Naval Research Laboratory
Stennis Space Center, MS 39529-5004

2

NRL/MR/7174-93-7032

Measurements of Volume Reverberation Off the Coasts of Southern California and Northern Mexico

RICHARD H. LOVE

Ocean Acoustics Branch
Center for Environmental Acoustics

April 1993

REPORT DOCUMENTATION PAGE

Form Approved
OBM No. 0704-0188

1. Agency Use Only *(Leave blank).*

2. Report Date. April 1993

3. Report Type and Dates Covered. Final

Title and Subtitle.
Measurements of Volume Reverberation Off the Coasts of Southern California and Northern Mexico

5. Funding Numbers.
Program Element No. 0602435N
Project No.
Task No. R035B03
Accession No. DN480045
Work Unit No. 710372A3

6. Author(s).
Richard H. Love

7. Performing Organization Name(s) and Address(es).
Naval Research Laboratory Detachment
Ocean Acoustics Branch
Stennis Space Center, MS 39529-5004

8. Performing Organization Report Number.
Memorandum Report 7032

9. Sponsoring/Monitoring Agency Name(s) and Address(es).
Office of Naval Research
800 N. Quincy Street
Arlington, VA 22217-5000

10. Sponsoring/Monitoring Agency Report Number.
Memorandum Report 7032

11. Supplementary Notes.

12a. Distribution/Availability Statement.
Approved for public release; distribution is unlimited.

12b. Distribution Code.

13. Abstract *(Maximum 200 words).*

Measurements were conducted to investigate the geographic and frequency variability of volume reverberation off the coasts of southern California and northern Mexico during the fall. Some locations show a peak in volume reverberation around 2 kHz. This peak is most notable at night and at those locations closest to shore. Northern anchovy are the most probable cause of this peak. There is a general south to north increase in volume reverberation between 1 and 5 kHz. Volume reverberation levels above 5 kHz are higher than at lower frequencies, generally increasing rapidly with frequency between 6 and 10 kHz and then increasing less rapidly between 10 and 20 kHz. At the higher frequencies there is a general south to north decrease in volume reverberation during the day, while at night levels are highest at the more inshore locations. Mesopelagic fish, siphonophores, and possibly, deep sea shrimp are suspected to be the dominant scatterers at the higher frequencies.

14. Subject Terms.
Volume Reverberation

15. Number of Pages. 16

16. Price Code.

17. Security Classification Unclassified

18. Security Classification of Report. Unclassified

19. Security Classification of This Page. Unclassified

20. Limitation of Abstract. of Abstract. SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

MEASUREMENTS OF VOLUME REVERBERATION OFF THE COASTS OF SOUTHERN CALIFORNIA AND NORTHERN MEXICO

INTRODUCTION

During October and November 1969 a volume reverberation experiment was conducted off the coasts of southern California and northern Mexico. The acoustic data obtained were analyzed but, due to the loss of key personnel and changes in program emphasis, the results were never reported. Two factors have provided the impetus for the current publication of these results: the first is recent naval interest in the characteristics of reverberation in coastal waters and the second is interest in active sonar frequencies below 2 kHz.

MEASUREMENTS

Figure 1 shows the locations of 6 major stations (numbers) and 23 substations (letters) that were occupied by the USNS *DE STEIGUER* (T-AGOR 12) during the course of the experiment. Day and night measurement sequences were conducted at each major station, although data were not obtained at station 1 due to equipment malfunctions. Either a day or a night sequence was conducted at each substation, as the ship transited between major stations.

Measurements were conducted using Mk 61 SUS (Signals, Underwater Sound) as broad-band sound sources and an omnidirectional hydrophone as the receiver. The hydrophone was suspended at a depth of 18 m and floated approximately 60 m away from the ship. The SUS were set to detonate at 18 m and were propelled away from the ship to the vicinity of the hydrophone using a compressed gas SUS launcher. Usually, six SUS comprised a sequence. Received signals were amplified, high-pass filtered at 500 Hz, and recorded in analog form on magnetic tape for subsequent laboratory processing. In the laboratory the recorded signals were played back through standard one-third octave filters ranging from 0.8 to 20 kHz and a logarithmic graphic level recorder that provided received voltage versus time envelopes for each third octave band.

When omnidirectional sources and receivers are used for volume reverberation measurements, returns are from scatterers within a hemispherical shell. Thus, the received signal is integrated over depths from the surface to the bottom of the hemispherical shell. Once the bottom of this shell gets below the depth of the deepest scatterers, the received signal gives the integrated scattering strength of all the scatterers in the water column, or the column scattering strength. Column strengths (S_c) were calculated from the voltage envelopes using the equation

$$S_c = 20\log V + 30\log t - 10\log E - FFVS + \alpha ct - Gain - 148, \qquad (1)$$

where S_c is in dB re 1 m^2, V is the received voltage amplitude, t is time in seconds after the blast, E is the source energy per unit area in a one-third octave band in ergs/cm^2 at 100 m, $FFVS$ is the free-field voltage sensitivity of the hydrophone in dB re 1 volt/μPa, α is absorption in dB/m, c is the sound speed in m/s, $Gain$ is the external gain in the amplifier and filter, and the constant of 148 dB includes the density of seawater and unit conversions for acoustic pressure and source energy, as well as a factor of $2/c$ from the theory and a factor of 4 for reverberation paths that include reflections from the surface. This equation was developed from Eq. 2-5 of Reference 1 [2]. Calculations were done for several times between 0.5 and 1.5 s to ensure that S_c was determined after the deepest scatterers had been insonified, that is, when the envelope was decreasing as $-(30 \log t + \alpha c t)$.

SCATTERERS

Scattering from the swimbladders of fish is the dominant cause of volume reverberation at frequencies between 1 and 20 kHz in most oceanic regions. However, off southern California and northern Mexico, physonect siphonophores containing air bubbles can also be a significant source of reverberation [3]. Also, at the higher end of this frequency band, organisms that do not contain gas can be important if they are very abundant.

The column strength of a group of scatterers is

$$S_c = 10 \log \sum_{i=1}^{n} \sigma_i(f), \tag{2}$$

where σ is the acoustic cross section in m^2 at frequency f of an individual scatterer and n is the number of scatterers per m^2 in the water column.

For fish with swimbladders, Reference 4 gives

$$\sigma = \frac{4\pi r^2}{\left(\frac{f_0^2}{f^2 H^2}\right) + \left(\frac{f_0^2}{f^2} - 1\right)^2}, \tag{3}$$

where f_0 is the resonance frequency of a swimbladder with equivalent radius r at depth z and H is its damping coefficient. In Eq. 3, σ is in cm^2, and r is in centimeters. Resonance frequency is a function of swimbladder size and depth,

$$f_0 r = P_0^{1/2} / \pi \rho, \tag{4}$$

where f_0 is in hertz, P_0 is the ambient pressure in dynes/cm^2 at depth z, and ρ is the density of fish flesh in gm/cm^3. Although there are variations between species and among individuals of the same species, swimbladder volumes are generally proportional to fish weight and swimbladder radii proportional to fish length. Thus, resonance frequency is inversely proportional to fish size. These equations should also hold for siphonophore air bubbles except the damping coefficients will differ.

At frequencies well below resonance, in the Rayleigh scattering regime,

$$\sigma \approx 4\pi r^2 \left(f^4 / f_0^4\right). \tag{5}$$

At resonance

$$\sigma = 4\pi r^2 H^2 \tag{6}$$

and at frequencies well above resonance, in the geometric scattering regime,

$$\sigma = 4\pi r^2. \tag{7}$$

Since $H > 1$ for fish, scattering from an individual fish peaks at resonance. In many areas of the ocean a wide size range of fish will be present, with smaller fish more numerous than larger ones. In such cases, curves of column strength versus frequency may not contain any peaks.

A-1

RESULTS

Figures 2 through 5 show column strength versus frequency curves for each station. At the lower frequencies, below 5 kHz, some of the curves have a peak around 2 kHz, some have a peak or plateau around 4 kHz, and others show a consistent increase with frequency. At frequencies above 5 kHz, column strengths are higher than they are below 5 kHz; they generally increase rapidly with frequency to between 6 and 10 kHz and then, in most cases, increase less rapidly at higher frequencies.

In the more detailed description of results that follows, day and night data will be discussed separately and then compared. In order to simplify this discussion, similar curves from adjacent stations and substations have been averaged. Figure 6 shows averaged day column strengths and Fig. 7 shows averaged night column strengths. Northern and southern stations have been separated for clarity, and the curve for stations between approximately 31°N and 33°N has been plotted with both sets of stations for ease in making comparisons.

Day

Between 1 and 3 kHz, day column strengths at stations south of 33°N, stations 2 through Q, increase with frequency, while values at stations north of 34°N, stations W, X and 5, have a peak at 2 kHz. The curve for station V, between stations Q and W, generally lies between those of the stations to the north and south of it, indicating a transition. Column strengths increase from south to north between stations 3 and 5. The curve for station 6, which is well to the east of the other northern stations, differs from the others in this range.

Between 3 and 5 kHz, day column strengths at stations 2 through 3, continue to increase with frequency, while those for stations L through X, and station 6, are relatively constant. At station 5, column strength is still decreasing with frequency in this range. There is no significant geographic variation in column strength in this frequency range, at 5 kHz all values are between -60 and -64 dB.

Between 5 and 8 kHz during the day, column strengths at all stations but 6 increase rapidly with frequency. At station 6, this increase begins at 6.3 kHz. In contrast to the lower frequencies, where column strengths increased from south to north, column strengths generally decrease from south to north in this range. Values are highest at stations 2 and D and lowest at station 5. Values at stations E through V are about equal

During the day, stations 2 and D have a peak at 10 kHz; while stations E through V, with exception of L and M, peak at 8 kHz. Curves that do not exhibit a peak, those for stations L, M, W, X, 5 and 6, nonetheless show a significant decrease in slope.

Between 10 and 16 kHz, day column strengths at all but stations 2, D, and 6 increase slowly with frequency. The curve for stations 2 and 6 has the same increase as the others between 12.5 and 16 kHz, after it drops from its 10 kHz peak. Once again the curve at station 6 differs from the others, this time increasing rapidly above 12.5 kHz. Between 8 and 16 kHz, column strengths are highest at stations 2 and D and lowest at station 5. Stations 3 and V keep the general south to north decrease from being monotonic.

The slopes of the curves for the stations south of 33°N, stations 2 through Q, decrease above 16 kHz, while the slopes of the stations north of 33°N either remain constant (stations W and X) or increase (stations V, 5 and 6). Thus, 20 kHz column strengths at all stations, with the exception of station 6, are between -47 and -50 dB. That for station 6 is substantially higher, -42 dB.

Night

Between 1 and 3 kHz, all night curves except the one for stations G through 3 have a peak between 1.6 and 2.5 kHz. Column strengths at the peak frequency increase from south to north, being -67 dB at stations 2 and C and -56 dB at station 5. The frequency of the peak does not vary with latitude but it does appear to decrease with distance offshore. At station 6 the peak is between 2 and 2.5 kHz, at stations A, B, and 5, it is at 2 kHz, and at the other stations it is at 1.6 kHz. Station 6 is well inshore of the others, stations A and B are somewhat inshore of the other southern stations, and station 5 is slightly inshore of all the other northern stations but Y.

Between 3 and 5 kHz, night column strengths at all stations increase with frequency. Values at 5 kHz are between -53 and -58 dB at all stations. At 6.3 kHz, column strengths at all night stations are quite close, between -52 and -55 dB. At higher frequencies the curves rapidly diverge, as values at stations G through T remain almost constant to 10 kHz, while the curves for stations to the north and south increase significantly between 6.3 and 8 kHz.

At 8, 10, and 12.5 kHz, nighttime column strengths at stations A and B are at least 3 to 4 dB higher than at any other station. Between 10 and 16 kHz, values at all stations increase with frequency, but at different rates, so that values at 16 kHz are all between -45 and -49 dB. Column strengths at stations 2 through 3 peak at 16 kHz but continue their increase with frequency at the other stations. Above 16 kHz, column strengths are highest at the more inshore stations, stations A, B, 5, and 6.

Day/Night

Figure 8 shows comparisons of averaged day and night column strengths. The most striking feature is that at virtually all locations and frequencies, night values are higher than day values. Another obvious feature is that the peak in the neighborhood of 2 kHz is more pronounced at night. Also, night and day curves diverge in the 3 to 5 kHz range. At stations south of 29.5°N, this divergence occurs because the night curves increase more rapidly than the day curves; at the other stations, it occurs because the day curves generally remain constant as the night curves increase. At stations south of 33.3°N, the curves converge again between 5 and 8 kHz. Thus, south of 33.3°N, the night curves exhibit a shoulder at 5 kHz and the day curves exhibit one at 8 kHz.

DISCUSSION

The omnidirectional measurement technique does not determine depth of the scatterers. Equation 4 shows that the effects of scatterer size and depth on resonance frequency cannot be separated. Thus, all that can be determined about the scatterers from Eq. 2 through 7 is that those that cause the peaks around 2 kHz are larger and/or shallower than those responsible for the increases in reverberation between 3 and 8 kHz, which in turn, are larger and/or shallower than those responsible for any increases in reverberation above 10 kHz.

Numbers of low-frequency scatterers increase from south to north. At midfrequencies, 3 to 8 kHz, there is some evidence that the greatest numbers of scatterers are at the most southern stations and the fewest at the most northern, but the change is not very great. Numbers of high-frequency scatterers appear to decrease from south to north during the day, but at night the decrease seems to be more from inshore to offshore.

Between 1966 and 1973, extensive fishery surveys were conducted off the coasts of California and Mexico from 23°N to 42°N, with the major effort being between 30°N and 35°N [5]. Results of high frequency acoustic measurements combined with trawling showed that schools of northern anchovy, *Engraulis mordax*, dominated the fish population in the region during this period. These surveys, which were conducted inside the 2000-m contour, showed that anchovy numbers generally decreased with distance from shore. Other, short term, acoustic surveys encountered schools out to 160 and 250 nm [6, 7]. Model results indicate that northern anchovies have a resonance peak around 1.6 kHz [8]. Therefore, the low-frequency peaks in the present data, which are strongest at station 5 during the day and stations 5 and 6 at night, stations that are the closest to shore, are probably produced by northern anchovies.

In October 1968, an experiment that included 12-kHz acoustic measurements, biological trawling, and research submersible dives was conducted at three sites: 28.9°N, 118.1°W; 31°N, 117.5°W; and 32.5°N, 117.8°W. Organisms caught by the trawl and observed from the submersible included mesopelagic fishes, especially lanternfish, hatchetfish, and *Cyclothone* (fish); siphonophores; and deep sea shrimp. Lanternfish, hatchetfish and siphonophores are probably the primary causes of scattering at 3 to 8 or 10 kHz. *Cyclothone* and shrimp may contribute to scattering at higher frequencies.

The fact that night column strengths are higher than day values at virtually all locations and frequencies, requires explanation. Equation 2 shows that column strength at any frequency changes only if the sum of the acoustic cross sections changes at that frequency. This will happen if the number of scatterers changes, or if their swimbladder sizes change, or if changes in scatterer depths shift the resonance frequency of the bladder. It is inconceivable that there would consistently be more fish at a station at night. Many species undertake diel vertical migrations that must be the cause of observed day/night changes in column strength. One possibility is that very deep scatterers that are below the measurement system's noise threshold during the day migrate upward to a depth where lower transmission loss brings their echoes above that threshold, effectively increasing their numbers at night. Some fish species can regulate their swimbladder volumes so that they are near a state of neutral buoyancy both night and day. Other species cannot control their swimbladders; it is generally presumed that, as they rise in the water column near sunset, their swimbladders expand according to Boyle's law to provide neutral buoyancy at night. In either case, as the scatterers rise, swimbladder resonance frequency drops. Thus, the increase at night in the 3- to 8-kHz range may just be a shift in scattering to lower frequencies at night. Similarly, increases in the 10- to 20-kHz range may be caused by fish that scatter at even higher frequencies during the day. Finally, any fish whose swimbladders expand as they rise will have greater acoustic cross sections at all frequencies. Hence, increased nighttime scattering strengths can reasonably be attributed to the upward shift in scatterers at night. However, since the measurement technique could not determine scatterer depths, this hypothesis can not be proved or disproved.

SUMMARY

During October and November 1969 volume reverberation measurements were made at a series of stations between 28°N and 35°N between 40 and 200 nm off the coasts of California and Mexico. Column strengths were measured between 800 Hz and 20 kHz using near surface SUS and an omnidirectional hydrophone. At lower frequencies, below 5 kHz, some stations show a peak in volume reverberation around 2 kHz. This peak is most notable at night and for those stations closest to shore. Northern anchovy are the most probable cause of this peak. There is a general south to north increase in column strengths at these frequencies. Column strengths above 5 kHz are higher than at lower frequencies, generally increasing rapidly with frequency to between 6 and 10 kHz and then increasing less rapidly between 10 and 20 kHz. At these frequencies there is a general south to north decrease in column strengths during the day, while at night values are highest for the more inshore stations. Mesopelagic fish, siphonophores, and possibly deep sea shrimp are suspected to be the dominant scatterers at the higher frequencies. Night column strengths were higher than day values with very few exceptions. This day/night change is attributed to the upward migration of scatterers around sunset, but the measurement technique used does not permit this explanation to be verified.

ACKNOWLEDGMENTS

The scientists who collected and initially processed these data, especially Peter Van Schuyler and Arthur A. Hunger, and the officers and crew of the USNS *DE STEIGUER* (T-AGOR-12) are gratefully acknowledged. Publication of this report was funded by the Office of Naval Research under Program Element 0602435N, T. Warfield, Program Manager.

REFERENCES

1. S. Machlup and J. B. Hersey, "Analysis of Sound-Scattering Observations from Non-Uniform Distributions of Scatterers in the Ocean," Deep-Sea Res. **3**, 1-22 (1955).

2. J. R. Marshall and R. P. Chapman, "Reverberation from a Deep Scattering Layer Measured with Explosive Sound Sources," *J. Acoust. Soc. Am.* **36**, 164-167 (1964).

3. G. V. Pickwell, R. J. Vent, E. G. Barham, W. E. Batzler, and I. E. Davies, "Biological Acoustic Scattering off Southern California, Baja California, and Guadalupe Island," in Proceedings of an International Symposium on Biological Sound Scattering in the Ocean, edited by G. B. Farquhar. Maury Center for Ocean Sci., Washington, DC, MC Rep. 005, pp. 490-507 (1970).

4. R. H. Love, "Resonant Acoustic Scattering by Swimbladder-Bearing Fish," *J. Acoust. Soc. Am.* **64**, 571-580 (1978).

5. K. F. Mais, "Pelagic Fish Surveys in the California Current," Cal. Dept. Fish and Game, *Fish Bull.* 162 (1974).

6. P. E. Smith, "The Horizontal Dimensions and Abundance of Fish Schools in the Upper Mixed Layer as Measured by Sonar," in Proceedings of an International Symposium on Biological Sound Scattering in the Ocean, edited by G. B. Farquhar. Maury Center for Ocean Sci., Washington, DC, MC Rep. 005, pp. 563-600 (1970).

7. I. E. Davies, R. J. Vent, and J. C. Brown, "Fish School Acoustic Target Strength," *J. Cons. int. Explor. Mer*, **37**, 288-292 (1977).

8. R. W. Nero, "Estimates of Low Frequency Volume Scattering off the Oregon-Washington Coast," Naval Research Laboratory, Stennis Space Center, MS, NOARL Technical Note 206 (1992).

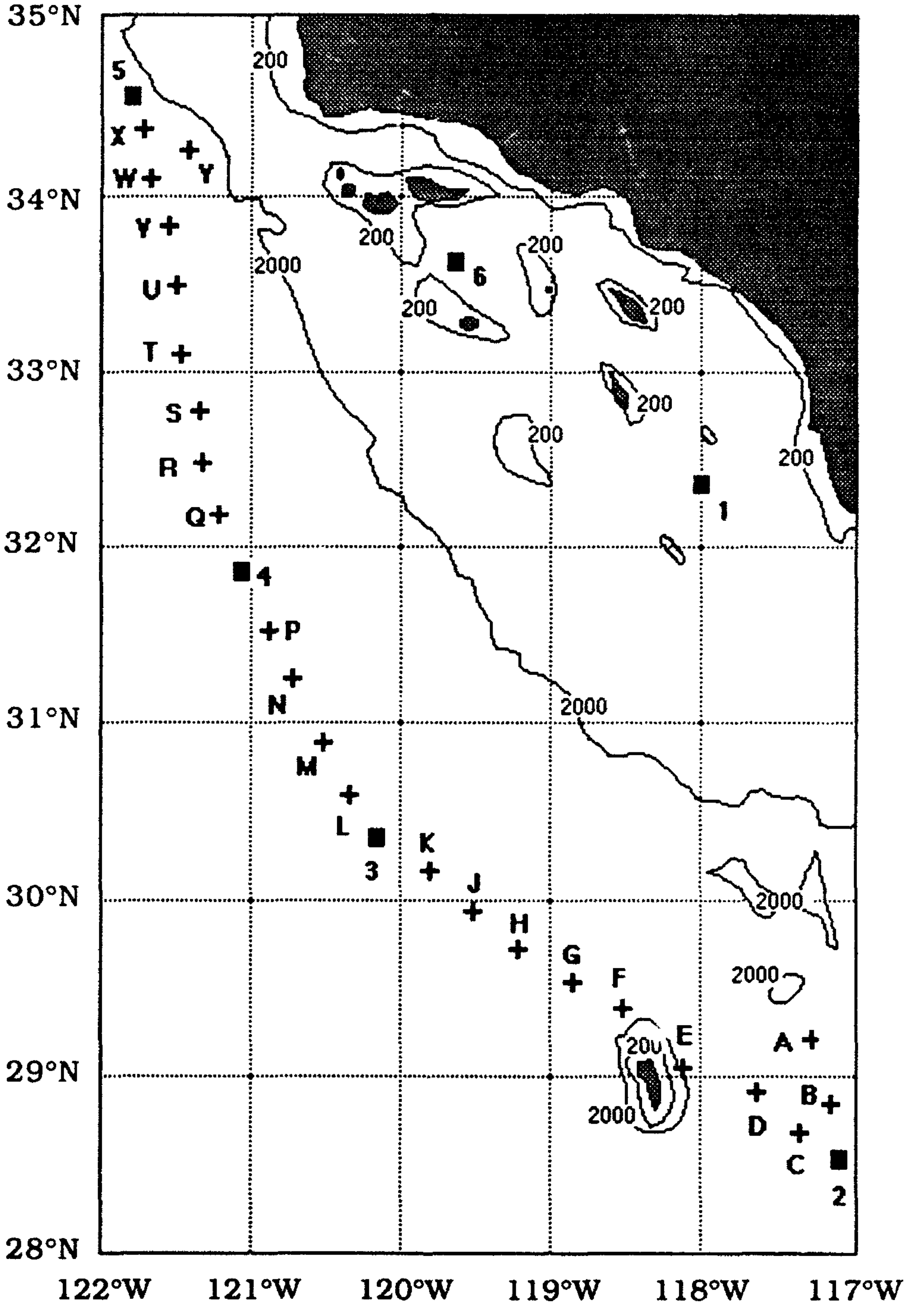


Fig. 1 - Station locations

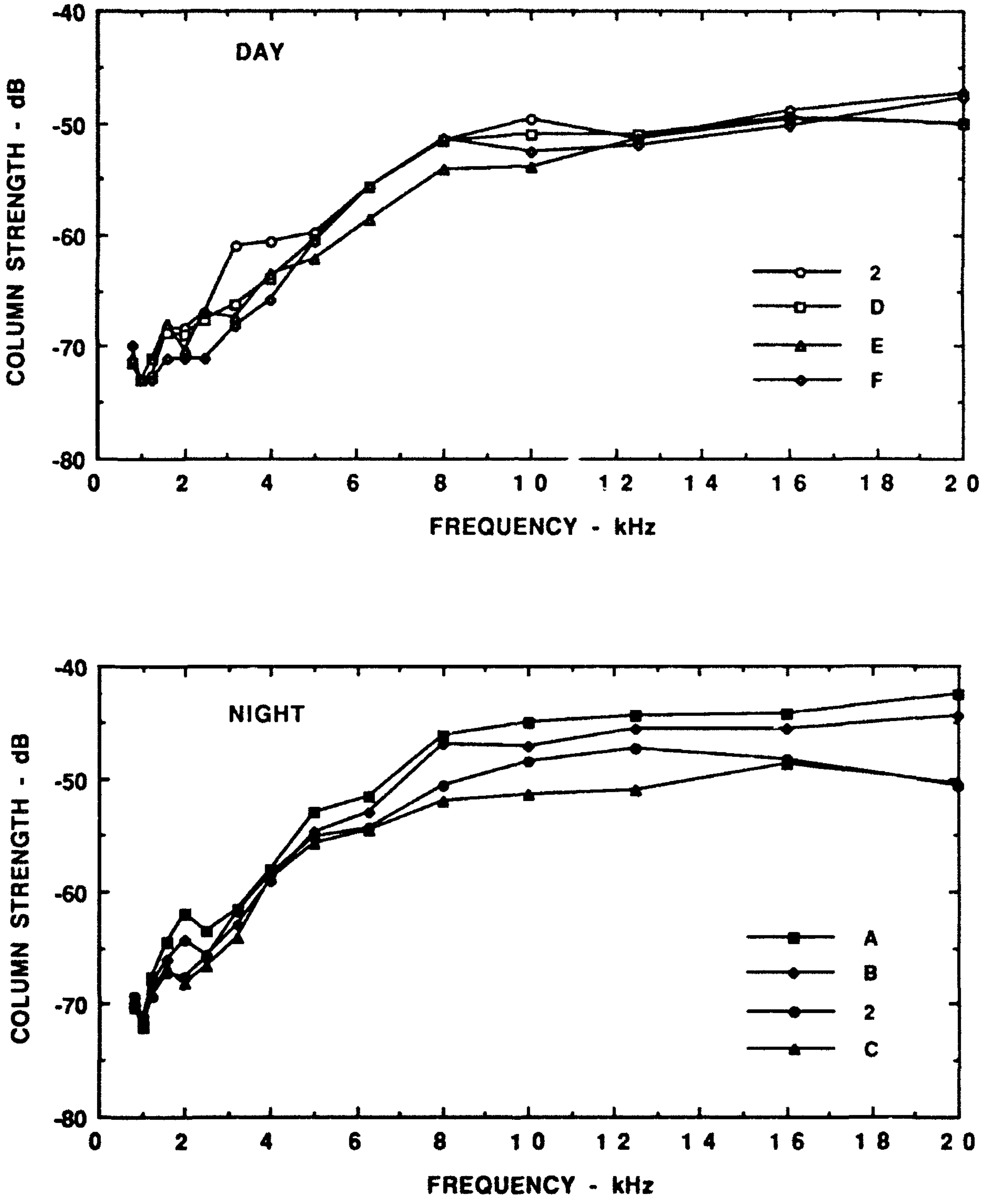


Fig. 2 - Column strengths for stations between 28.5°N and 29.5°N

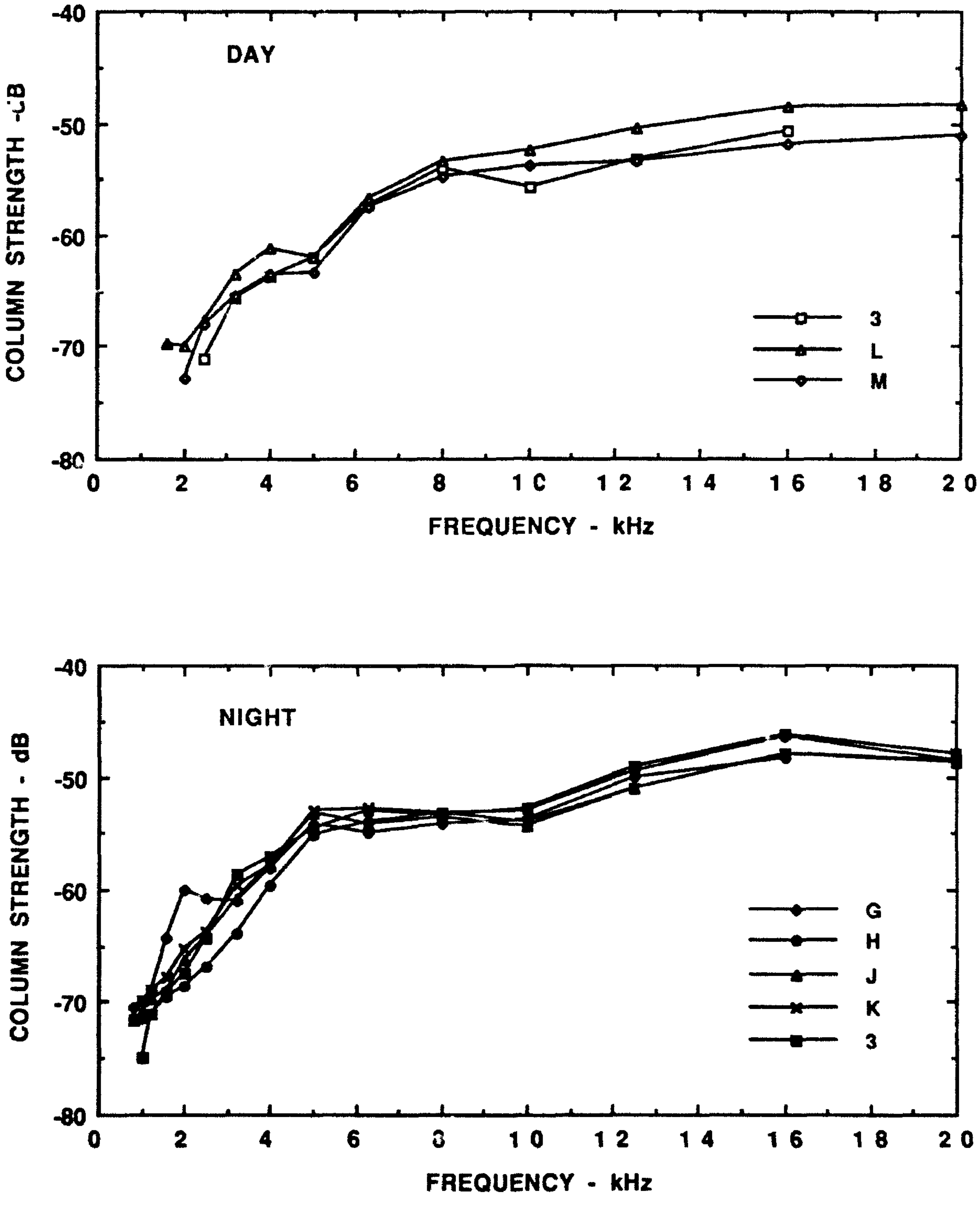


Fig. 3 - Column strengths for stations between 29.5°N and 31°N

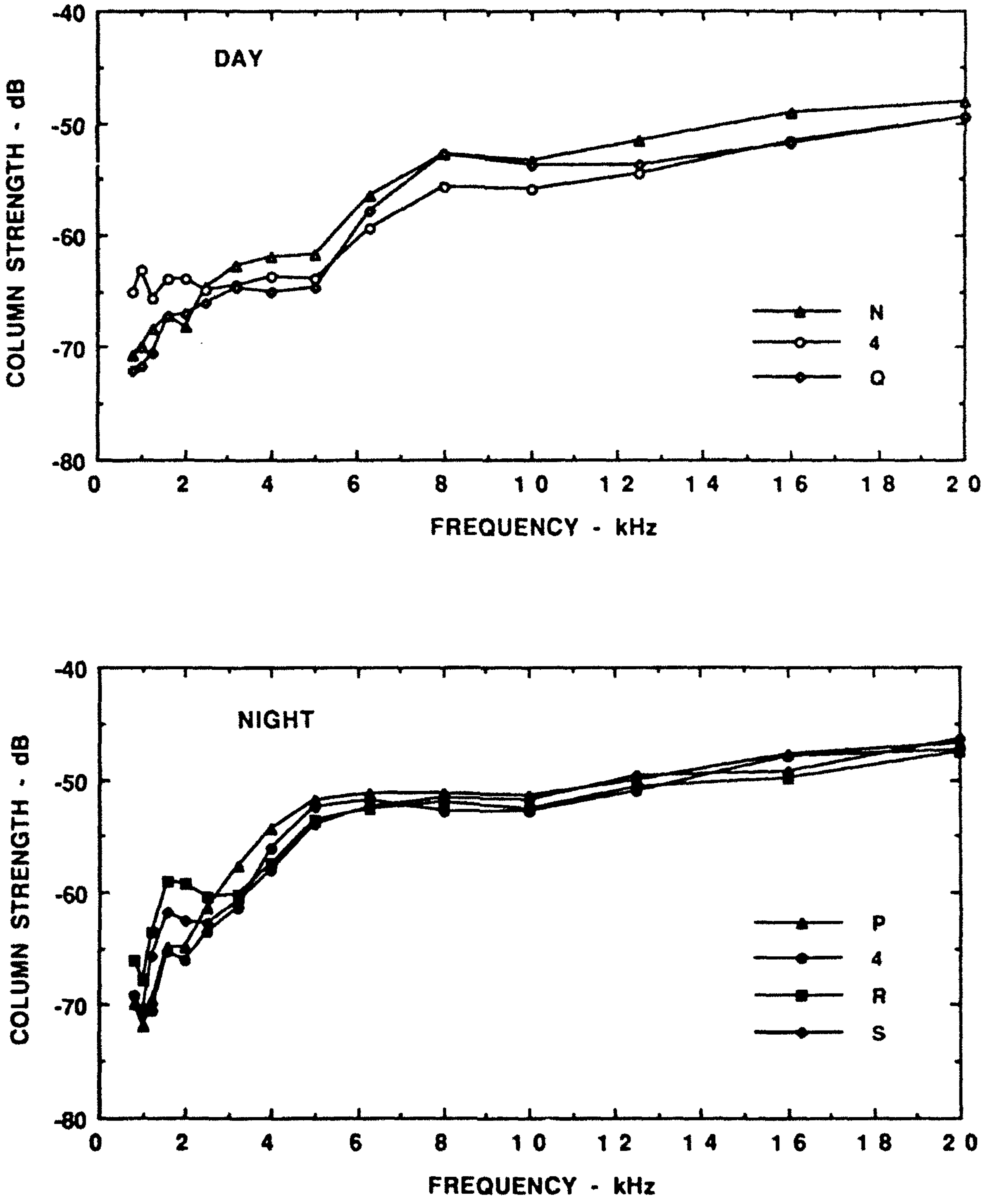
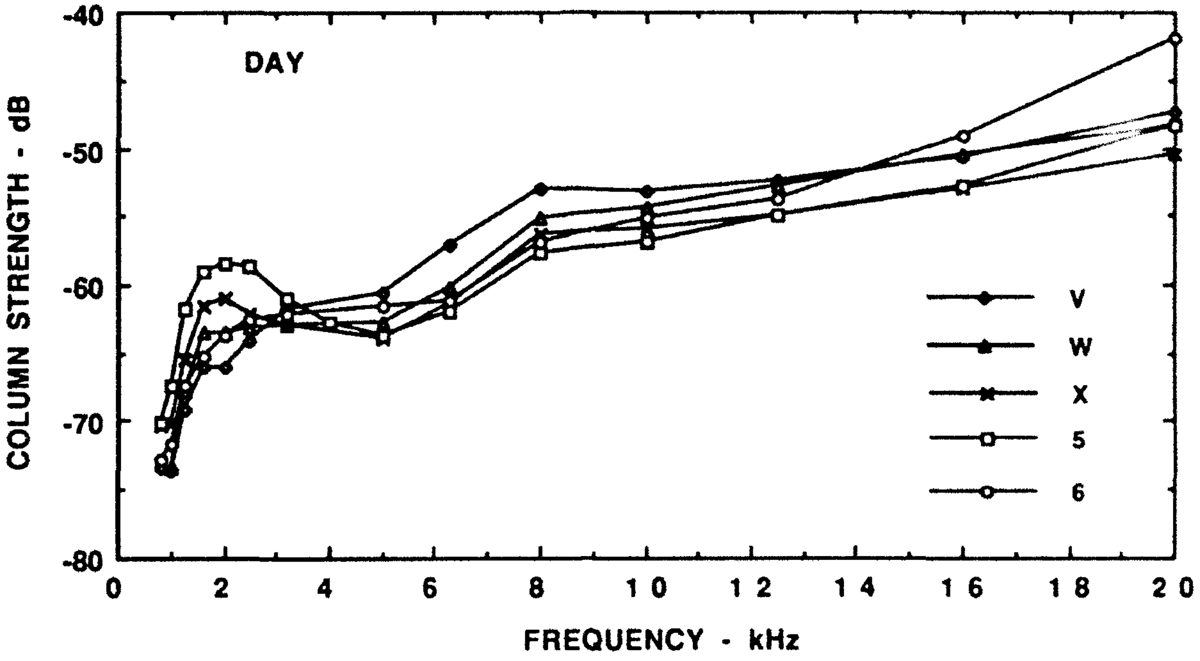


Fig. 4 - Column strengths for stations between 31°N and 33°N



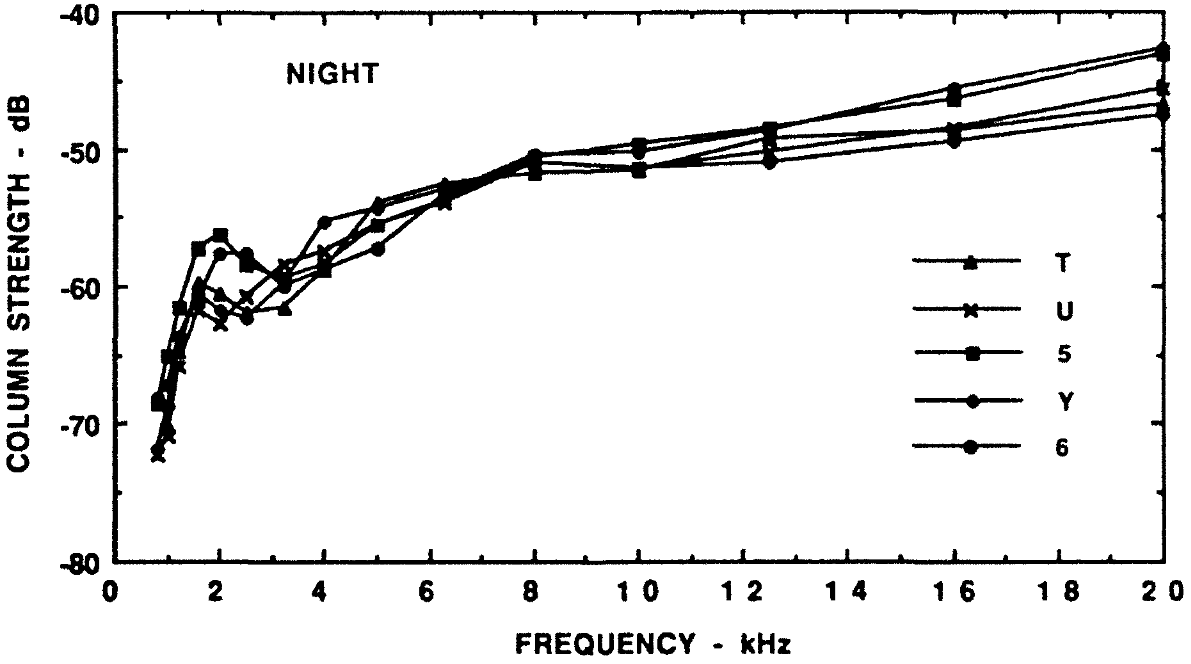
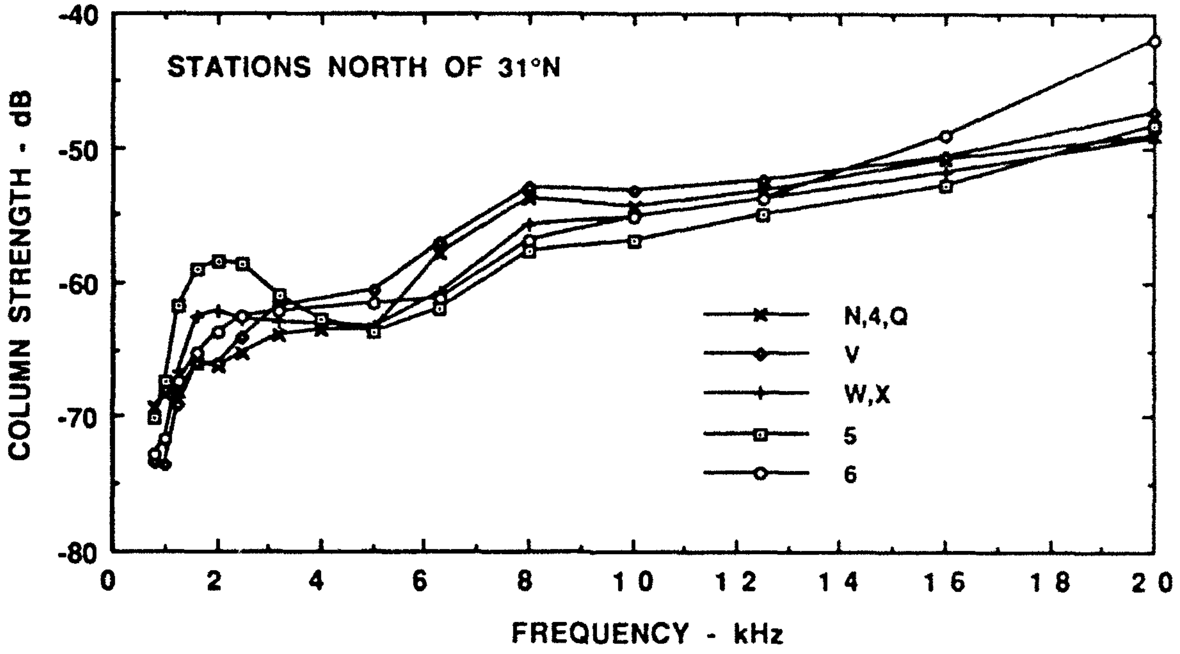


Fig. 5 - Column strengths for stations between 33°N and 35°N



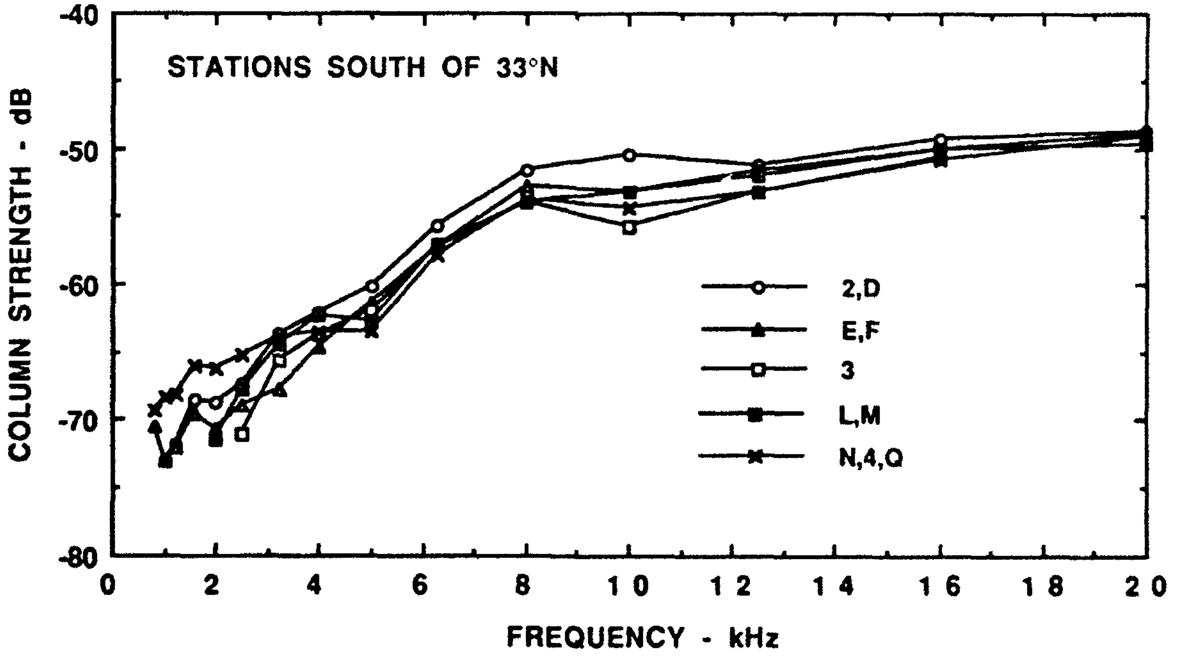


Fig. 6 - Averaged day column strengths

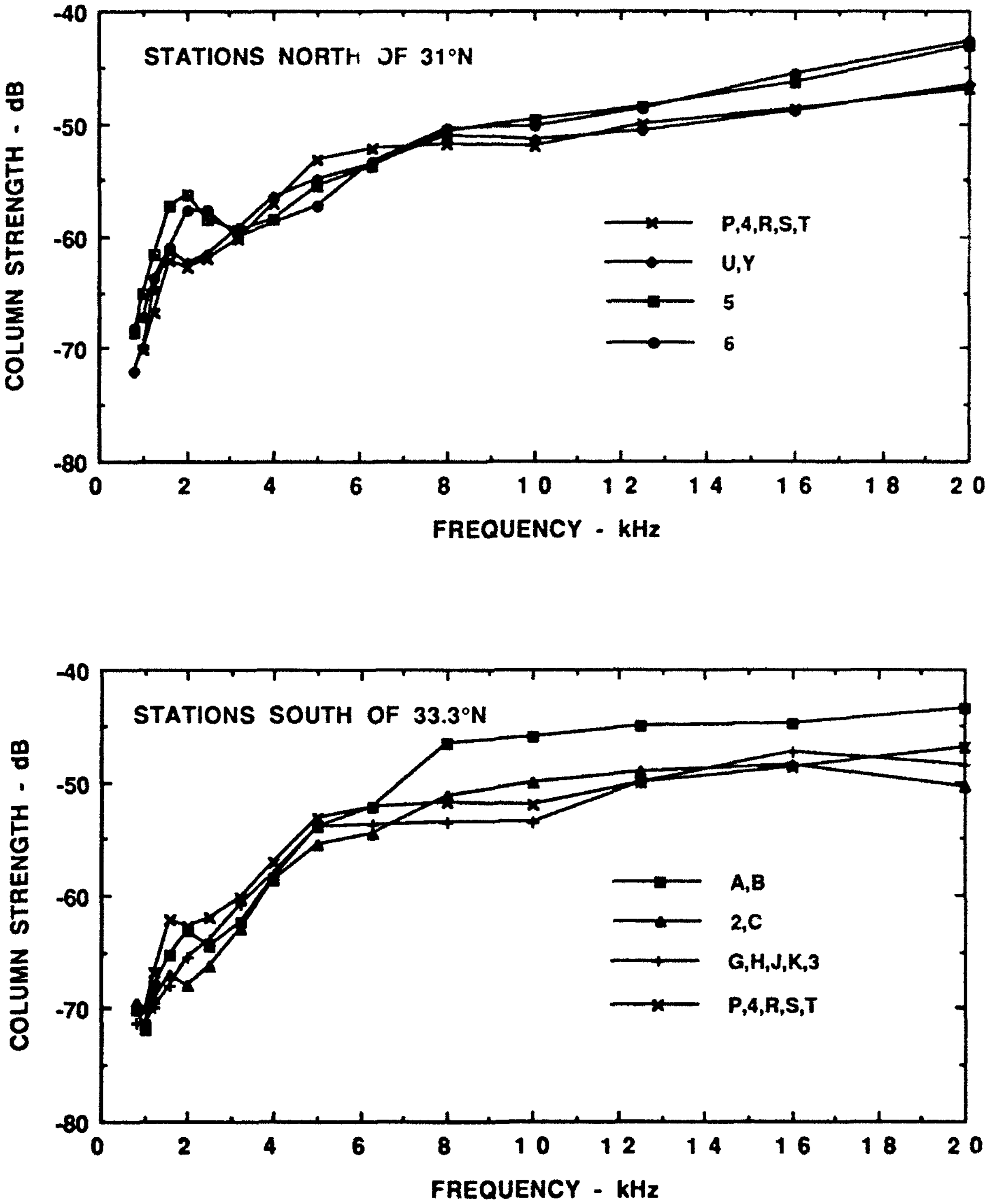


Fig. 7 - Averaged night column strengths

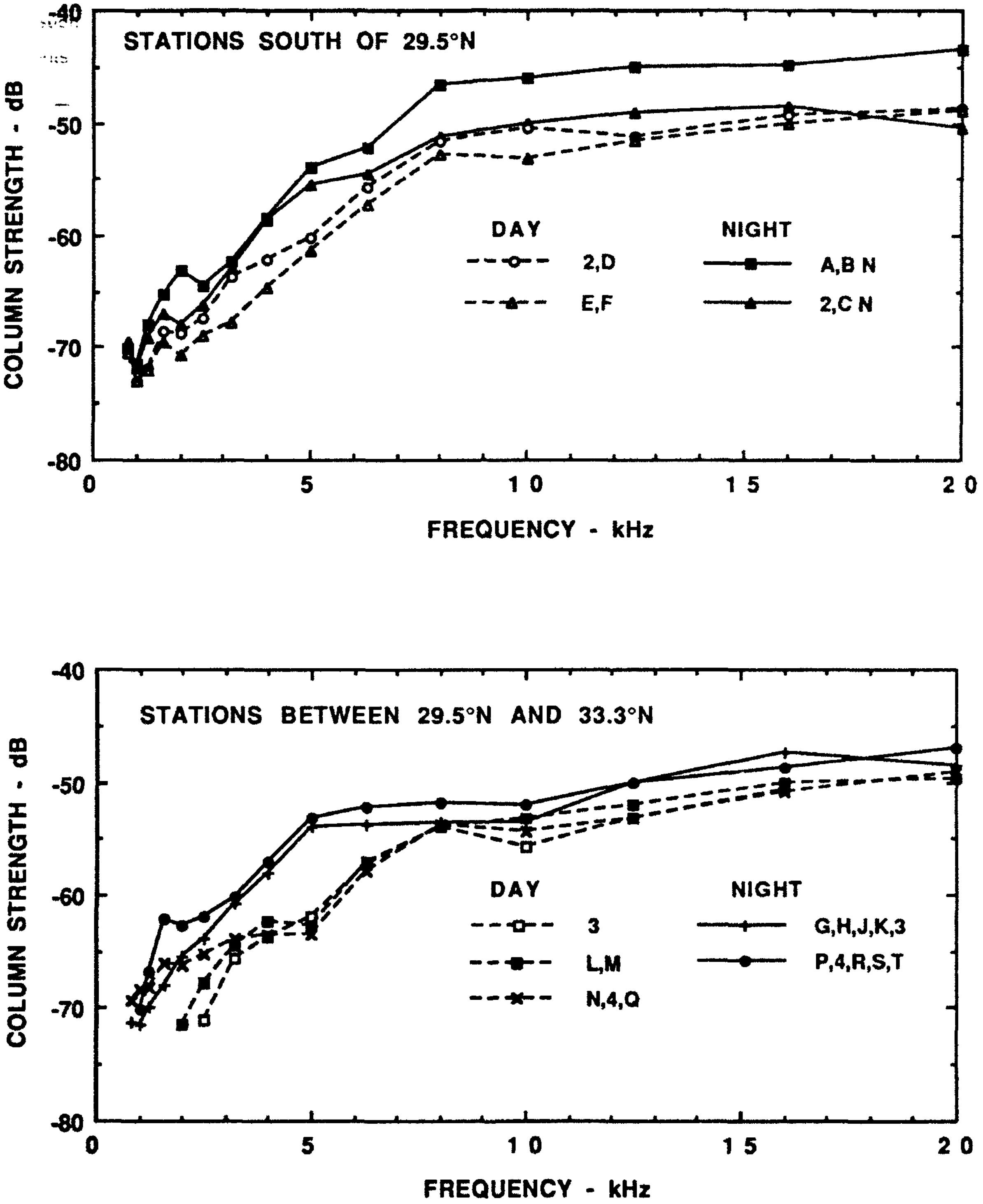


Fig. 8 - Comparison of day and night averaged column strengths

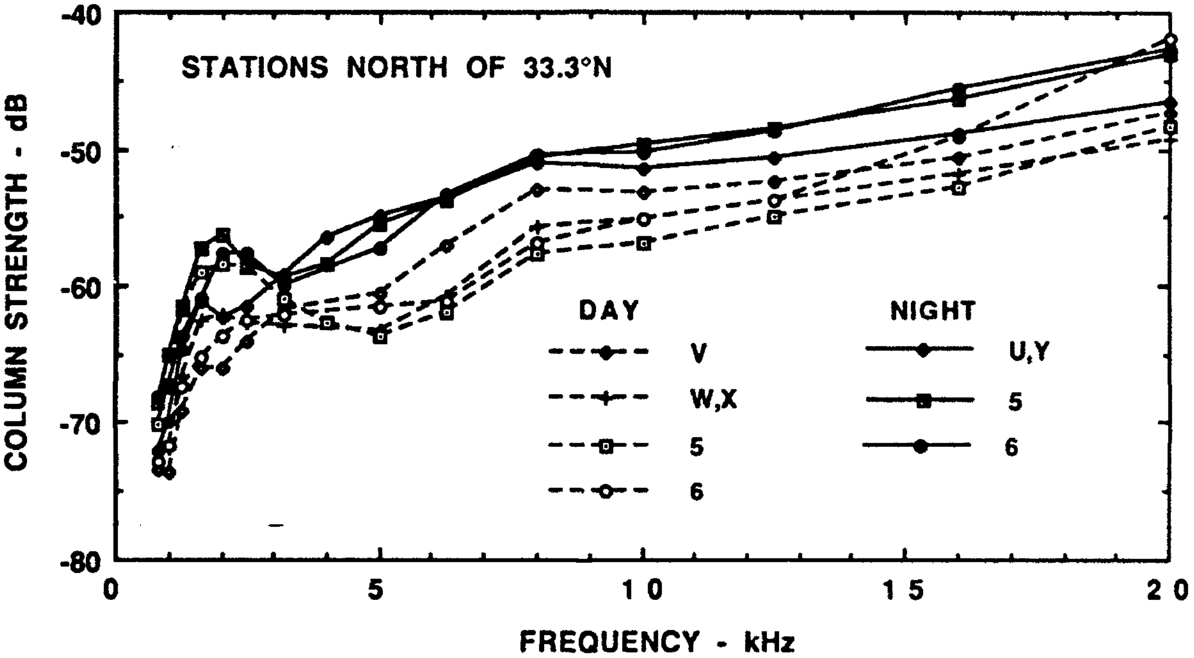


Fig. 8 (cont.) - Comparison of averaged day and night column strengths