SPECTRAL ANALYSIS OF SEISMIC MEASUREMENTS FROM EXPLOSIONS IN SOUTHERN MISSISSIPPI

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Abstract.—Twenty-one surface seismic recordings were made by the U.S. Geological Survey in southern Mississippi for Projects STERLING and SALMON which provided for the detonation of two nuclear devices and one chemical charge. Relative-amplitude spectral ratios from the first 10 seconds of the SALMON and STERLING nuclear recordings indicate that in the predominant teleseismic frequency band, 1 to 5 cps, the SALMON signal amplitudes were about 1,000 times as large as the STERLING signal amplitudes, but in the frequency band 10 to 25 cps, they were less than 200 times as large. Comparison of the amplitude spectral ratios for the SALMON to STERLING-nuclear recordings with similar ratios for the STERLING-chemical to STERLING-nuclear recordings indicates that the ratios are primarily dependent upon the properties of the seismic sources and independent of the propagation media.

Project STERLING was designed to study the decoupling of a nuclear explosion set off in an explosion-created cavity. The project provided for the detonation of a nuclear device in the cavity resulting from the SALMON explosion in the Tatum Salt Dome in southern Mississippi (fig. 1). It also provided for a high explosive (HE) comparison shot in a nearby drill hole.

The project was directed and coordinated by the Lawrence Radiation Laboratory at Livermore, Calif. Surface seismic measurements were made by the U.S. Geological Survey, the U.S. Coast and Geodetic Survey, and the Air Force Technical Applications Center. Near-source measurements were made by the Sandia Corp.

The objectives of this paper are to discuss the surface seismic measurements made by the U.S. Geological Survey, to describe the spectral analyses which have been made of these data, and to investigate the resulting relative amplitude spectra for comparison of the seismic energy sources.

FIELD PROCEDURES

The surface seismic recordings were made using U.S. Geological Survey seismic-refraction recording systems

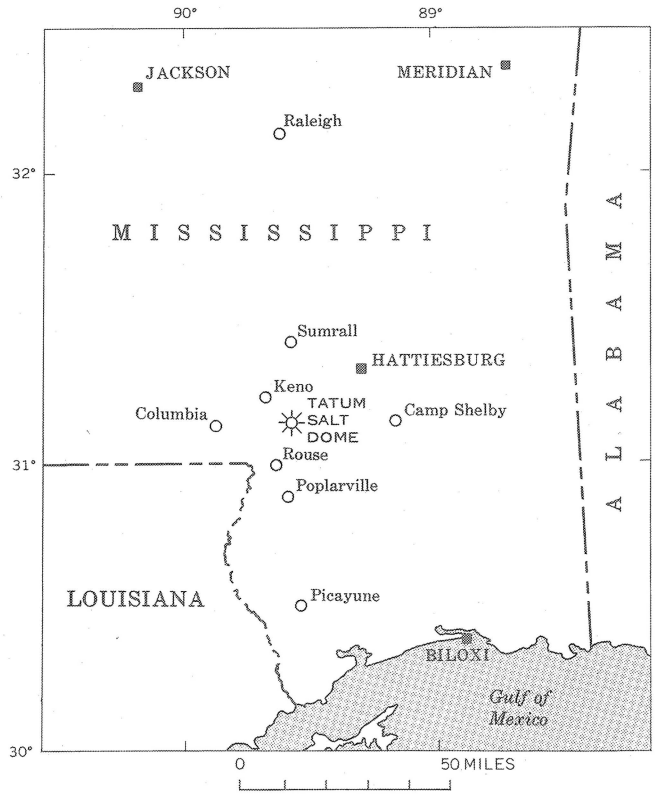

FIGURE 1.—Index map showing U.S. Geological Survey recording locations (circles) for Projects SALMON and STERLING.

(Warrick and others, 1961). Each system records the signals from eight seismometers on both photographic paper and magnetic tape. Six of the seismometers register vertical ground motion, and two register horizontal ground motion. The six vertical seismometers were placed along secondary roads at 500-meter intervals, and the two horizontal seismometers were placed at one of the vertical seismometer positions near the center of the spread.

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The Electrotech Corp. EV–17 seismometer used in this experiment has a resonant frequency of 1 cycle per second and a nearly flat response to a unit impulse in ground velocity from 1 cps to 30 cps. The recording instruments have a nearly flat response from 1 cps to an upper limit imposed by a preselected high-cut filter. For this experiment a high-cut filter of 37 cps was used. Calibration of the seismic recording systems showed that they are comparable from 1 to 30 cps but are different below 1 cps.

To record the 2 STERLING explosions, 9 seismic recording systems were used at 8 locations ranging in distance from 13.5 to 112.2 kilometers from the shotpoint (fig. 1). The Poplarville location was occupied by two recording units. Between the STERLING-HE explosion on November 17, 1966, and the STERLING-nuclear explosion on December 3, 1966, the seismometers were not moved in order that the conditions at the recording sites would be duplicated as closely as possible. The Poplarville, Picayune, and Raleigh locations were used in October 1964 to record the SALMON explosion and were duplicated as closely as possible for the STERLING event.

Playbacks were made from the magnetic tapes recorded at the Poplarville location (fig. 2). The first 6 traces on each record are the outputs from vertical EV–17 seismometers, with the exception of traces 2 and 5 of the SALMON record, which are the outputs from Hall-Sears type-10 vertical seismometers that have a resonant frequency of 4 cps. Traces 7 and 8 on the 2 STERLING records were recorded by horizontal EV–17 seismometers.

The two STERLING explosions were recorded at all the locations with the maximum sensitivity permitted by the seismic background noise, but the SALMON event was recorded at much higher attenuation levels based on preshot estimates of the seismic amplitudes. Hence, the noise on the seismograms and the magnetic tape recordings of the two STERLING events is predominantly seismic noise, while that on the SALMON records is recording-system noise.

SPECTRAL ANALYSIS

Assuming that the earth may be treated as a linear system in regard to the transmission of seismic signals, the ratios of the relative-amplitude spectra obtained at a recording site from two fixed seismic explosions will be dependent upon the relative differences in the source characteristics and independent of the propagation media. Consider the following notation for the SALMON and STERLING nuclear recordings:

$S_{SA}(f)$ and $S_{ST}(f)$ denote Fourier transforms of the seismic signals obtained at a fixed recording site from the SALMON and STERLING nuclear explosions, respectively,

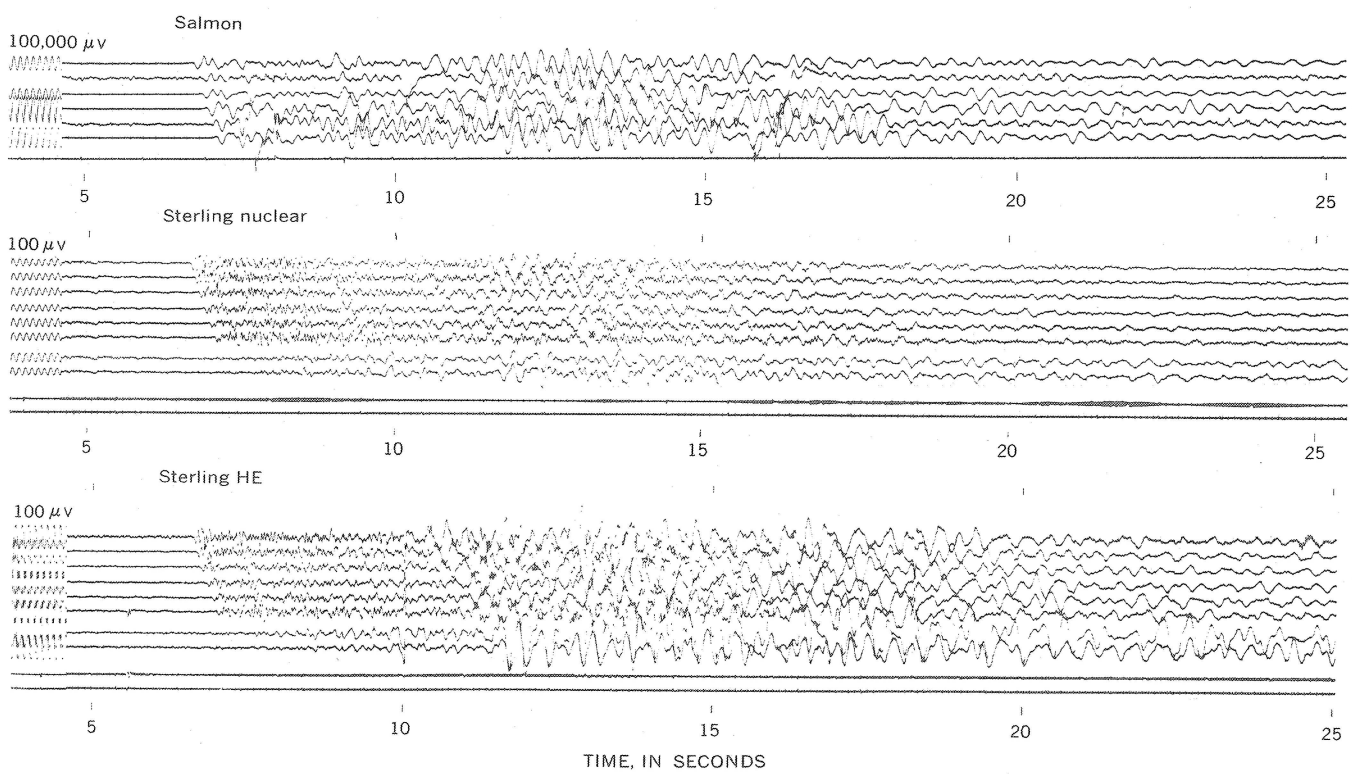

FIGURE 2.—Analog playbacks of magnetic tape recordings at the Poplarville location. Traces 1 through 6 are outputs from vertical seismometers; traces 7 and 8 on the STERLING records are outputs from horizontal seismometers. The time is measured with respect to the corresponding shot times.

$I_{SA}(f)$ and $I_{ST}(f)$ denote Fourier transforms of the seismic input signals generated by the SALMON and STERLING nuclear explosions, respectively,

$H_E(f)$ denotes the transfer function for the earth from the source to the recording site, and

$H_R(f)$ denotes the transfer function for the recording instruments.

By using this notation, $S_{SA}(f)$ may be expressed as $S_{SA}(f)=H_E(f)\cdot H_R(f)\cdot I_{SA}(f)$, and by assuming that $H_E(f)$ and $H_R(f)$ are the same for the two explosions, $S_{ST}(f)$ may be expressed as $S_{ST}(f)=H_E(f)\cdot H_R(f)\cdot I_{ST}(f)$. Hence, the amplitude ratio $S_{SA}(f)/S_{ST}(f)$ simplifies to $I_{SA}(f)/I_{ST}(f)$.

Insofar as $I_{SA}(f)/I_{ST}(f)$, as determined at the different recording sites, is independent of the recording location, the amplitude spectral ratios at the three recording locations may be averaged at each frequency to obtain an average estimate of $I_{SA}(f)/I_{ST}(f)$.

By extending the preceding notation, the amplitude ratios for the STERLING-HE to STERLING-nuclear shots may be simplified, in a similar fashion to $I_{HE}(f)/I_{ST}(f)$ whose values also may be averaged at each frequency.

On the basis of the spectral analysis plan in the preceding considerations, the data from the magnetic tape recordings were prepared for an IBM 7090 computer using an analog-to-digital converter system which digitized the data at 0.01-second intervals. A digitization interval of 0.005 second was used for comparison on some of the data and no change in the spectral amplitudes up to 40 cps resulted. Four seconds of the 10-cps sinusoidal calibration signal was also digitized and used to calibrate the seismic amplitudes in the computer.

The amplitude spectra were computed for each seismic trace from the expression

$$\left|\int_{-1}^{10} \nu(t)e^{-iwt}dt\right|$$

where $t=0$ is the time of the first identifiable seismic energy on the seismogram and $\nu(t)$ represents the digitized data on a seismic trace after the amplitudes have been normalized by the calibration signal. The integral was evaluated on the 7090 computer by the use of the Filon quadrature (Filon, 1928, p. 38). The computer program written for these computations was tested with an exponentially decaying sine function and was accurate to 0.05 percent for frequencies from 0.1 to 50 cps. Practical limitations and an attempt to avoid personal bias by an interpreter called for analysis of a constant 11-second time interval which began 1 second before the first identifiable energy.

Since the time the data were analyzed, spectra for some of the seismograms have also been obtained by the use of an expanded version of a fast Fourier transform (FFT) program written by J. W. Cooley (Cooley and Tukey, 1965). The spectra obtained by the two programs are practically the same, and the FFT has the advantage that it is much faster. However, the Filon quadrature program is not restricted to a set of frequencies predetermined by the size of the digitization interval and the number of digital points.

Amplitude spectra were computed for recordings made at the Poplarville location (fig. 3 and 4). For spectra of all the traces see Borcherdt, Healy, Jackson, and Warren (1967). The amplitude scale in microvolts is based on the 10-cps calibration signal. The amplitude spectra for the STERLING-nuclear explosion have been placed next to the corresponding spectra for the SALMON and the STERLING–HE explosions to make their comparison easier. Filtered analog playbacks were made at equal gain settings of the first trace from the three seismograms obtained at the Poplarville location (fig. 5). Visual determination of the frequency content of the signals in the successive passbands tends to verify

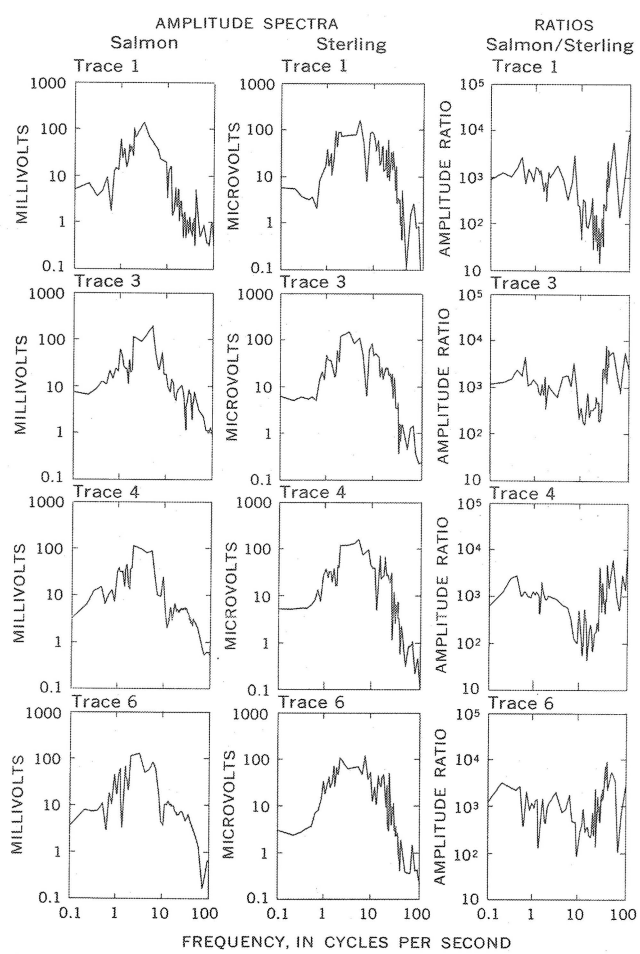

FIGURE 3.—Amplitude spectra and their ratios for four traces of the SALMON and STERLING-nuclear recordings at the Poplarville location.

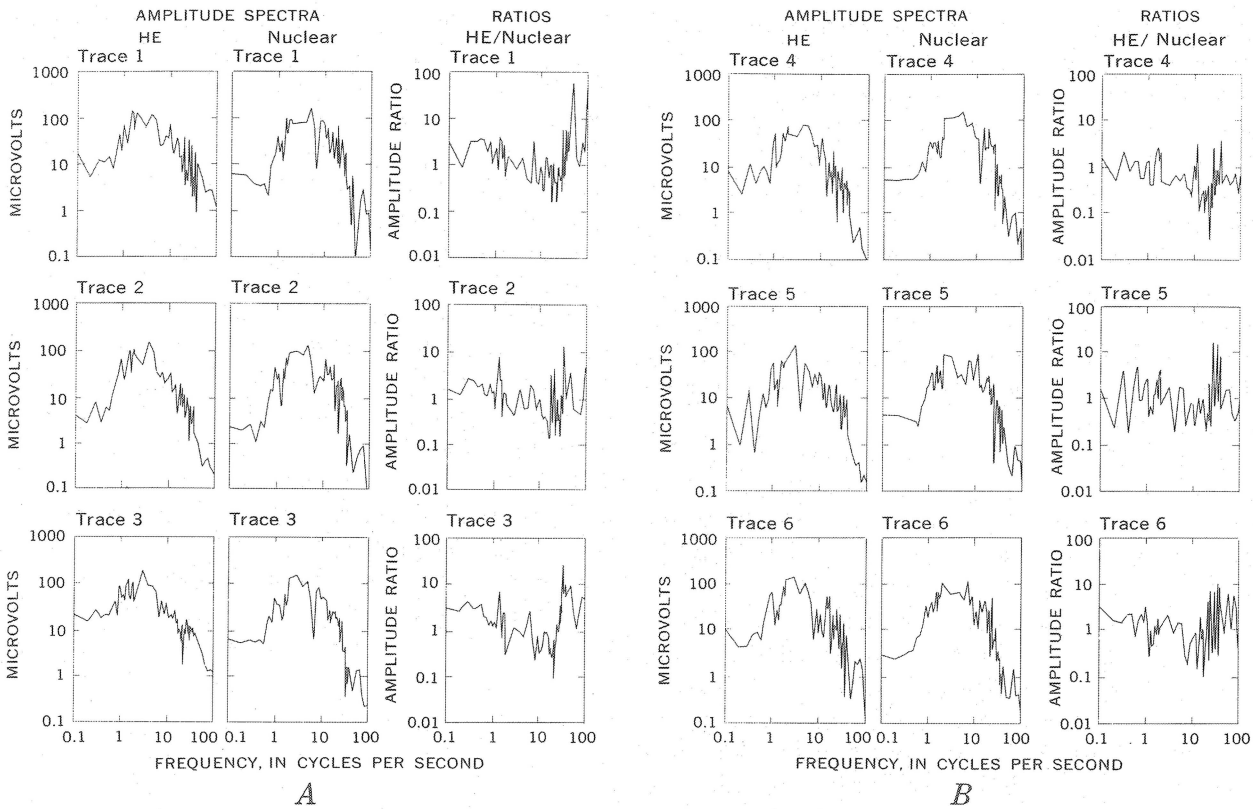

FIGURE 4.—Amplitude spectra and their ratios for six traces of the STERLING-HE and STERLING-nuclear recordings at the Poplarville location.

the results obtained from the amplitude spectra. For example, the STERLING-nuclear signal appears to contain more energy in the 10- to 20-cps passband than either the SALMON signal or the STERLING–HE signal.

All the spectra were plotted by the computer, and their numerical values were punched on computer input cards, which were in turn used to compute the relative-amplitude spectral ratios. These ratios were not computed for any unreliable seismic traces.

The amplitude spectral ratios for the Poplarville location are shown in column 3 of figures 3 and 4. Spectral ratios for the SALMON and STERLING-nuclear recordings were not computed for traces 2 and 5 because two different types of seismometers were used to record the shots.

The amplitude spectral-ratios from corresponding individual traces for two explosions were averaged at each frequency to form average spectral ratios for each recording site. Three such average plots for the SALMON to STERLING-nuclear recordings, together with the corresponding STERLING-HE to STERLING-nuclear average spectral ratios, were obtained (figs. 6, 7, and 8). Finally, the ratios from all usable individual traces obtained at the three locations used to record SALMON were averaged to form a single plot for the SALMON to STERLING-nuclear ratios and one for the STERLING-HE to STERLING-nuclear ratios (fig. 9).

DISCUSSION

The seismic noise and the system noise limit the accuracy of the amplitude spectra and the spectral ratios, particularly at the higher and lower frequencies. Amplitude spectra were computed for intervals of noise preceding the seismic energy on each trace (Borcherdt and others, 1967). Examination of these spectra and the noise characteristics of the digitization system indicate that the spectral ratios give a valid indication of the relative differences in the source properties only between 1.0 cps and 25.0 cps. The zones of questionable reliability were omitted from the plots in figures 6, 7, 8, and 9.

An examination of the average spectral ratios for each location (figs. 6, 7, and 8) reveals marked differences in their detailed structure; however, the relative differences in the gross shapes of the two types of curves (STERLING-HE/STERLING-nuclear and SALMON/STERLING) are roughly comparable at each of the three locations. This is especially noticeable above 8 cps where the STERLING-HE/STERLING-nuclear curves are consistently above the SALMON/STERLING curves.

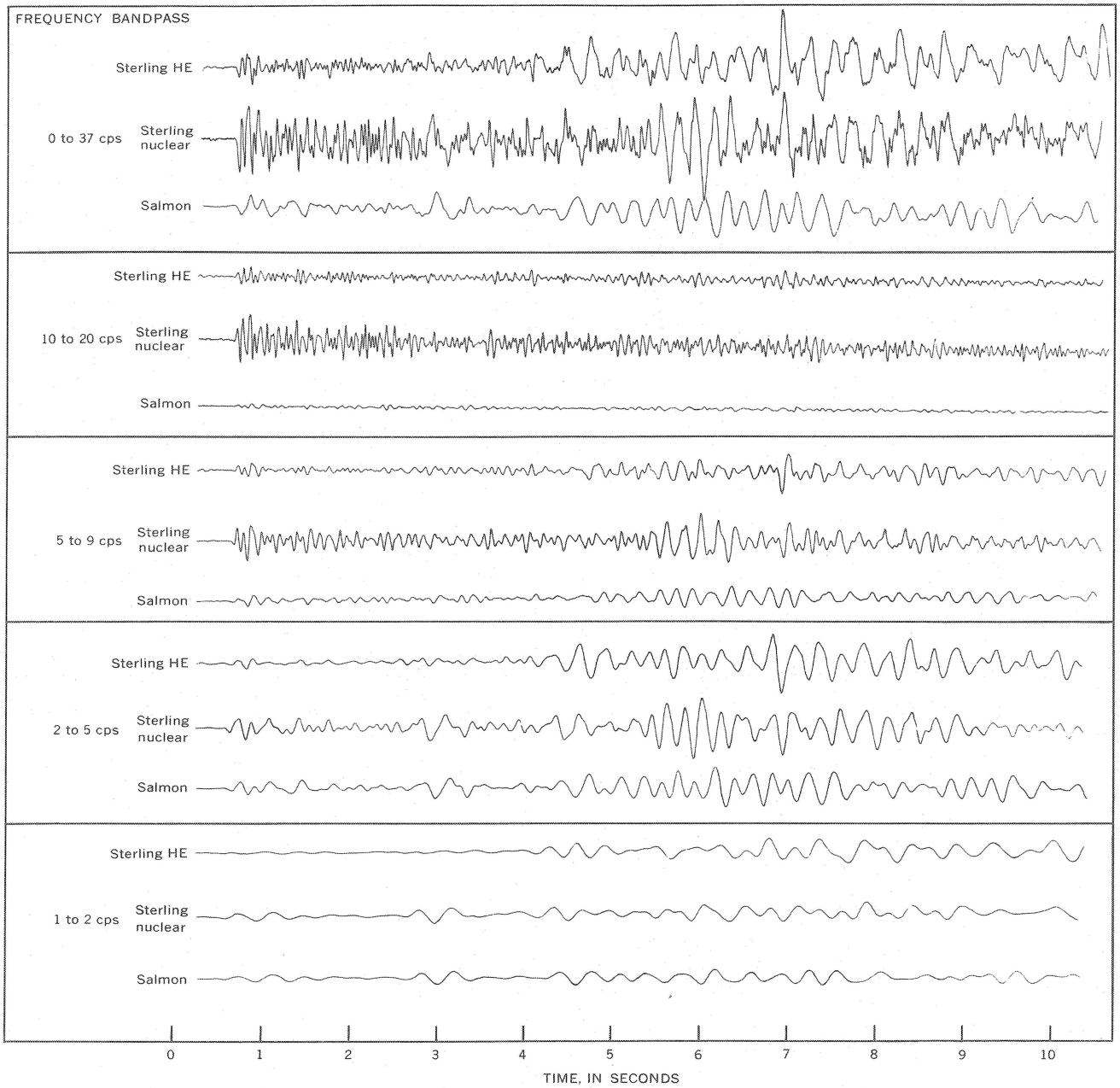

FIGURE 5.—Filtered analog playbacks of the first trace from three seismograms obtained at the Poplarville location.

The extent to which the relative differences in the two types of curves are consistent among the three locations tends to confirm the previous theoretical conclusions that the ratios are primarily dependent on the characteristics of the seismic-energy sources and independent of the wave-propagation paths and the recording instruments.

The relative differences at the Poplarville location are less pronounced than they are at the Picayune and Raleigh locations; however, a more complete analysis of the data, including the use of larger data windows, would be required to determine the extent to which spectral ratios depend upon the distance from the seismic source. The dependency which seems to exist is partly a function of the window length chosen and also the nature of the noise at the recording locations.

Conclusions about the seismic sources may be drawn from the relative differences in the average amplitude-spectral ratios of the SALMON/STERLING and STERLING-HE/STERLING-nuclear curves (fig. 9). The ratios show that above 8 cps the STERLING-nuclear signals contain more energy than the SALMON and STERLING-HE signals.

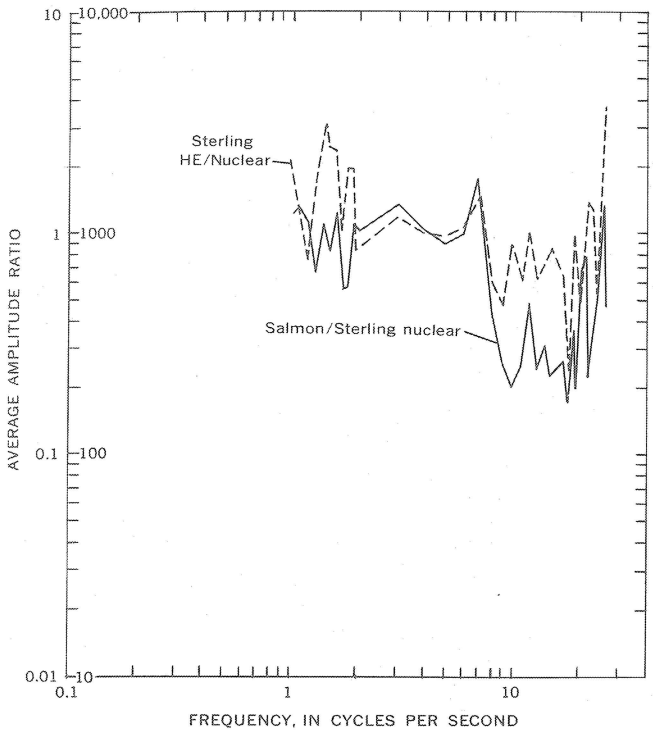

FIGURE 6.—Average amplitude-spectra ratios from vertical seismic recordings at the Poplarville location. The higher ordinate scale is for the SALMON/STERLING-nuclear curve, and the lower ordinate scale is for the STERLING-HE/STERLING-nuclear curve.

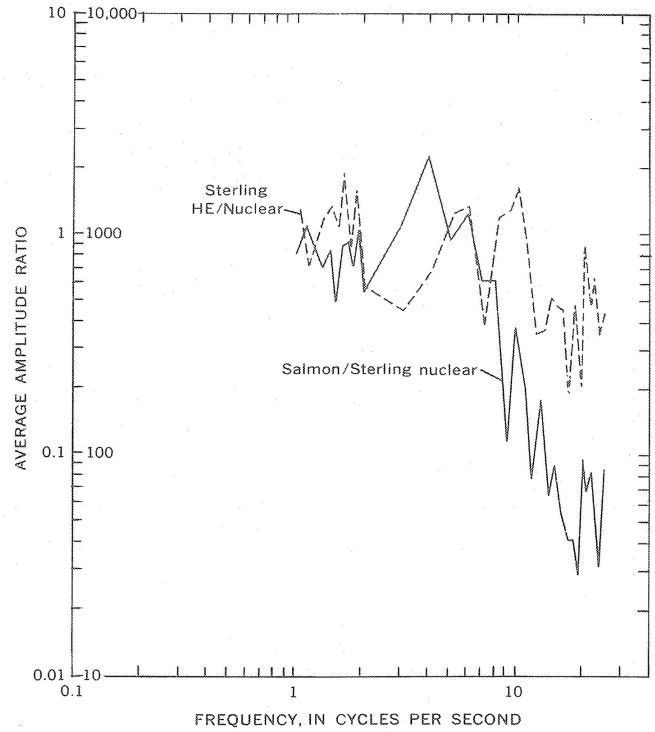

FIGURE 8.—Average amplitude-spectra ratios from vertical seismic recordings at the Raleigh location. The higher ordinate scale is for the SALMON/STERLING-nuclear curve, and the lower ordinate scale is for the STERLING-HE/STERLING-nuclear curve.

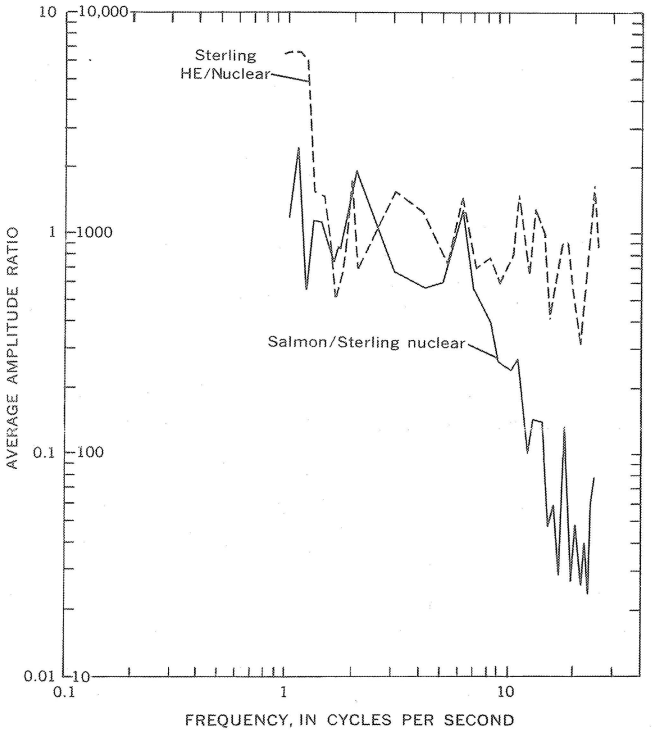

FIGURE 7.—Average amplitude-spectra ratios from vertical seismic recordings at the Picayune location. The higher ordinate scale is for the SALMON/STERLING-nuclear curve, and the lower ordinate scale is for the STERLING-HE/STERLING-nuclear curve.

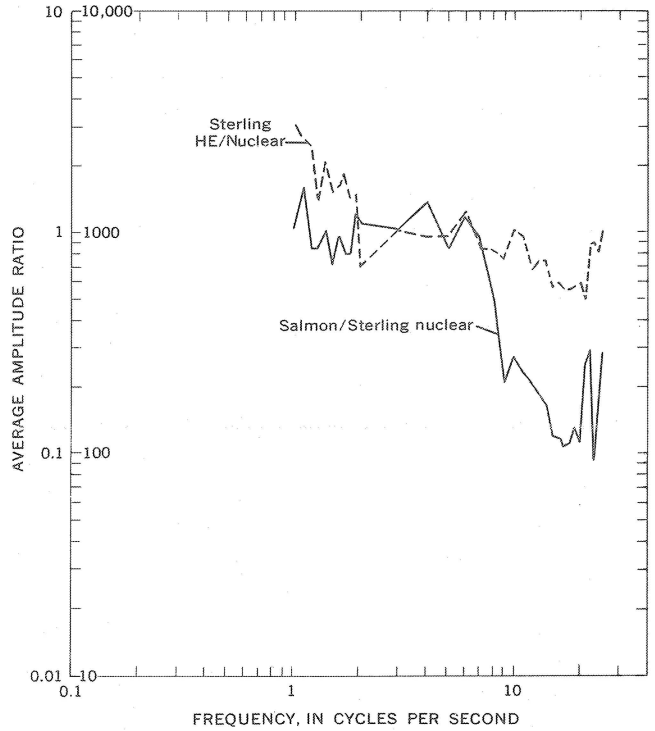

FIGURE 9.—Average amplitude-spectra ratios determined from the SALMON to STERLING-nuclear ratios and the STERLING-HE to STERLING-nuclear ratios which were associated with the Poplarville, Picayune, and Raleigh recording locations. The higher ordinate scale is for the SALMON/STERLING-nuclear curve, and the lower ordinate scale is for the STERLING-HE/STERLING-nuclear curve.

This agrees with visual examination of the filtered analog playbacks and the amplitude spectra. In the frequency range (1 to 5 cps) which predominates in teleseismic signals, the STERLING-nuclear explosion produced, on the average, about the same seismic amplitudes as the STERLING-HE explosion, but at frequencies between 8 and 25 cps it produced seismic amplitudes about 1.4 times greater than the STERLING-HE explosion. The SALMON nuclear explosion, on the other hand, generated seismic amplitudes in the 1- to 5-cps band about 1,000 times as large as the STERLING nuclear, and in the 10- to 25-cps band the SALMON amplitudes were less than 200 times as large.

The consistency of the relative differences in the overall structure of the 2 types of amplitude spectral ratios obtained from 10 seconds of the seismic signals at the 3 recording locations tends to confirm the theoretical conclusions that spectral ratios determined from the entire seismogram are dependent on only the relative differences in the seismic-source properties and not on the propagation path or the recording instruments. The relative differences in the seismic-source properties as determined from the average spectral ratios for the SALMON and STERLING nuclear recordings vary more than a factor of 5 in the frequency band 1 to 25 cps, with the STERLING-nuclear recordings being richer in the 10- to 25-cps frequencies.

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