A Statistical Analysis of Ambient Noise Monitored in the Arctic Ocean Basin

by

Nicholas Constantine Makris

Submitted to the Department of
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Chairman, Physics Departmental Committee

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ABSTRACT

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Low frequency ambient noise, 10-20 Hz, monitored in the Arctic Ocean Basin during FRAM IV was reduced and statistically analyzed. Discrete samples taken at 15 minute intervals from the continuous record of a strip chart recorder comprised a set of 2263 data points representing an underwater noise history from 3/30 5:30 Z to 4/22 23:45 Z in the environment of FRAM IV's main camp site. Due to various randomly occurring man-made underwater disturbances 1112 of these points were ommitted.

Statistical analysis of the remaining 1151 points showed two noise level states to be most frequently occupied, at approx. 95 dB re 1μPa and 84 dB re 1μPa; the average noise level to be 87.8 +/- .25 dB re 1μPa; and the deviance to be 7.1 dB. A time scale of 1.46 days +/- 2 hours characterizing the variation in ambient noise level was derived from the autocorrelation of a version of the reduced data which bridged ommitted points via a linear interpolation.

Thesis Supervisor: Dr. Ira Dyer
Professor of Ocean Engineering

ACKNOWLEDGEMENTS

****

I can lay claim to very few of the ideas and concepts expressed in this thesis. For, one way or another they all came from the same source: Prof. Dyer.

Peter Stein, your adept interpreting saved me some embarrassment and Prof. Dyer some time. Thanks for helping me through the FRAM IV artifacts.

"JoJo" you %#$?&lavian, five minutes of your physical insight sadly kept a time worn page pressed with mathematical heirogylphs from meeting the light of day for another "whoknowshowlong". Thanks for the Rustrack Schematic too.

This thesis is dedicated to Sue, who is very lovely but couldn't yank me from the terminal when my time was up.

TABLE OF CONTENTS
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LIST OF FIGURES

****

INTRODUCTION
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The general topic of this thesis is underwater acoustics. Specifically it involves the statistical analysis of ambient noise monitered over a period of about three weeks (3/30 5:30 Z to 4/22 23:45 Z 1982) during the FRAM IV Arctic Ocean Basin experiment.

In order to develop a better feeling for the type of information analyzed in this thesis, please consider the following brief description of the data acquisition process.

Acoustic noise stimulated a hydrophone suspended appproximately 90 meters beneath the Arctic pack ice. A signal corresponding to this noise was then sent to a Rustrak recorder where it was filtered, averaged and finally recorded. Via calibrations of the Rustrak recorder's gain and a close attention to the noise levels recorded, it was possible to store a time series of these noise levels on a paper chart 2.25 inches wide and 20 yards long. The width of this chart corresonds to a 50 dB window in the ordinate and the length to a 30 day window in the abscissa. Four of these charts were obtained simultaneously. These charts represent noise level in dB re 1μPa vs. time for the following frequency bands: 5-10 Hz, 10-20 Hz, 20-40 Hz, 40-80 Hz. For reasons which will be revealed later in the thesis, only the chart representing the time variation of noise in the 10-20 Hz band was reduced and analyzed. From now on, this chart will be referred to as the 'Rustrak record' or 'the record'. The charts corresonding to the time variation of noise in the other three bandwidths will be subsequently referred to as 'the Rustrak record from 20-40 Hz' for instance.

The object of the statistical analysis of the Rustrak record was to:

i) Determine the most frequently occupied states in the 10-20 Hz band by taking representative discrete samples from the record which ranged from 75 dB re 1μPa to 105 dB re 1μPa in one dB increments.

ii) Determine the time average and variance of the ambient noise levels over the period of the experiment.

iii) Determine the time scale after which change in the ambient noise level might be expected by taking the autocorrelation of an approximate and compressed version of the record.

In order to make such a statistical analysis it was necessary to convert the continuous Rustrak record into a corresponding series of discrete values. This was accomplished by eye, taking readings at fifteen minute intervals from the beginning to the end of the record. However, approximately one half of all the values which should have been taken via this method had to be omitted. These samples were omitted because during certain periods naturally occuring ambient noise levels were masked by man-made sounds. The effect which these missing data had on the methods and results of the statistical analysis is rather subtle and will be discussed elsewhere in the thesis.

FRAM IV Experiment
****

In the FRAM IV experiment of 1982 researchers from M.I.T., W.H.O.I., and several other institutions made studies on such varied topics as seismic refraction and reflection, long range acoustic transmission and reverberation, ice dynamics, meteorology, physical oceanography and ambient noise.

The majority of the data was collected at the main camp site which rested upon a drifting sheet of polar pack ice due north of Svalbard.
The ice separated the researchers from the cold Arctic waters by a thickness of about three meters.

Essential to the refraction, reverberation, reflection, transmission and ambient noise experiments was the deployment of twenty four hydrophones suspended from the drifting ice sheet upon which the main camp rested.

The hydrophones were used in various contexts corresponding to the different objectives of the listed experiments. Specifically, in the refraction, reverberation and reflection experiments charges of TNT were detonated some distance from the hydrophones. The subsequent underwater acoustic effects were detected by the phones and recorded on magnetic field tapes to be reduced and analyzed as mandated by the particular study. Similarly, during transmission experiments certain pure tones were sent into the water via the camp's signal generator to be detected by the hydrophones, recorded and analyzed.

When no other experiments were in progress, the hydrophones picked up any naturally occurring ambient noise which happened to propagate in their vicinity . This noise was often recorded on field tapes solely for the purpose of studying ambient noise conditions in the Arctic Ocean Basin.

Fundamental Characteristics of the Rustrak Record and Recorder
****

Underwater noise detected by the apex hydrophone, corresponding to the hydrophone at the intersection of the two axes along which hydrophones were deployed, was recorded throughout the experiment on the Rustrak recorder except when the camp's main power generator was not in operation. However, the log shows that the generator was only malfunctioning or turned off approximately once every four days for intervals not exceding 20 minutes. So, the Rustrak record is a rather complete history of the acoustic events which occurred underwater in the vicinity of the main camp during the FRAM IV experiment.

However, much of the recorded data cannot be used for ambient noise analysis. The primary purpose of the Rustrak is to give researchers in the field some indication of the underwater noise level as it evolved. For example, if the weather suddenly changed for the worse and heavy winds began to set on the camp environment, one might check the Rustrak record to see if there was any corresponding increase in ambient noise levels underwater. But if a charge of TNT was set off some distance away, one might watch the Rustrak's output to see if and when the explosion's initial compressional wave reached the apex hydrophone. So, the Rustrak record also represents the acoustic characteristics of many artificially induced phenomena besides the naturally occurring ambient noise of the Arctic Ocean Basin.

The band pass and averaging circuits for the Rustrak recorder were designed and built by Josko Catipovic.

The schematic for the Rustrak recorder is given in figure 1. As fig. 1 indicates, the signal from the apex hydrophone is first boosted by a 20 dB preamplification stage. Then it is sent through a switchbox which sets on one of four amplifiers which could increase the voltage by 20,40,60 or 80dB respectively.

The purpose of the selectable gain was to fit the ambient noise into the 50 dB Rustrak window. Going into more detail, for each gain setting there was a 50 dB window. Specifically, for the gain settings 20,40,60,and 80dB the corresponding windows were 101-151,81-131,61-111,41-91 dB re 1μPa respectively. The chart upon which the noise level was recorded could only represent a width of 50 dB in the ordinate. So, in order to include noise which might range from 41 to 151 dB re 1 μPa, a spread of 110 dB re 1μPa, within the 50 dB window of the chart, gains had to be adjusted as the data came in.

After passing through the switchbox the signal was filtered and separated into four distinct signals corresponding to data from the 5-10,10-20,20-40 and 40-80 Hz frequency bandwidths. The characteristics of this filter are shown in figure 1. The reason for separation of the data is extremely important. For each of these four bandwidths the general characteristics of the data vary greatly. This is because in each of these frequency bands the mechanisms or events which create acoustic signals are of a distinct nature. Since the study of ambient noise in the Arctic Ocean aims primarily to correlate noise conditions with their hypothetical driving mechanisms or events, it is imperative that data should be catagorized in this manner.

Next, the four resultant signals were averaged by the Root Mean Square 'box' as indicated in figure 1. This averaging of the data is significant in that it: i) smooths random fluctuations associated with data taken over very short periods,on the order of minutes; ii) compresses the record to a time scale in which the changes in noise level over a period of, say, a few hours could be easily referenced (ideal for field work); iii) introduces a subtle error after sharp impulses in the noise level.

Finally, the signals were passed through an apparatus which converted voltage to log(voltage). This reduced the conversion to dB of subsequent output produced by the strip-chart recorder (which imprinted the amplified, filtered and separated, averaged and 'logged' signal) to a simple linear relation different for each gain setting.

Specific Characteristics of the Rustrak Record
****

Because of certain discrepancies in the logs concerning the gain settings, approximately the first two days of reliable data had to be omitted from the present analysis of the record. The segment of the record which remains, from 3/30 5:30 to 4/22 23:45, fortunately was always at the same gain setting of 60 dB .

Now the particular reason for choosing to study the Rustrak record from 10-20 Hz instead of the record from 5-10,20-40,40-80 Hz has to do with the characteristics of ambient noise in the Arctic Ocean Basin as a function of frequency. Consider I. Dyer's noise level spectrum presented in figure 2. This characterizes the frequency dependence of ambient noise in the Arctic Ocean.

The strongest peaks occur from approximately one to ten Hertz. However, the location of these peaks is often unpredictable within this range, although it is probable that they will not extend beyond. Susprisingly enough, these peaks are not due to real acoustic noise. They are the result of an apparently unpredictable phenomenon known as cable strumming. Specifically, this phenomenon is supposed to be the result of ocean currents driving the cables from which the hydrophones are deployed. This driving motion apparently sets the cables vibrating in rather complicated modes. As a result of this vibration, the end of the cable upon which the hydrophone is attached tends to move up and down through the water's pressure gradient, causing fluctuating pressure to be dectected. The vertical motion of the hydrophone is of low frequency, and is confined to regions approximately below ten Hertz. So, this phenomenon known as 'strumming' or 'strum' masks all naturally occuring ambient noise in the band from 1-10 Hz. Therefore the Rustrak record from 5-10 Hz is inappropriate for the present study.

There are two reasons for not choosing to analyze data in the 20-40 Hz and 40-80 Hz range. First, the camp used a 60 Hz generator, and the 40-80 Hz record is contaminated with electrical pickup at 60 Hz. Also, the 20-40 Hz record is conatiminated with noise emanating from a 30 Hz vibration of the generator. Second, examine the steady fall in spectral density in figure 2 after about 20 Hz. Clearly the noisiest, most energetic and active frequency band is where the spectral density is highest. As figure 2 indicates, this is in the 10-20 Hz range.

So, with respect to the discussion of the last section, the predominant and most energetic mechanisms or events which cause ambient noise in the Arctic Ocean Basin must work in the 10-20 Hz range; hence the choice of the record from 10-20 Hz for statisical analysis of ambient noise levels monitored during the FRAM IV experiment.

Please consider two final and important idiosyncrasies of the record concerning actual events which it portrayed:

i) Besides the charges which were set off for the relevant FRAM IV experiments, for periods of time spanning up to one day and totalling about one third the entire time of the experiment, a collegial Norwegian scientific team was setting off an underwater air gun. Since the airgun went off mostly at intervals spanning less than 25 minutes between consecutive shots, and the Rustrak recorder's time averaging seems to have lasted up to 15 minutes, all data taken while the air gun was in operation had to be dismissed from ambient noise analysis. The combined effect of the air gun blasts and the detonation of explosives reduced the amount of ambient noise data which could be extracted from the record to roughly one half the record's length.

ii) On 4/11 9:00 to 14:15 the record leveled off at 77 dB re 1μPa for no apparent reason. Long periods of nearly constant noise have been observed in previous experimental situations.

Examples of airgun blasts, detonation of explosives, and integration effects associated with these, are contrasted with examples of naturally occurring noise and the leveling observed on 4/11 in figure 3.

Methods of Reduction, Statistical Analysis, and Results
****

As was mentioned in the introduction, the primary objective in the reduction of the Rustrak record was to sift out all but a discrete and representative set of naturally occurring ambient noise levels. This was accomplished by:

i) omitting all man-made events, i.e. the acoustic noise resulting from TNT detonations and airgun blasts.

ii) selecting data samples corresponding to the noise level in dB re 1μPa at 15 minute intervals throughout the record. See figure 3 (1) for time and dB scale of Rustrak.

The error in selecting the correct noise level by eye was minimal. It was on the order of 1/4 dB. This estimate comes from the fact that the width of the curve printed on the Rustrak record is about 1/2 dB. The eye is only off by 1/2 the width of the curve at most in estimating its center.

The error associated with improper selection of representative ambient noise levels could be much more severe. It would seem that the only way in which such errors might occur, given peaks from air gun shots and underwater TNT explosions were intentionally passed over, would be from the failure to notice the Rustrak record's subsequent integration.

Consider the series of air gun shots portrayed in the segment of the record shown in figure 3 (2). Apparently, in the first series of air gun shots displayed the Rustrak recorder has had time to average out the initial impulse before recording the next one. For, the record appears to level off for a couple of minutes before the next pulse arrives.

However, notice that in this series of air gun blasts the record always levels off to the same value of 82 dB re 1μPa after every impulse has been integrated. If such points were included, there would be large stretches of constant noise level in the reduced or compressed record. Such segments are clearly inconsistent with data taken when the air gun was not in use and charges were not being detonated, see figure 3 (3).

Only in one case did the record level off to some constant value during a period when the water was free of artificially induced sounds as was mentioned in the last section.

Consequently, no segments of the record in which the airgun was active, including segments where the record apparently leveled off before the arrival of consecutive shots, were included in the reduced record. However, the segment from 4/11 9:00 to 14:15 is included since there is every reason to believe in its reality.

The reduced record was plotted and statistically analyzed at M.I.T's Joint Computer Facility. A condensed plot of the final version of the reduced record is given in figure 4.

Since the reduced data only took on 31 distinct integer dB values, ranging from 75 dB re 1 μPa to 105 dB re 1 μPa , a histogram was made, from samples comprising the entire reduced record, in which the frequency per count for each of the possible integer dB values was plotted against increasing dB value. This plot is shown in figure 5. The mean, and root mean square of the reduced record are 87.8 +/- .25 dB re 1 μPa and 7.1 dB respectively.

Points where data were omitted (holes or gaps in figure 4) were not included in the construction of the histogram or in the calculation of the mean and root mean square.

In order to find a time scale characterizing changes in ambient noise levels it was necessary to preserve the natural time scale of the events but somehow deal with data holes. This was accomplished by bridging the holes with a linear approximation as shown in figure 6. The mean and root mean square for this version of the data are 86.5 dB re 1 μPa and 6.4 dB respectively. Errors shall be discussed later.

To obtain the ambient noise time scale, the autocorrelation was computed. The autocorrelation function is:

8

$$A_{c_j} = \left[\frac{1}{wl} \sum_{i=1}^{lw-j} (w_i - \text{mean})(w_{i+j} - \text{mean}) \right] \left[\text{VARIANCE} \right]^{-1}$$

$$j = 1,2,3 \cdots (2263-1)$$

where lw is the length of the reduced record, w_K is a point from the graph in figure 6.

The autocorrelation is plotted in figure 7.

The time scale, T, was estimated as the time in which the initial decay of the autocorrelation reached 1/e of its maximum value of 1 at the origin. This time scale was found by graphical means, see figure 8, as T=1.46 days +/- 2 hours, where the error comes solely from reading the 1/e value from figure 8. Other errors will be considered in the discussion. Notice, however, that the error associated with reading the Rustrak record of +/- .25 dB is quite small and likely not to affect the autocorrelation nor the histogram.

Discussion
****

The two pronounced peaks in the histogram of figure 5 indicate that there were two most heavily populated noise level states over the period spanned by the reduced record (3/30 5:30 to 4/22 23:45). Notice that the centroid of the peak closer to the origin falls at approximately 84 +/- 4 dB re 1μPa and the centroid of the peak with higher dB value falls at appproximately 95 dB +/- 3 dB re 1μPa. Figure 9 explores the significance of this phenomenon with respect to the condensed plot of the reduced record.

Perhaps the presence of these two peaks in the histogram combined with the relatively long periods in which these peaks were observed without interuption, as displayed in figure 9, indicates that one type of phenomenon may be responsible for ambient noise for some extended period before giving way to another.

The presence of the peak at 77dB re 1μPa corresponds to leveling off of the record on 4/11 9:00 to 14:15. Again, it is assumed to represent ambient noise conditions.

The histogram of figure 5 is representative of the relative frequency of noise level states over the entire period of the reduced record regardless of the omission of approximately one half of all possible samples. This is so because:

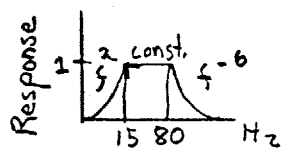
i) the omissions were entirely random, because the choice of time and day to set off explosives or the air gun was entirely random with respect to naturally occurring underwater ambient noise conditions;

ii) an increase or decrease in the number of random samples will only increase or decrease the resolution and absolute magnitude of the peaks displayed in the histogram of figure 5, not their general shape.

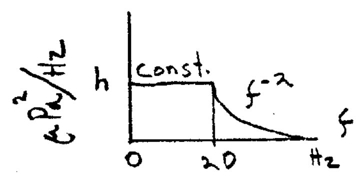
Whether the time scale derived from the autocorrelation is representative of the actual scale of underwater ambient noise levels over the sampling period of the reduced record depends primarily upon how accurately the approximation to the reduced record mimicked what might have happened in the absence of artificial disturbances. Certainly, the mean remained close; it was 87.8 dB re 1μPa in the original reduced record and 86.5 dB re 1μPa after the approximation. However, as may have been expected from the inclusion of so many straight line segments, the variance changed somewhat with this first order approximation; the original reduced record had a standard deviation of 7.1 dB and the linear interpolation to the reduced record had a standard deviation of 6.4 dB.

Finally, noise levels recorded via the Rustrak were very consistent with noise levels recorded digitally on magnetic tape via more precise apparatus. For example, consider the following estimate:

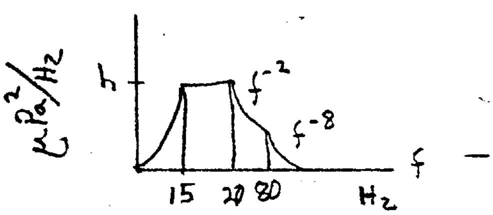
Peter Stein took data from magnetic tape recordings corresponding to noise levels measured from 2:07 to 2:27 on 4/20/82 by integrating over consecutive two second windows. His filter characteristics were



Assuming the noise spectrum level which he filtered had the characteristic suggested by figure 2,

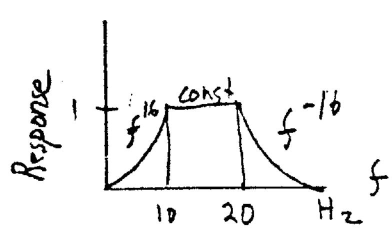


the resultant noise for any two second window is the area under the following curve

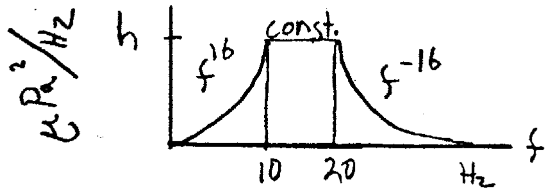


This area is $$\int_0^{15} h\left(\frac{f}{15}\right) df + \int_{15}^{20} h\, df + \int_{20}^{80} h\left(\frac{20}{f}\right)^2 df + \int_{80}^{\infty} h\left(\frac{80}{f}\right)^8 df = 26h$$

The Rustrak system had a filter characteristic



The characteristic frequency spectrum of the noise to be filtered by the Rustrak is, of course, the same as the one filtered by the digital tape system. The resultant noise for any point in the reduced record is the area under



where h is the same in both cases. The area under this curve is

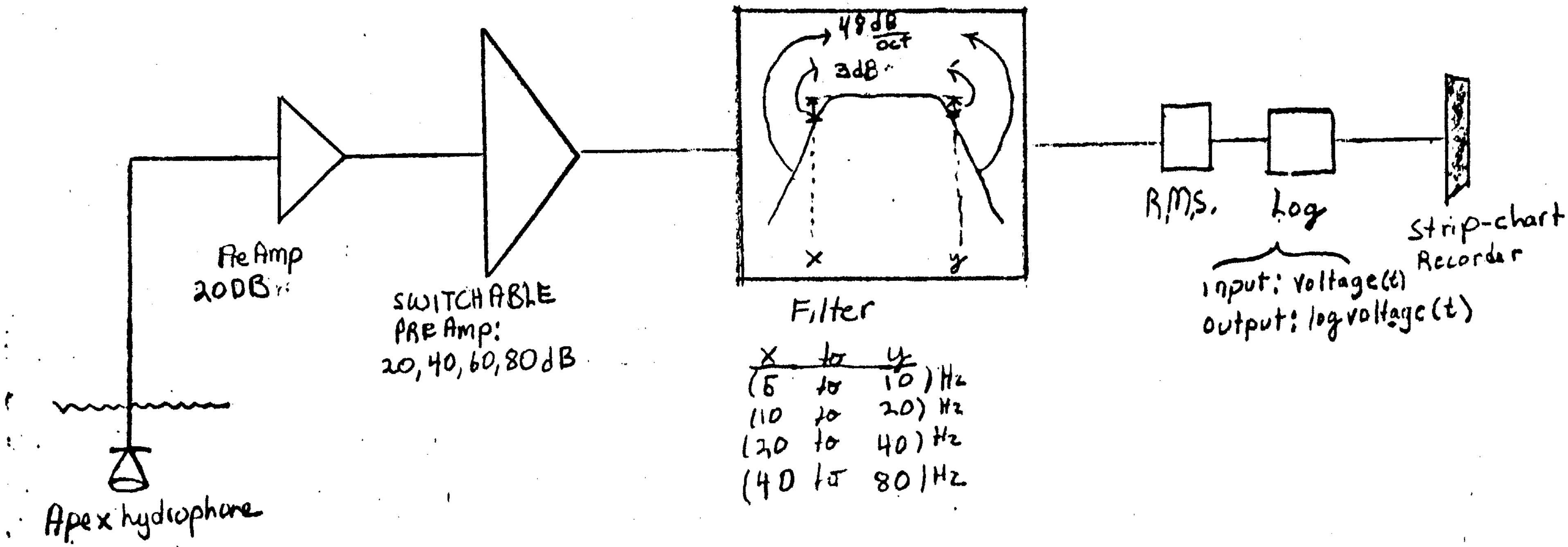
$$\underbrace{\int_0^{10} h\left(\frac{f}{10}\right)^{16} df}_{\text{small}} + \underbrace{\int_{20}^{\infty} h\left(\frac{20}{f}\right)^{16} df}_{\text{small}} + 10h = 10h$$

So, the expected difference between the two measurements due to their different filter characteristics is on the order of

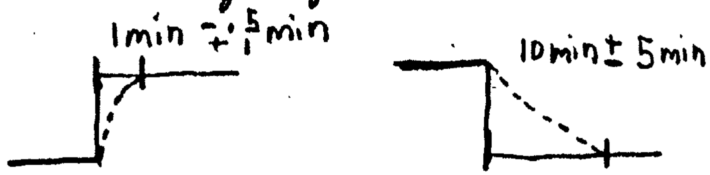
$$L_p\Big|_{\substack{mag\\tape}} - L_p\Big|_{Rustrak} = 10\,\mathrm{Log}\,\frac{26}{10} \cong 4.1\,\mathrm{dB}$$

Over the period of the magnetic tape data, there was a large 'hole' in the reduced record due to airgun shots. So, a comparison had to be made between such data and a corresponding point representing an approximation to the reduced record. The difference between these two points is approximately 5 +/- 1 dB. So, the correlation between the linear approximation to the reduced record and the more precise data recorded magnetically is rather good. Several other similar correlations have been made between data on magnetic tape and actual segments of the reduced record. The discrepancy was never more than one dB.

Fig. 1

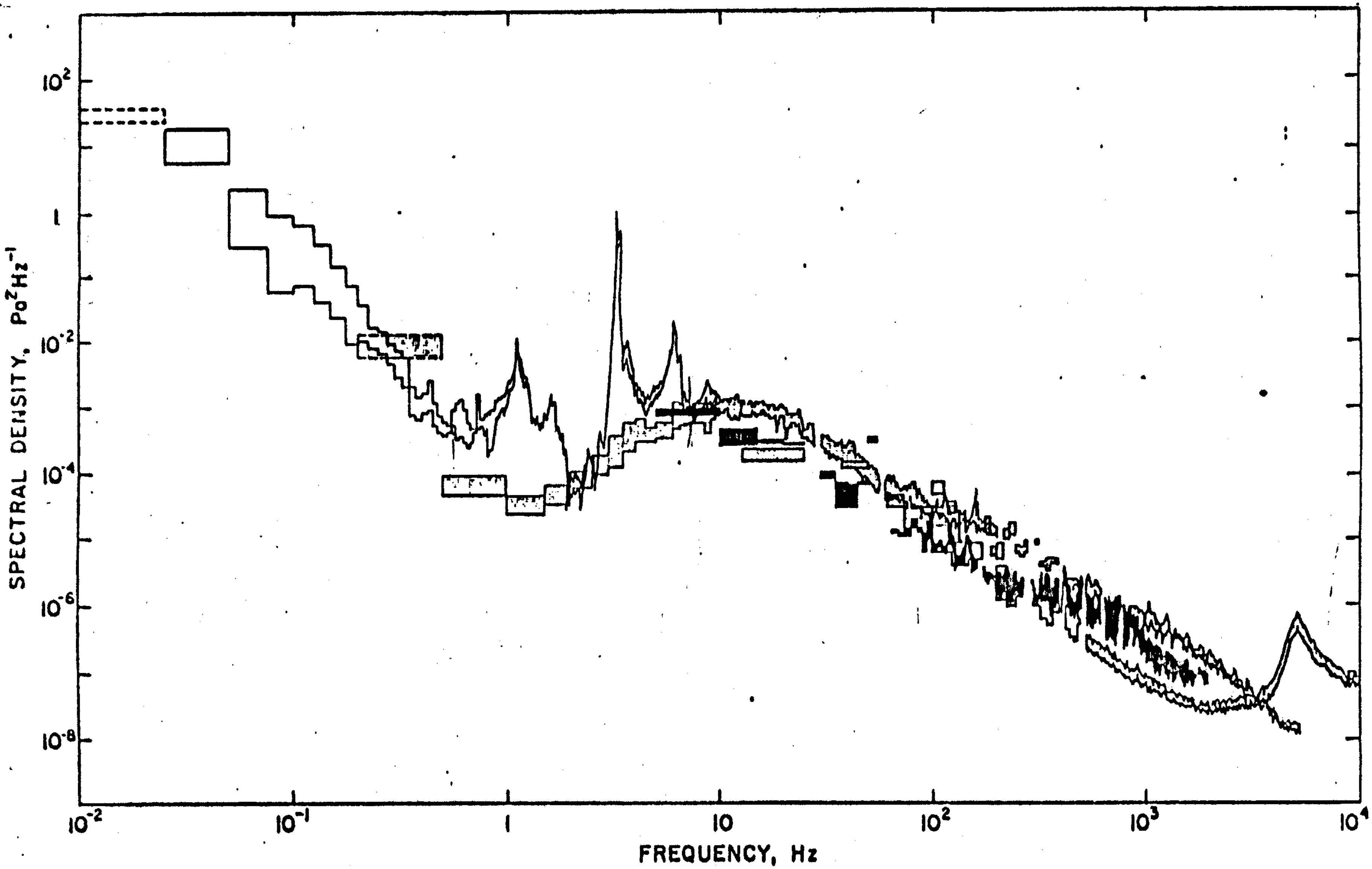


R.M.S. takes square of signal, V^2, the time average of V^2: $\frac{1}{\tau}\int_0^{\tau} V^2\,dt$, and square root of time average of V^2 is the output. Characteristic values for τ in a step function are:



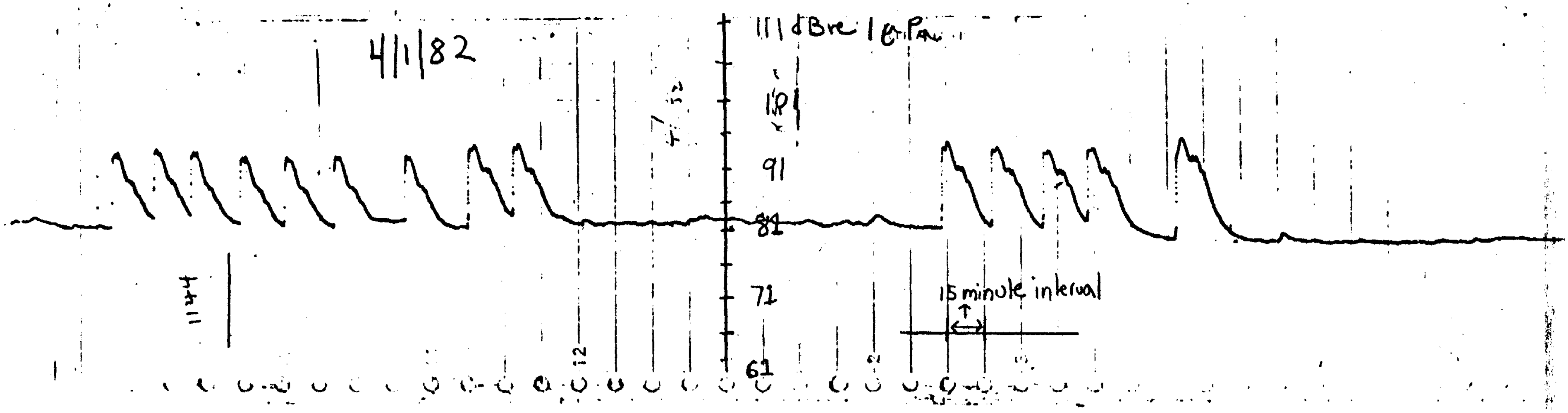
according to designer Jasko Catipovic[1].

FIG.2



REPRESENTATIVE AMBIENT NOISE SPECTRUM[2]

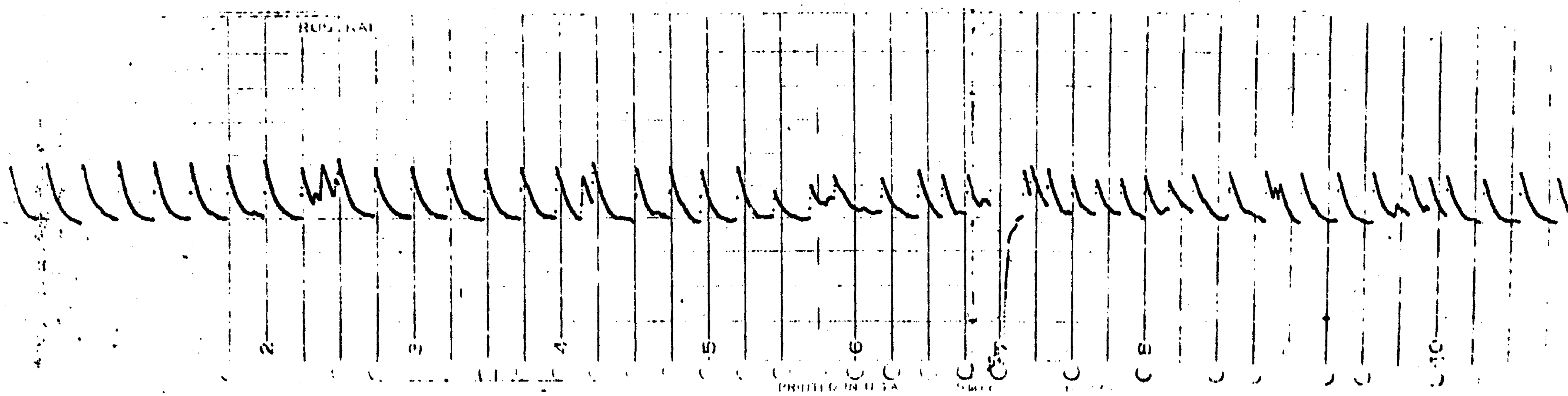
FIG 3(1)



EXAMPLE OF TNT BLASTS AS MEASURED WITH THE APEX HYDROPHONE AND RECORDED BY THE RUSTRAK SYSTEM. NOTE TAILS AFTER EACH BLAST CORRESPONDING TO THE RUSTRAK'S INTEGRATION. (SCALE IN THE FOLLOWING SERIES IS THE SAME AS ABOVE)

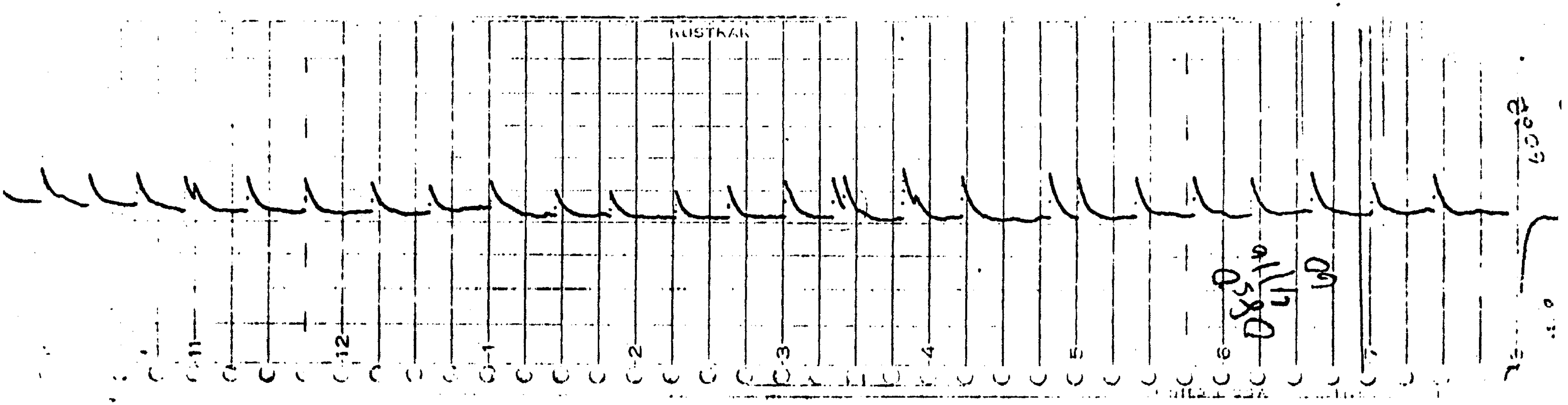
FIG. 3(2)

EXAMPLES OF AIRGUN SHOTS FROM THE RUSTRAK RECORD



4

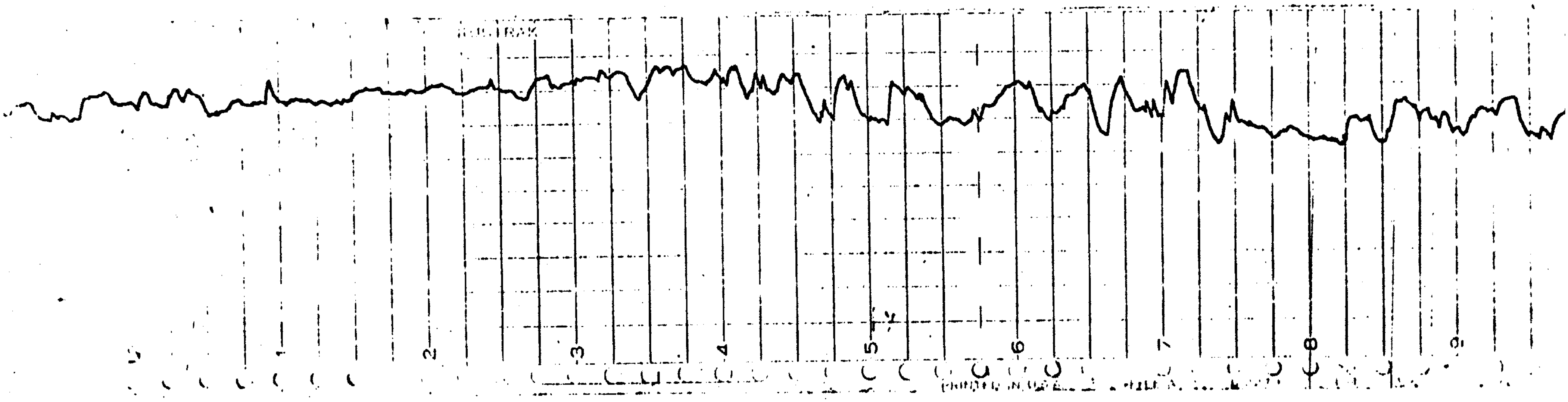
DENSLY PACKED, NO LEVELING BETWEEN SHOTS..



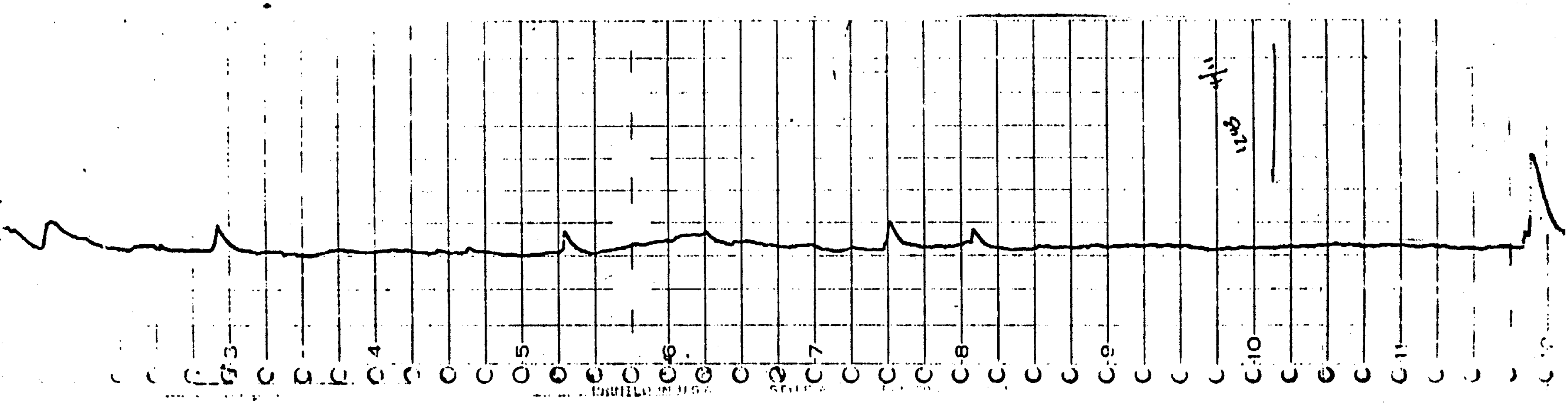
5

MORE SPARSELY PACKED WITH LEVELING BETWEEN SHOTS.

FIG. 3(3)

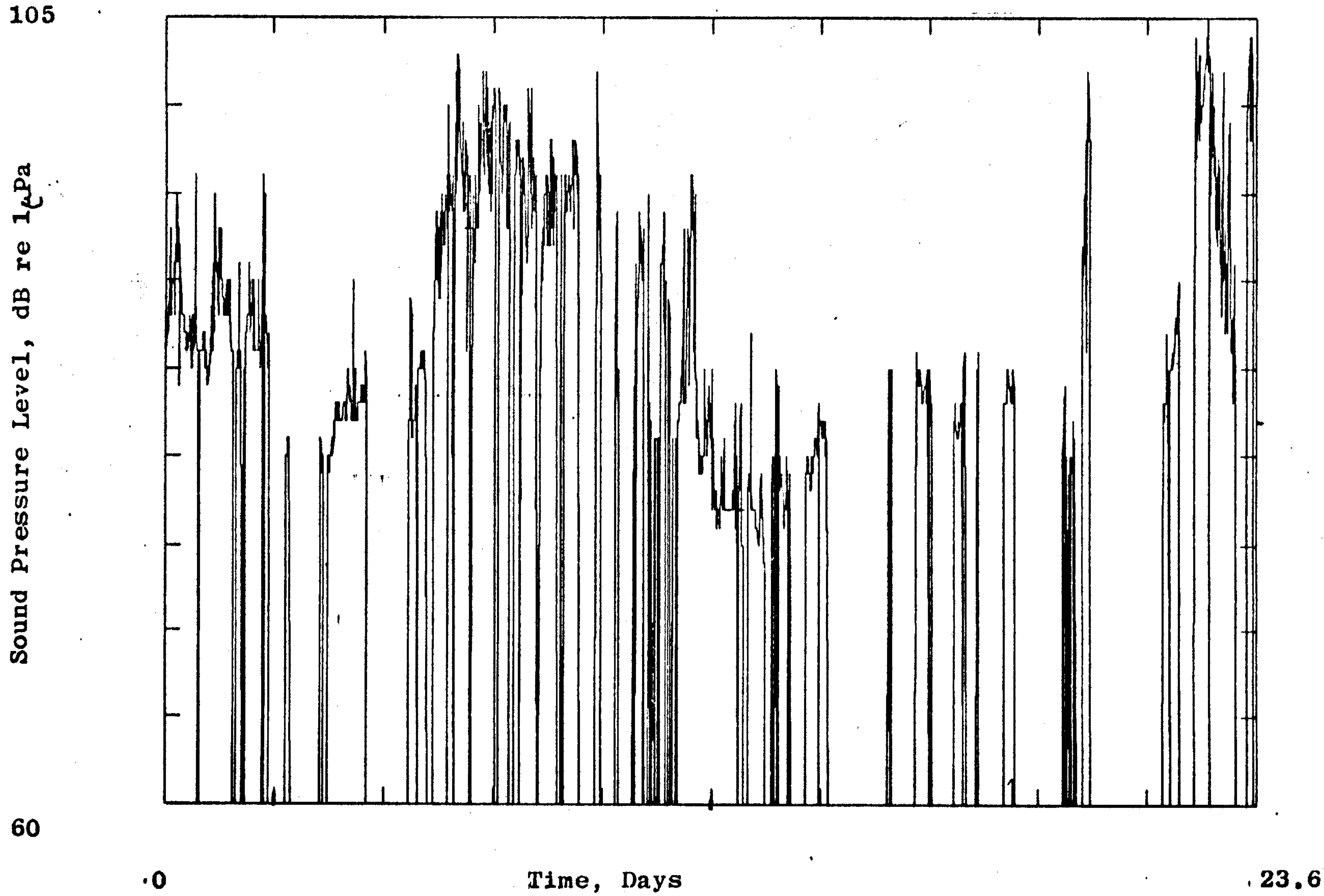


TYPICAL AMBIENT NOISE AS OBSERVED BY RUSTRAK RECORDER[6]



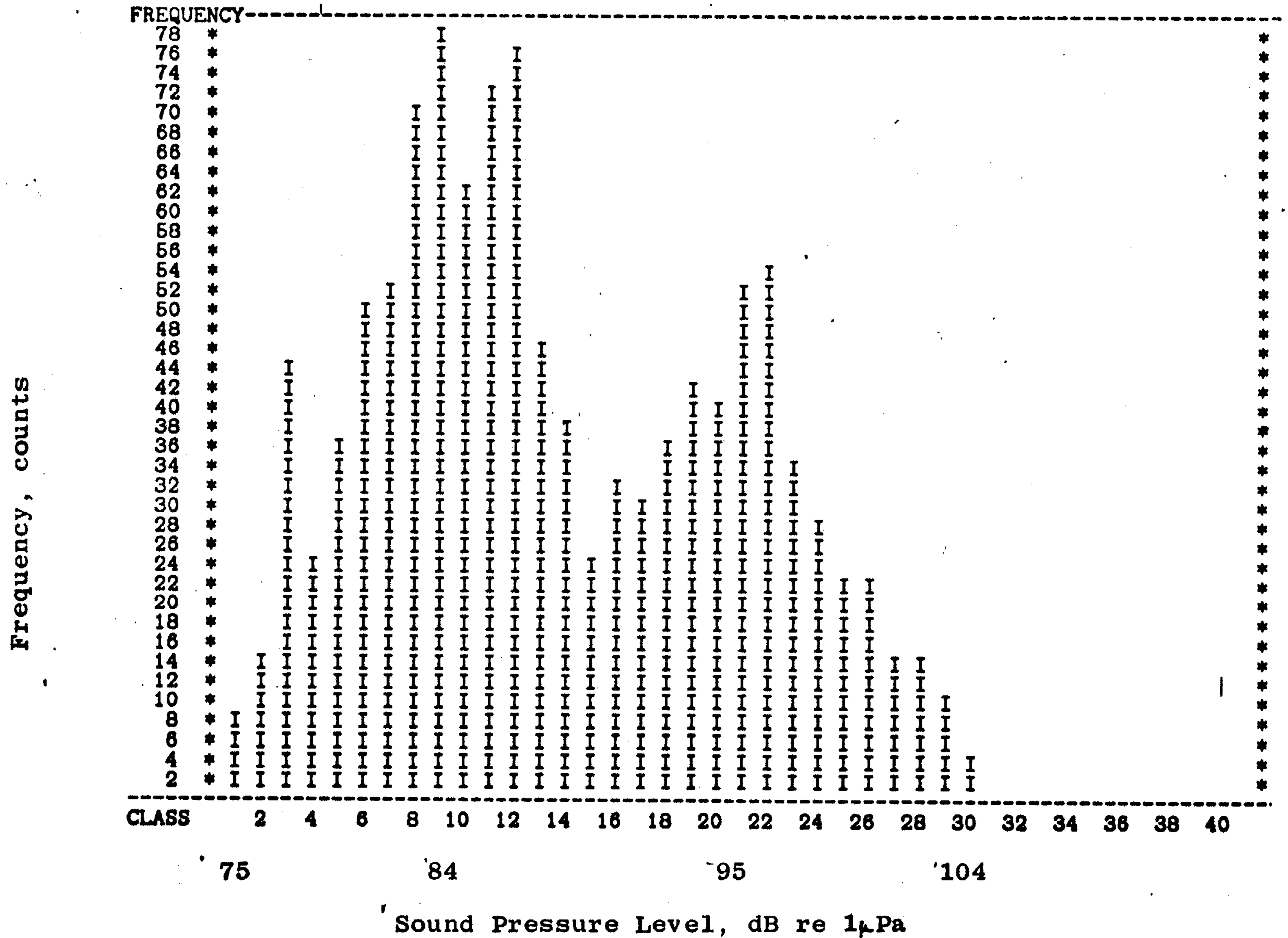
LEVELING OFF OF THE RECORD AT 4/11 9:00 to 14:15

FIG. 4



<u>Reduced Record (Condensed Plot)</u>
2263 points at 15 minute intervals
1112 null points (data contaminated and therefore nulled)

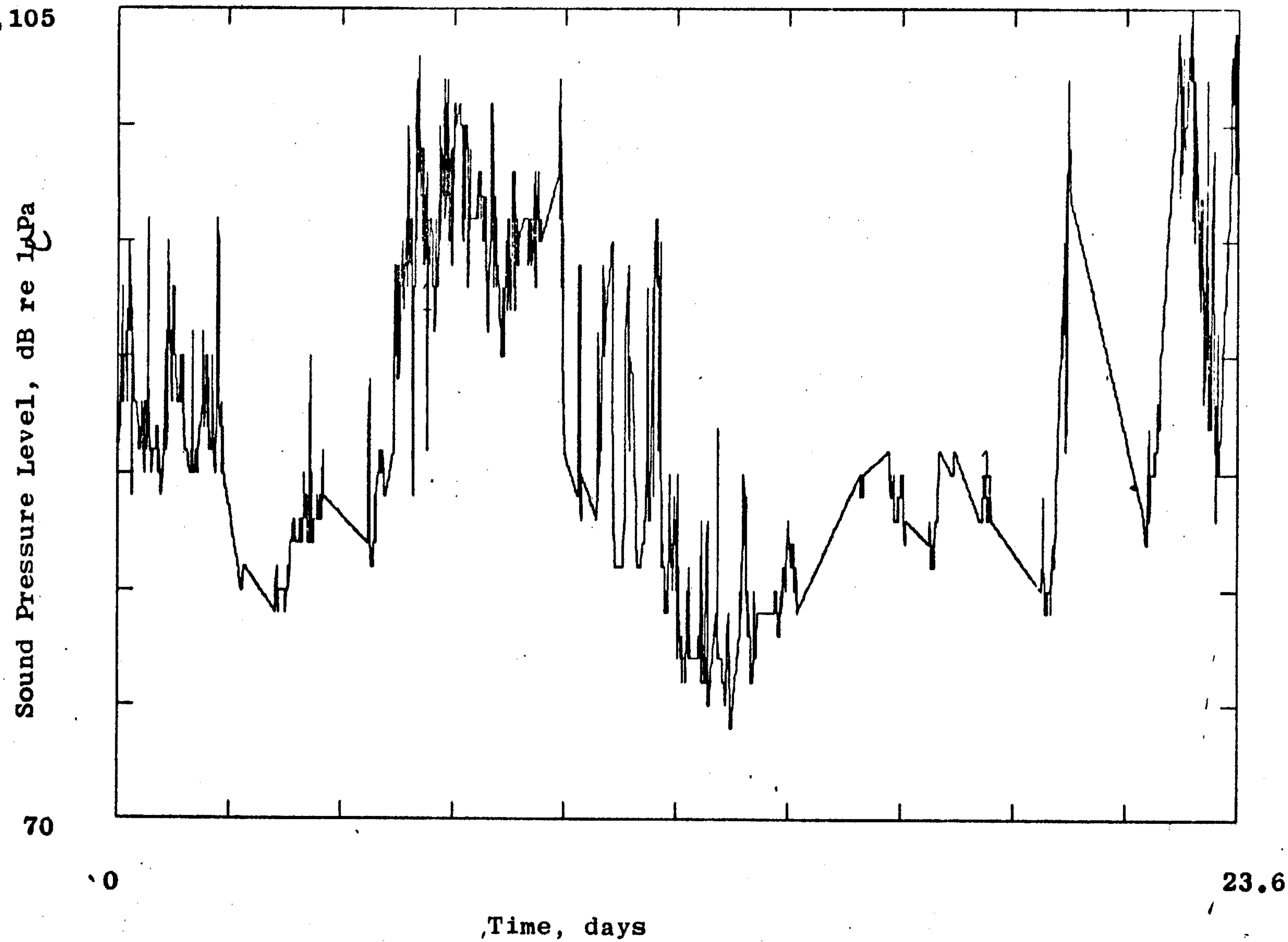
FIG. 5



<u>Histogram of Sound Pressure Level</u>

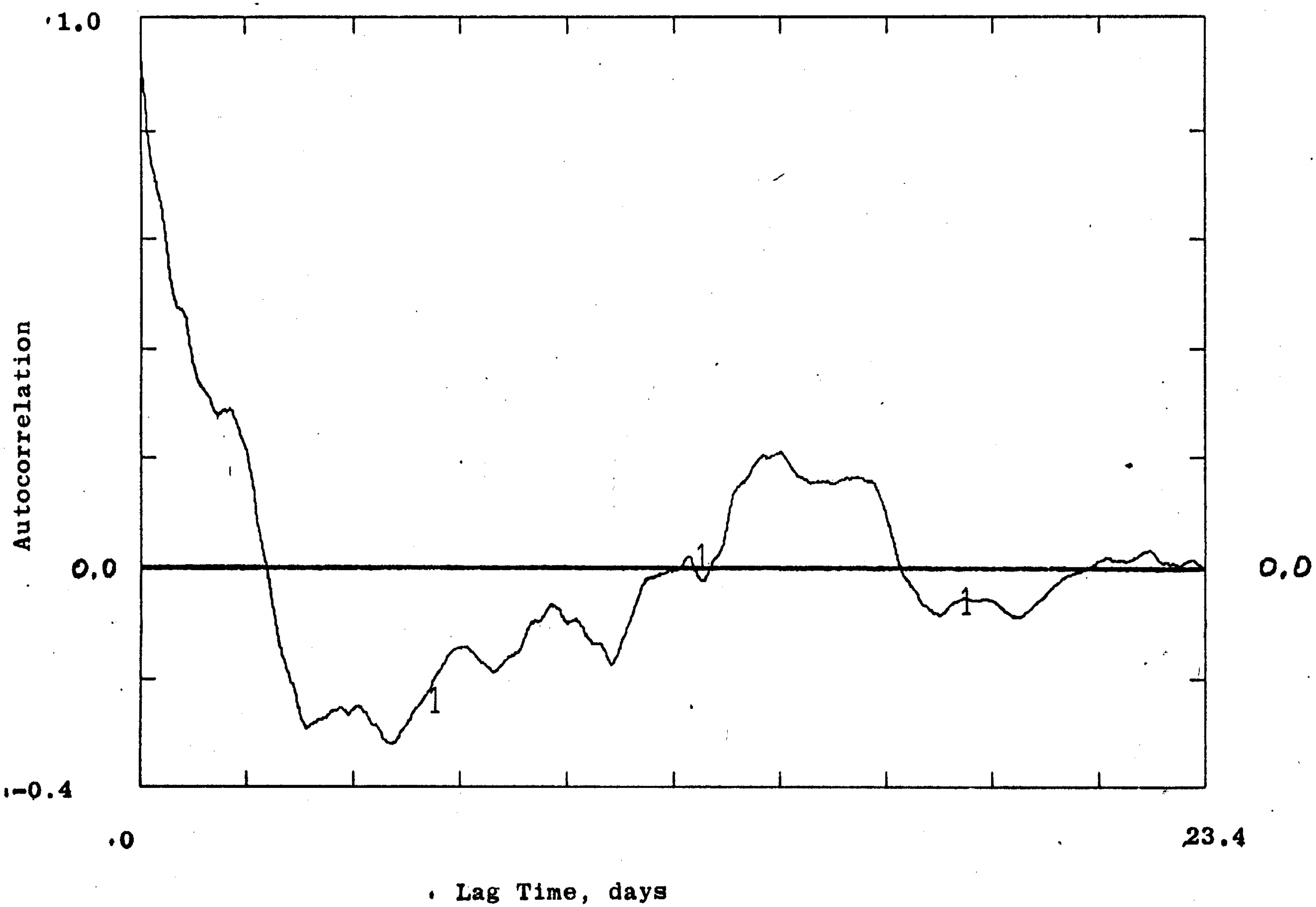
consisting of 1151 non-empty points of the Reduced Record

FIG. 6



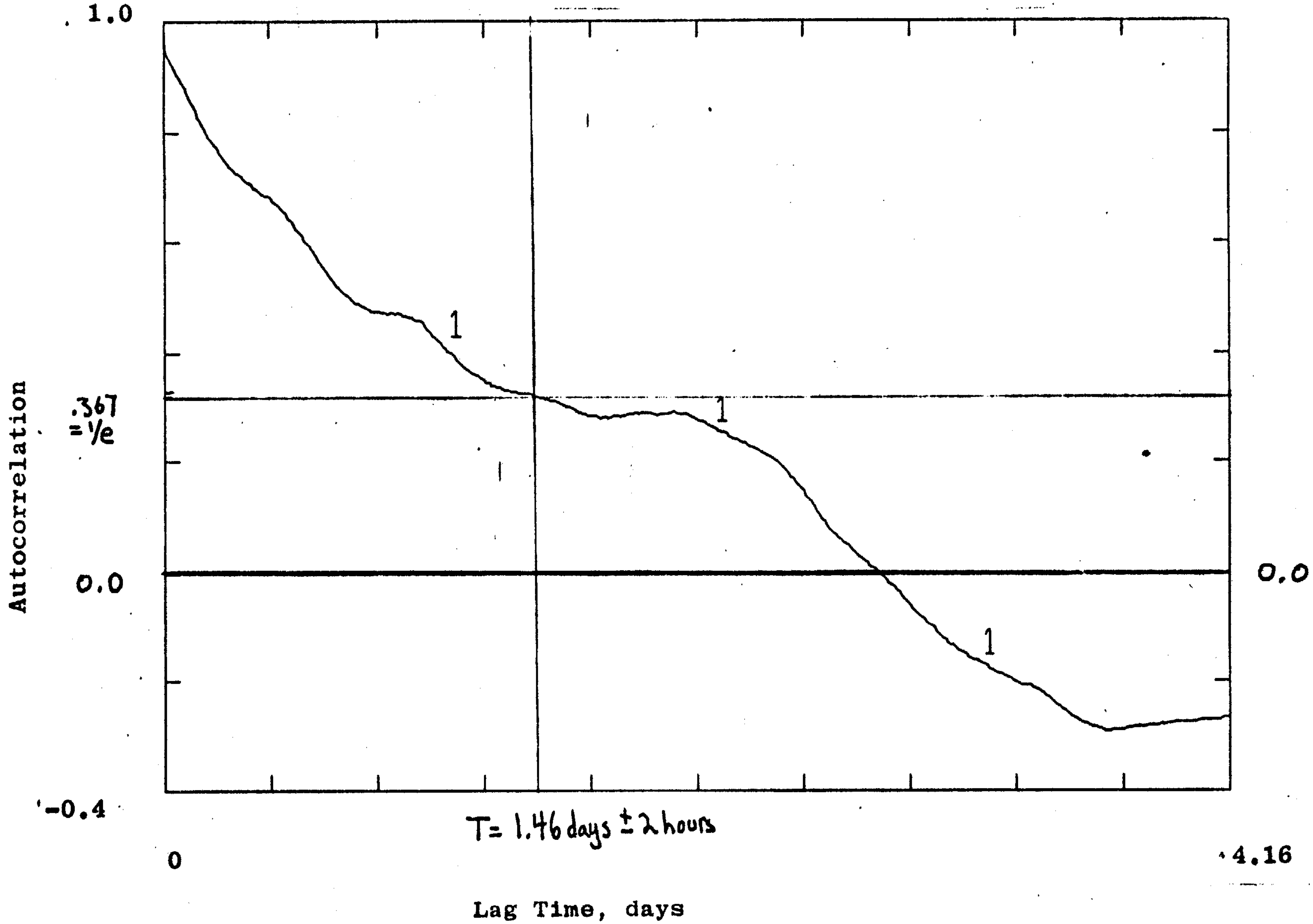
Reduced Record with a linear interpolation spanning the 'holes'

FIG. 7



Autocorrelation of the Reduced Record (Figure 6)

FIG. 8



<u>Blown up version of the Autocorrelation from 0 to 4.16 days in which the time scale T is derived.</u>

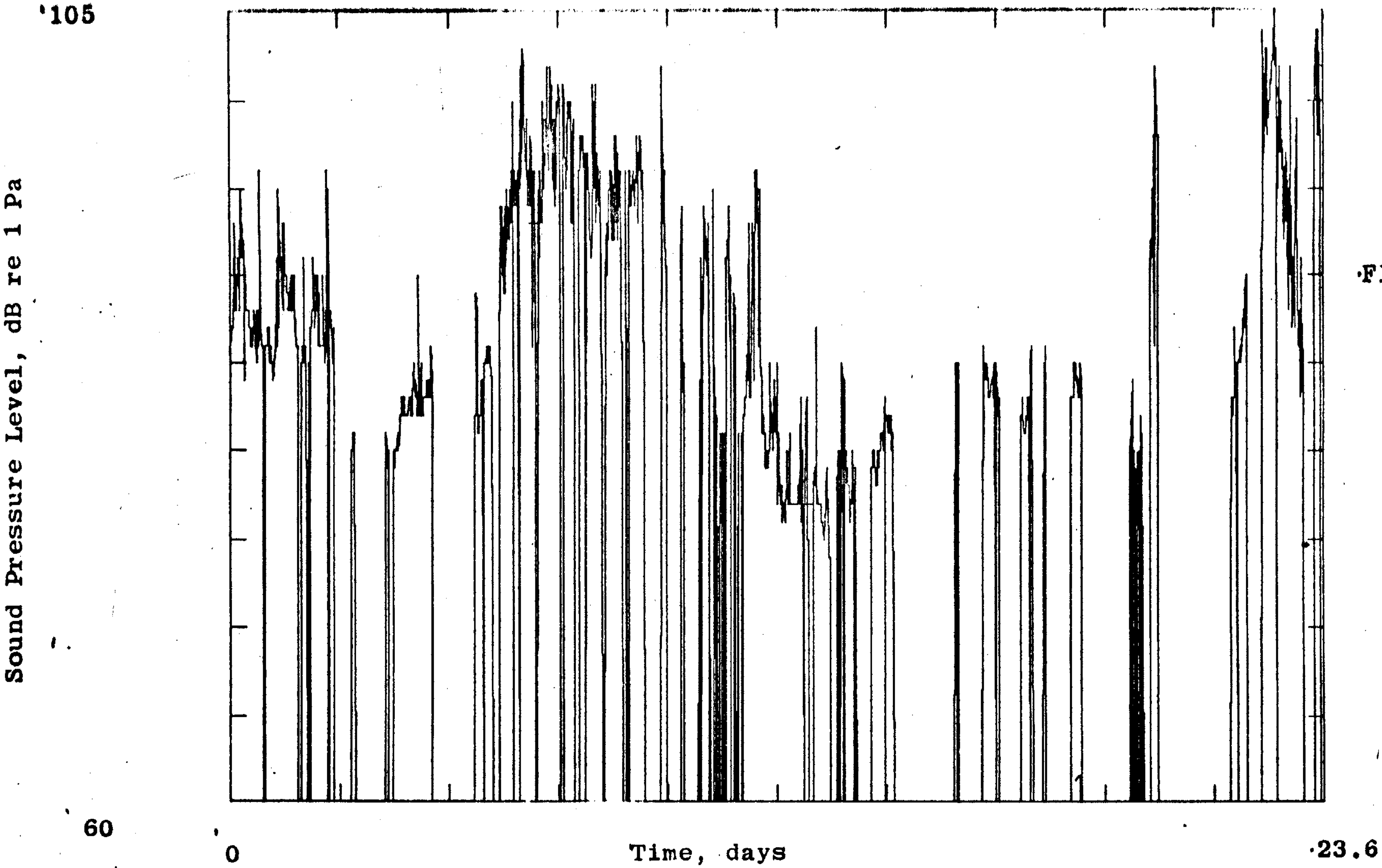


FIG. 9

<u>Analysis of Some Segments of the Reduced Record</u>

Time segments A and C, both approx. 2.3 days, comprise the primary contribution to the 84 dB paek in the histogram, FIG.5.

Time segment B, approx. 3.4 days, is the primary contribution to the histogram's peak at 95 dB.

Time segment D, approx. 1.9 days, is a good example of rapid change in noise level and is quite opposite from the relatively constant segments A,B, and C.

So, notice that the main peaks of FIG. 5 had primary contributions from time segments in which the noise level remained relatively constant.

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2. I. Dyer, The Song of Sea Ice and Other Arctic Ocean Melodies, The Robert Bruce Wallace Lecture: 2 March 1983 M.I.T.

3. FRAM IV's Rustrak Record 4/1/82 10:00 to 20:00

4. " " 4/20/82 12:00 to 22:00

5. " " 4/16/82 3:00 to 11:00

6. " " 4/21/82 18:00 to 4/22/82 4:00

7. Peter Stein is also a graduate student in the M.I.T.,W.H.O.I. joint program.

8. M.I.T. J.C.F., Description of Scientific Subroutines, under FTAUTO.