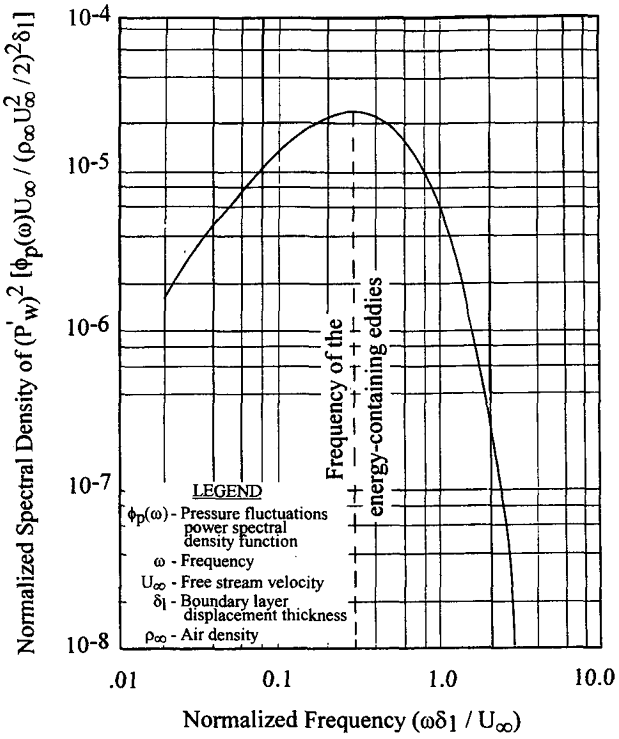

FIG. 3. Power spectrum for turbulent pressure fluctuations on a surface (Hodgson 1962).

can be obtained by calculating the rate of energy expended E_τ by the tornado due to turbulent shear. This rate would be

$$E_\tau = \tau_w A_t \bar{U}_\infty, \qquad (3)$$

where $\bar{U}_\infty$ is the average surface wind speed of tornado, $A_t = \pi D_t^2/4$, and D_t is the diameter or swath of tornado base at ground level.

Based on the preceding relations, an estimate of the rate of energy transfer can be obtained as a function of tornadic wind speed and swath, as shown in Fig. 4. In generating this figure, for the sake of conservatism, the average surface wind speed $\bar{U}_\infty$ used in the calculation of shear stress and rate of energy transfer was taken to be one-half of the wind speed used to characterize the tornado. Based on the definition of the different intensities of tornadoes ranging from F0 to F5 (Fujita 1971), the figure also depicts the relationship between tornadic intensity and rate of energy transfer. Examination of the figure reveals a wide variation in the rates of energy transfer, ranging from 10^{-3} MW for an F0 tornado to 10^5 MW for an F5. These results are, however, preliminary, with a much more detailed analysis remaining to be performed.

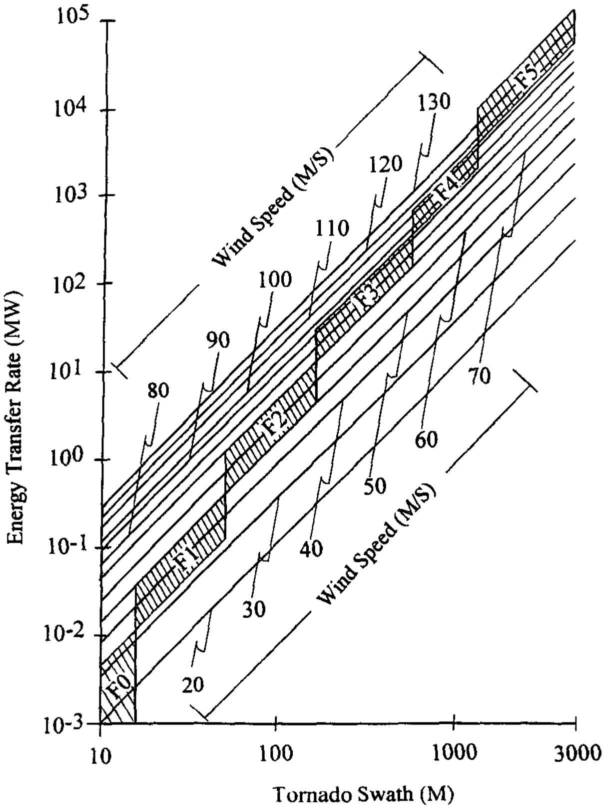

FIG. 4. Estimated tornado-to-ground energy transfer rate as a function of tornadic wind speed, swath, and intensity.

2) SEISMIC NOISE/VIBRATIONS PRODUCED BY TORNADIC DESTRUCTIVE PROCESSES

In addition to the seismic vibrations produced by turbulent pressure fluctuations at the ground surface, additional noises and vibrations are very likely to be produced by the structural failure of various man-made and/or natural objects exposed to the tornadic winds.

In the case of man-made structures, typical examples would include 1) both residential and office buildings, 2) house trailers, 3) transmission towers and telephone poles, 4) storage tanks and containers, and 5) vehicles and mobile equipment. In the first four categories two types of noise sources would be generated. The first type would involve the straining process by which the strength of the structure would be exceeded by the dynamic forces generated by the tornado. This type of noise (failure noise) source would tend to build up rapidly and would abruptly end when the structure failed. The second type of noise would result from the remnants of any parts of structures in the first four categories impacting with the ground surface or other structures. This type of noise source (transport noise) would commence immediately after structural failure occurred and would continue intermittently so long as the structural remnant was swept along by the tornado. In the case of the fifth category (vehicles and mobile equipment), the noise source would be the result of the impact of the vehicle/equipment with the ground surface as it was swept along, and thus would be essentially the same as the second type (transport noise) previously noted.

In the case of natural structures the most obvious example would be trees. The noise generated by the breaking of a tree trunk would be similar to that produced by the breaking of a telephone pole, and would include both the failure type and the transport type. Likewise, the uprooting of a tree would resemble the failure of a pole or tower, but in this case the failure noise would very likely be more extensive because of the large shear stresses between the root system of the tree and the ground. Other natural objects such as rocks could also generate transport noise as they were dragged along.

Prediction of the magnitude of the vibration energy produced by these destructive processes is currently not possible. Clearly, such "destruction noises" would be greatest in areas characterized by large numbers of structures of the categories noted. In such regions the destruction noise might exceed the turbulent pressure noise. Furthermore, these noise sources would tend to be more discrete with respect to time and more spatially localized than turbulent pressure noise, which would be distributed over the entire surface area exposed to the tornado and which would be continuous for the lifetime of the tornado maintaining contact with the ground.

As with the mechanical energy associated with turbulent pressure fluctuations, some portion of the energy of destruction will be transformed into vibrational energy and the remainder into thermal energy, with perhaps some small fraction converted into potential energy. Because of the more discrete, pointlike characteristics of sources of destruction noise, however, a greater fraction should be transformed into vibration energy. Additional mathematical modeling is necessary in order to obtain a better understanding of the nature of destruction noises.

TABLE 1. Estimated frequency of energy-containing eddies for tornadoes.

	Tornado parameters (Fujita 1971)		Frequency of energy-containing
F scale	Wind speed (m s^{-1})	Swath (m)	eddies f_e (Hz)
0	<32	<16	>141
1	33–50	16–50	71–221
2	51–70	51–160	23–97
3	71–92	161–508	10–40
4	93–116	547–1448	4.5–15
5	117–142	1609–4989	1.7–6.2

b. *TSS spectral properties*

As previously noted, the mechanical energy of the tornado is characterized by the spectral density of turbulence-induced pressure fluctuations, such as shown in Fig. 3. Associated with the spectrum is a frequency f_e corresponding to the wavenumber of the energy-containing eddies k_e according to the relation

$$f_e = \frac{U_\infty k_e}{2\pi}, \tag{4}$$

where U_∞ is the ambient free-stream velocity. Now

$$k_e = \frac{1}{l_e}, \tag{5}$$

where l_e is the scale of the energy-containing eddies. The magnitude of l_e should be on the order of the displacement thickness δ_1 of the boundary layer between the tornado and the surface. For a rough surface (Harrison 1967),

$$\frac{\delta_1}{x} = 0.009, \tag{6}$$

where x is the distance from the leading edge of the flow. A reasonable value of x would be one-half the radius or one-quarter the swath of the tornado. Based on the preceding development, the estimated frequency of the energy-containing eddies in a tornado can be summarized, as shown in Table 1. This table indicates that the characteristic frequency f_e of a tornado decreases with increasing intensity.

4. Possible existence of TSS measurements

A large number of seismologic monitoring stations and networks are currently in operation throughout the United States. Such systems are designed primarily to detect seismic events associated with earthquakes, blasting operations, and oil and gas exploration. Some of those monitoring stations are located in regions where tornadoes are most likely. These stations may have accidentally recorded seismic signals whose tornadic origin has not been previously identified. As an example, some of these stations located in the Southeast (Long et al. 1981) are indicated in Fig. 5. Superposed on this figure, based on the site analysis of tornado threat (SATT) software (Tatom 1992), are the tracks of all F4 and F5 tornadoes in the Southeast for the period from 1950 through 1993.

If the times and locations of tornado tracks can be compared with such seismologic records, there is a distinct possibility that such tornadic seismic events can be identified. A preliminary review of existing seismographic records has been carried out using the SATT software, in conjunction with the known locations of seismographic stations, to identify potential TSS. Except for the station at The Pennsylvania State University, all of the stations studied were part of either the Southeastern Seismic Network (Long et al. 1981) or the U.S. National Seismic Network (U.S. Geological Survey 1992). Unfortunately, none of the stations reviewed was operational at any time when a tornado passed within 3 miles. Also, in many cases, the stations seismic sensors filtered out all signals above 10 Hz and, thus, according to the frequency range presented in Table 1, were only capable of detecting F4 or F5 tornadoes. Efforts are currently under way to review other records in Tennessee and North Carolina (C. Powell 1994, personal communication).

5. Seismic tornado detector (STD)

If TSV exist, they may constitute a detectable TSS, which could be used as a means of determining when a tornado is on the ground. The seismic tornado detector (STD) as currently envisioned, is depicted Fig. 6. The system would consist of a velocity transducer buried in the ground, connected to an alarm system installed in the building to be protected. Before this version could be developed, however, an initial version of the system would have to be developed to test the concept. Both the USGS NEIC and the NOAA NSSL have offered to serve as advisors in the design of this system (E. Bergman 1994, personal communication; E. Rasmussen 1994; personal communication).

Based on a combination of eyewitness accounts and engineering calculations noted in subsection 3a(1), there is very likely some threshold below which the seismic energy produced by smaller, less intense tornadoes cannot be detected, except at extremely short

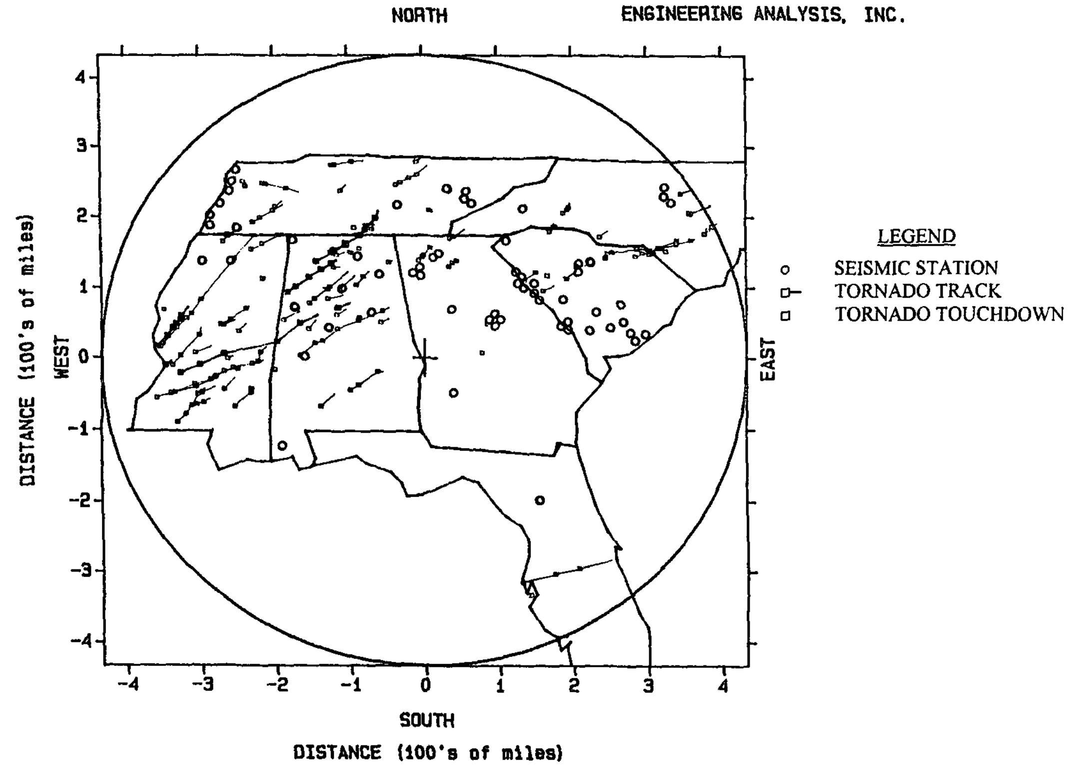

FIG. 5. Seismic station locations in the Southeast with F4 and F5 tornado tracks superposed.

ranges. Fortunately, such storms cause only a small percentage of the property damage and few, if any, fatalities. Large intense tornadoes (F4 and F5), which represent only 3% of the total, account for almost all fatalities and most of the property damage (Galway 1975). These most dangerous tornadoes can transfer energy into the ground at estimated rates of 10^3–10^5 MW, based on Fig. 4.

a. Initial version of STD

The STD initial design, as currently envisioned, based in part on suggestions from NEIC (J. McMillan 1994, personal communication), would be capable of measuring both TSS and atmospheric turbulent pressure fluctuations. As shown in Fig. 7, the design includes an instrument package containing four parallel circuits, three for measuring TSS and one for measuring atmospheric turbulent pressure fluctuations. Each TSS circuit contains a geophone, an amplifier, and a voltage-controlled oscillator (VCO). The three geophones are set to different frequency bands (4–25, 25–75, and 75–200 Hz). The turbulent pressure circuit consists of a pressure transducer (covering frequencies 1–1000 Hz), an amplifier, and a VCO. The output of each sensor is fed into an amplifier for scaling, and then to a VCO that transforms from AM to FM. The output of the four VCOs are fed into a mixer, producing a single multiplexed FM serial stream to be recorded on a single channel of the tape recorder. The entire assembly is housed in a sturdy, lightweight container capable of surviving exposure to a tornado.

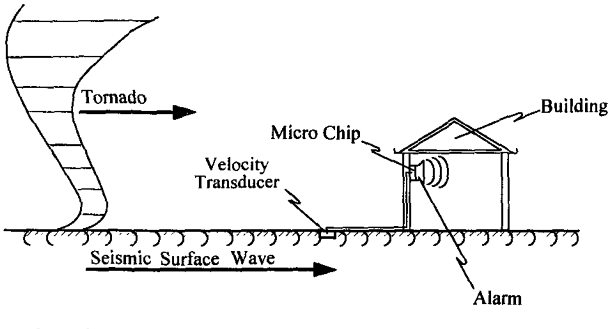

FIG. 6. Tornado detection and warning by the STD system.

After recovery of the instrument package, data stored on the tape are processed by the postacquisition signal analysis equipment, consisting of a multichannel discriminator, a multichannel analog-to-digital converter (ADC), and a personal computer (PC), as indicated in Fig. 7. The discriminator demultiplexes the stored signal into the original four channels and converts from FM to AM. The four channels are fed into the ADC and then to the PC where appropriate software provides analysis of the digitized signals. The analysis of these

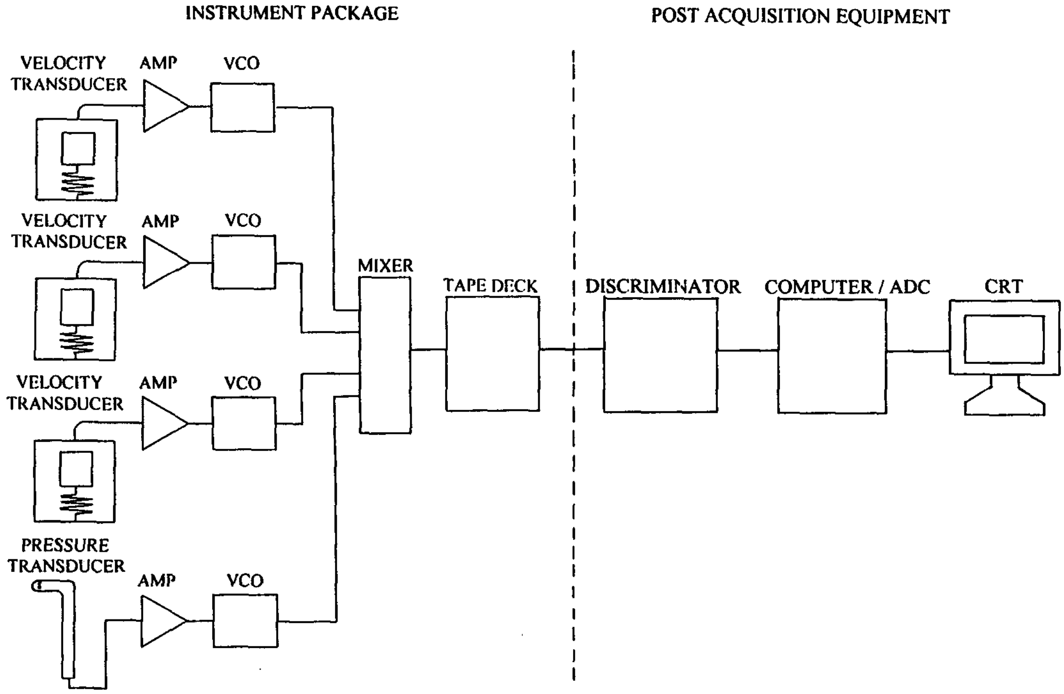

FIG. 7. STD initial design.

digitized signals would be of special value in the design of a discriminatory filter for the commercial STD.

b. Commercial version of STD

In the commercial version of the STD, as depicted in Fig. 8, the design of a discriminating filter becomes of paramount importance, along with requirements for compactness and low cost. The single geophone or velocity transducer will be similar to those used in the prototype, but will perhaps represent a less costly model, produced in greater numbers. In the final version, no need to measure atmospheric pressure fluctuations or to store the signal should exist. The microchip will replace the personal computer. The key component of the microchip will be the digital filter. In this final design the digital filter must be capable of screening out unrelated noise signals, primarily from transportation equipment (Long 1993; Hanazato et al. 1991; Jones and Petty 1993; Watts 1992; Massarsch 1993) or from high winds, to such a degree that the false-alarm rate is held below some acceptable level. The complexity of the filter design will depend on TSS characteristics to be measured during the validation of the initial version of STD. When the output of the digital filter exceeds a predetermined threshold, the switch is closed and the alarm activated. Based on the eyewitness accounts, there is reason to believe that TSV can be detected by the human sensory system at distances of up to one mile. The detection range of the STD can thus be estimated conservatively at one mile. The ground speeds of tornadoes range from 15 to 30 m s^{-1} or 33 to 66 mph (Davies-Jones 1982). An estimate of the available warning time would thus be 55–110 s, based on this very conservative assumption for detection range.

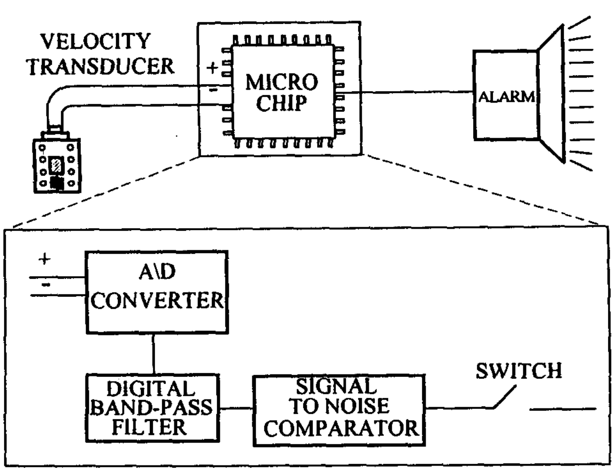

FIG. 8. Schematic of commercial STD.

6. STD validation

Validation of the STD concept poses a special set of problems. Because individual tornadoes are generally restricted to relatively small areas and are normally short lived, the probability of selecting a specific point, which would be exposed to a tornado during a specified time period, is not very great. Furthermore, if such a point were selected, problems of personnel safety would become of special significance. The validation of the initial STD must thus deal with several key issues, including 1) determining whether or not a nontornadic seismic signal source would be of any value, and 2) for the case of a tornado, developing a procedure for introducing the initial STD instrument package into the tornado proximity.

With regard to the first issue, some physical phenomenon of a less threatening nature than a tornado, involving turbulent fluid flow over a solid surface, might be used as a source of the seismic signal to test certain aspects of the concept. A number of candidate flow processes have been considered including 1) exhaust of a jet aircraft during takeoff, 2) helicopter downwash, 3) exhaust from large ventilation fans used in mine shafts, 4) exhaust from a space shuttle during liftoff, and 5) white-water river rapids. Clearly, none of these processes closely resembles a tornado, but one of the basic technical issues associated with the STD concept is the magnitude of the energy transferred into the ground by turbulent flow processes in general. A second and equally important issue is the distance such energy may propagate in the form of a surface wave. For the candidate flow processes noted, calculation of the energy transferred into the ground appears feasible (in the absence of destruction noises). Given the magnitude and spectral properties of such energy, combined with a knowledge of the soil surface layer and underlying rock stratum, calculation of the range of propagation also appears feasible. If seismic measurements that corroborate such calculations can be obtained from some turbulent flow process, greater confidence in the basic concept would be gained even though a nontornadic source was involved.

The last of the candidate flow processes appears especially attractive because it involves tangential flow (as opposed to impinging flow) and because the white-water rapids of a large river represent a sizable energy source, which can be approached fairly closely without any question of personnel safety. In a number of cases such rivers are dam controlled upstream, and, thus, the time when the rapids will occur is predictable, and not weather dependent. In one case in Norway, flow in the river Glomma produced seismic noise detected at a distance of 15 km by the Norwegian Regional Seismic Array System (Kværna 1990).

For validation of the initial STD involving an actual tornadic seismic source, the question of making contact becomes a major concern. Three important considerations are involved: 1) maximizing the probability of contact with a tornado, 2) maintaining personnel safety, and 3) ensuring the survival and retrieval of the initial version of the STD system. The first two considerations can best be handled by using an existing program designed to make ground contact with tornadoes. Perhaps the best candidate program would be the Verification of Origin of Rotation of Tornadoes Experiment (VORTEX) program, sponsored by NSSL and the National Science Foundation, and scheduled to commence field measurements in the summer of 1994 (E. Rasmussen 1994, personal communication). The third consideration can be satisfied by designing a protective container for the tape recorder rugged enough to withstand the tornadic effects and sufficiently locatable and identifiable to permit retrieval. As with the first two considerations, experience derived from the VORTEX program may be extremely useful with respect to this last consideration.

Validation of the commercial version of STD would involve extensive testing, both of the geophone and the digital filter. The recorded signals obtained during the testing of the initial version would be used in this validation program, along with any chance TSS measurements obtained from seismologic stations. The final portion of the commercial validation process would involve actual field testing based on some program such as VORTEX.

7. Anticipated results

From the standpoint of both state and federal government agencies involved in the detection of tornadoes, a network of STD devices, when used in conjunction with Doppler radar, should provide an accurate, efficient method to determine when a tornado is actually on the ground. This would especially apply in the Southeast where the low altitude of the cloud base, combined with the uneven terrain and numerous trees, tends to prevent timely visual sighting.

In addition to the development of STD networks by government agencies, a commercial STD version could be developed for the individual homeowner. The alarm and microchip components of the device would be installed in a residence in a manner similar to a smoke detector. The geophone component would be buried outside in the ground. As noted in section 5b, the warning time provided by such a device would be on the order of 1–2 min, which should be sufficient for residents to move to the safest part of a home. In some locations, such as trailer parks, one STD could be used to warn the residents of a number of trailers to proceed to any available tornado shelter.

8. Concluding remarks

Although no reports of seismic vibrations produced by tornadoes appear in the open literature, evidence in the form of eyewitness testimony, combined with preliminary calculations, would strongly suggest that the vibrations do occur. If this is the case, such vibrations could represent a totally new way of detecting a tornado on the ground. Obviously, the range at which a tornado could be detected by this technique would be of special importance. Likewise, the means of discriminating between TSS and other ground noise would be a major concern. Further collection of eyewitness accounts would be appropriate, combined with a review of records of existing seismographic monitoring stations to check for possible accidental measurements. A search should be conducted for any recordings of seismic noise produced by hurricanes, typhoons, or other sources of high winds. In addition, a need exists for more detailed mathematical modeling of the energy transfer process between the tornado and the ground.

Initial development of the TSD should commence when the evidence and understanding of the basic phenomenon are sufficient to warrant the investment.

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