A Model of a Shallow Water Hydroacoustical Communication Channel

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The pulse response of a horizontal hydroacoustical communication channel is measured in shallow water environment at a location in the Adriatic Sea. From the experimental data statistical characteristics of the error and good channel states are extracted for different bit error probabilities, and they are fitted to some descriptive channel models until the χ^2 test is satisfied. Application of the model to the testing of data protection codes is illustrated.

Keywords: hydroacoustical communication, shallow water, communication channel, channel model, data protection codes, Marlov-chain model.

1. Introduction

Underwater acoustic communications have been proved as an applicable communication channel but high data rates have been achieved at short ranges or in near vertical bottom to top acoustic paths. Solutions have been offered for different applications [1]. Acoustic communication channel could be modeled as time-varying stochastic filter corrupted with Gaussian noise. To improve reliability of the communication through water, attention has been paid to channel modeling and signal processing [2].

Further performance increase could be achieved through appropriate error correcting procedures such as automatic repeat request (ARQ) schemes [3].

Due to the fading and multipath of underwater acoustic channels direct application of standard forward — error — control (FEC) correcting techniques is prevented. In order to improve the error rate in data transmission, error correcting codes are used. The application of these codes is difficult, because of the presence of error bursts.

The average bit error rate in the channel is not sufficient to describe the condition in the communication channel. In the case of convolutional codes, the Gallager bound

$$\frac{g}{b} \geq \frac{1+R}{1-R}$$

should be consideraed if it is necessary to correct all bursts of length b or shorter than b. Here b is the length of burst, g denotes guard space between errors, and R is the code rate. To evaluate the effectiveness of error correcting codes, statistical characteristics of error bursts, as well as of good periods between bursts should be taken into consideration. Statistical characteristics of errors in the channel are also important for block and interleaved codes performances.

In one of the approach, as a mathematical model of the channel was used [4],[5], but the channel model could as well be based on experimental data, as was done with some other types of communication channels [6].

To improve data transfer performances of hydroacoustical communication devices [7] digital frequency_shift_keying (FSK) is commonly used, together with frequency diversity.

The most severe and locally dependent conditions are known to be found in a horizontal shallow water acoustic channel. In such complex environment, models based on experimental data have special importance.

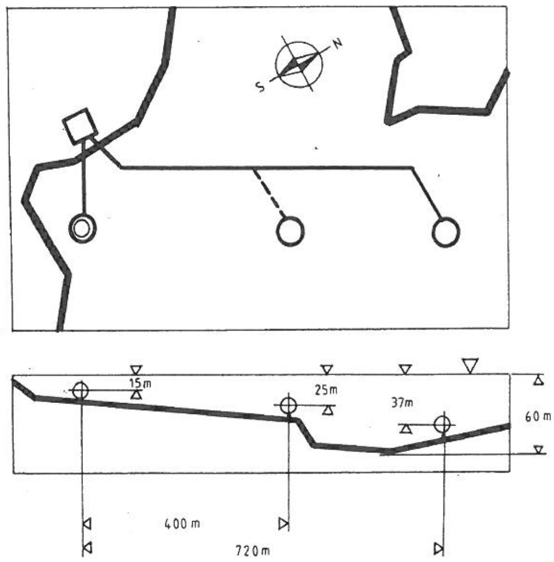

Fig. 1. Measurement location with depth profile

2. Experimental measurements in the Adriatic Sea

The measurements were performed at a location with a slightly inclined sea bottom, close to the Smokvica Island, about 50 km southeast of the town Sibenik. In many aspects this location is (depth, bathythermograpichal conditions, bottom characteristics, sea conditions) a good representative of inter-island channels along the Croatian seashore. The data were measured on several occasions during spring and autumn in the period from 1986 onward. The measurements were generally performed in the morning at sea state 0 to 1.

Mostly due to the Doppler effect caused by reflection from surface waves, frequency of emitted signal was slightly spread. Every surface reflection changes emitted frequency for about

$$\lambda = \frac{v}{c} f \, [Hz]$$

where v is the velocity of surface waves, c is the velocity of sound in the water and f is the frequency of emitted signal.

During measurements the expected frequency spread was calculated to be around 50 Hz, and could be neglected in comparison with amplifier bandpass width of 6 KHz. As in the previous experiments at the same location time spreads of 10 ms pulse were observed to be up to 40 ms, the time spread was taken into consideration when choosing the parameters of transmitting signal.

The basic measurement scheme is presented in Fig. 1. A signal generator (Bruel & Kjaer (BK) 1027) with a power amplifier (BK 2713) and an omnidirectional projector (Brodarski Institute (BI) HP 28) was used in transmission. In later experiments, done for the same purpose, a DU 03/Pd, hydroacoustical communication device of own design [8] was used. There was an omnidirectional hydrophone, BI HM 85 at the receiving side and received signal was recorded on a tape recorder (BK 7005).

Bathythermographical information was collected by Grundy 4316 unit.

At the sea bottom, at a depth of about 15 m, a projector was placed, and 400 to 720 m away from it, at a depth of about 35 m, there was a hydrophone. The bottom at the measurement location is covered by sand and mud.

On the basis of the measured bathythermographical data, a simple ray tracing was calculated. The results are presented in Fig. 2.

A pulse train was used for the transmitted signal. Short bursts of a sine wave at 25 kHz were repeated every 100 ms, and $T = 1$ ms, 3ms and 10 ms were used as burst lengths for different measurements.

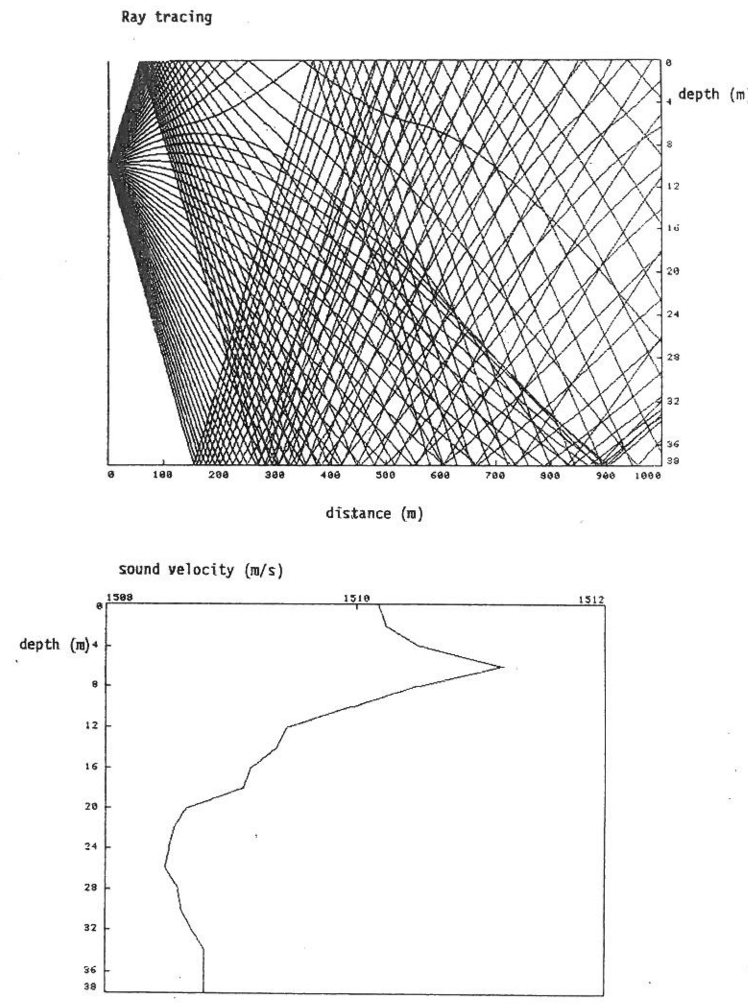

Fig. 2. Sound velocity depth profile and ray tracing

In the laboratory, the signal processing suitable for FSK modulation was applied. The recorded analogue signals were amplified, filtered with a bandpass filter, centered on 25 KHz with a bandwidth of 6000 Hz, half_wave rectified and suitably low_pass filtered, then sampled at a rate of 5 kHz (in the case of 1 ms and 3 ms pulse length) or 1 kHz (10 ms pulse length data) and stored on a disk.

An example of the stored data related to the pulse train with 3 ms bursts is presented in Fig. 3. In addition to the pulse train denoted by ∇ in Fig. 3, pulse noise can be also observed.

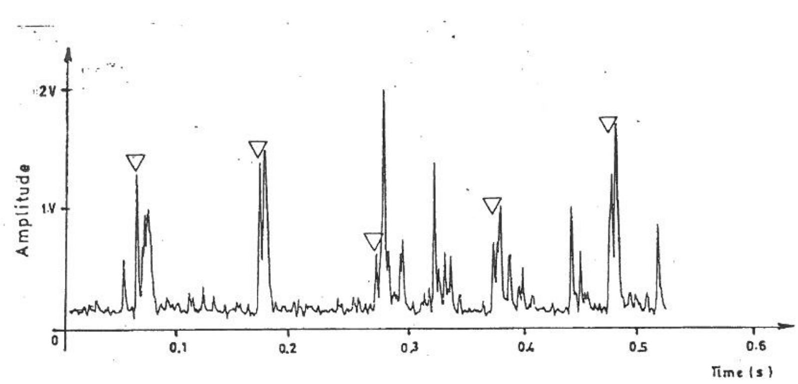

Fig. 3. Received pulse train

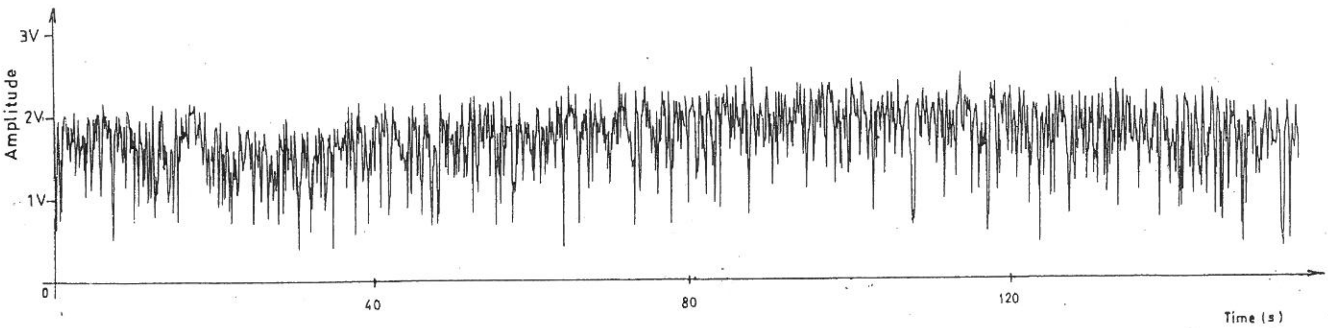

Fig. 4. Time sequence of envelope peaks

3. Amplitude peaks envelope fluctuations

A fast software implemented peak detector initialized for every burst was used to find the peak in the envelopes. The program detects amplitude peak value together with the information about the time delay relative to the first input data. As the transmitted signal was precisely time-defined, it was easy to find out if and when the program loses the synchronization (due to noise in received signal) with the emitted pulse train. In this case, the doubtful parts of input data were checked and, if necessary, the corrected value was written into the output data file. On different experimental data about 0.8% to 1,5% of the values were checked in this way.

The amplitude fluctuations (sequence of envelope peaks) presented in Fig. 4. make an example of the channel response to a pulse train excitation in a shallow water horizontal hydroacoustical channel. The typical sequence length measured was between 8 and 15 minutes.

Distribution of the envelope amplitude peaks was obtained from the time sequence data for each of the tests. As a next step, the threshold amplitude value of anvelope peaks was chosen, so that the required percentage p of the amplitude greater than $A(p)$, was obtained. For FSK (or MFSK) modulation in the data transmission, p represents the bit error probability. The purpose was to obtain data sets with the same biterror probability from different measurements (and with the different threshold values).

This procedure is correct only when the ambient situation is taken into consideration, because in a channel with large time spread the inter symbol interference will occur. Inter symbol interference is usually suppressed by using techniques such as frequency diversity. When frequency diversity is properly matched to channel characteristics, amplitude threshold can be used again to calculate the bit error probability. Some other techniques such as spatial diversity can be used for multipath channels as well.

Besides, from the experimental data it is also possible to obtain continuous time periods whose the amplitude values are greater than $A(p)$. Such periods could be named "good" channels. Of course, for the amplitude values less than $A(p)$, continuous time periods represent error state in the channel. On each set of experimental data different of bit error p values were applied.

Frequency histogram of continuous time period of a "good" channel for measured one set of data is presented in Fig. 5. and that for error state in the channel in Fig. 6. Absolute frequency of occurrence is shown on the vertical axis and the time length periods on the horizontal one. The data in Figs. 5. and 6. do not represent the data obtained from the same experiment.

For typical p values between 0.90 and 0.98 in hydroacoustical communication, "good" channel states could have 5 to 10 seconds length, and error periods are usually under 0.5 second, as can be seen from the frequency of occurrence histograms in Figs. 5 and 6.

4. Hydroacoustical channel model

Statistical properties of the experimental data were compared to some descriptive models of channels. The results were evaluated according to the χ^2 test for the "good" and the error state of the channel respectively.

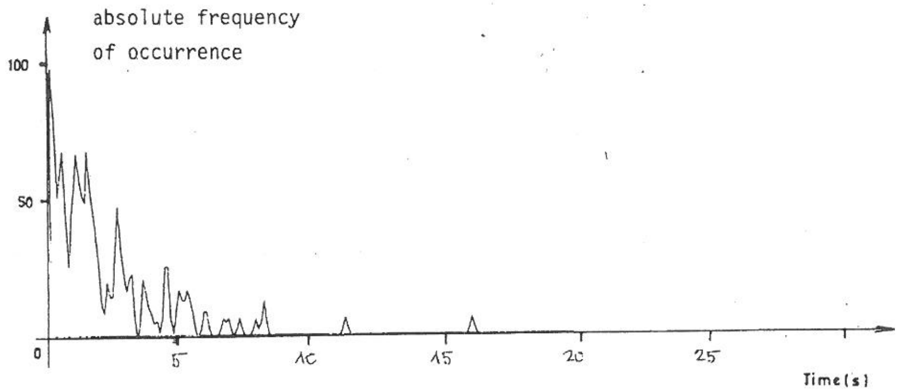

Fig. 5. Frequency histogram of continuous time periods for "good" channel

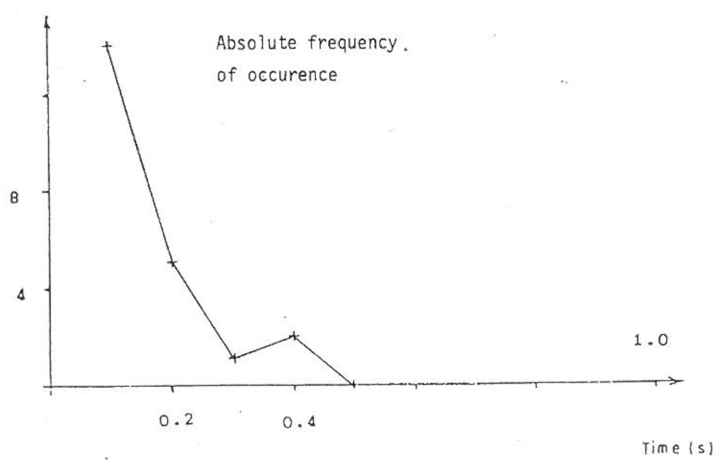

Fig. 6. Frequency histogram of continuous time periods for error state in channel

The χ^2 test involves the use of statistics with an approximate chi-square distribution as a measure of discrepancy between an observed probability function and the theoretical density function. A hypothesis of equivalence is then tested by studying distribution of these statistics.

From the experimental data the numbers of observations falling within the ith class interval, called observed frequency in the ith class and denoted by f_i, were taken. The number of observations expected to fall within the ith class interval if the true probability density function of x was $p(x)$ is called expected frequency in the ith class and denoted by F_i, were calculated from tested model. Discrepancy between the observed and expected frequencyes within each class interval is given by $f_i - F_i$. Values' $f_i - F_i$, i is random variable's which are elements of normal distribution with standard deviation σ_i.

The sum can be obtained as

$$X^2 = \sum_{i=1}^{k} \frac{(f_i - F_i)^2}{F_i}.$$

A hypothesis that experimental data have probability density function $p(x)$ can be evaluated considering the number of degrees of freedom n. In this evaluation $K - 1$ were chosen and a level of significance comparing X^2 with $\chi^2_{n,\alpha}$ values was calculated or taken from statistical tables.

A simple Markov_chain model of the first order was chosen as a model of communication channel. The model had two types of states, error_free states and error states. In the model,

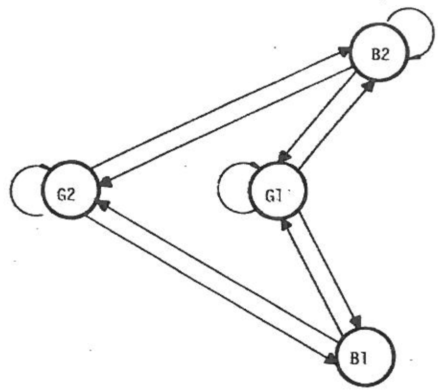

Fig. 7. **Channel model**

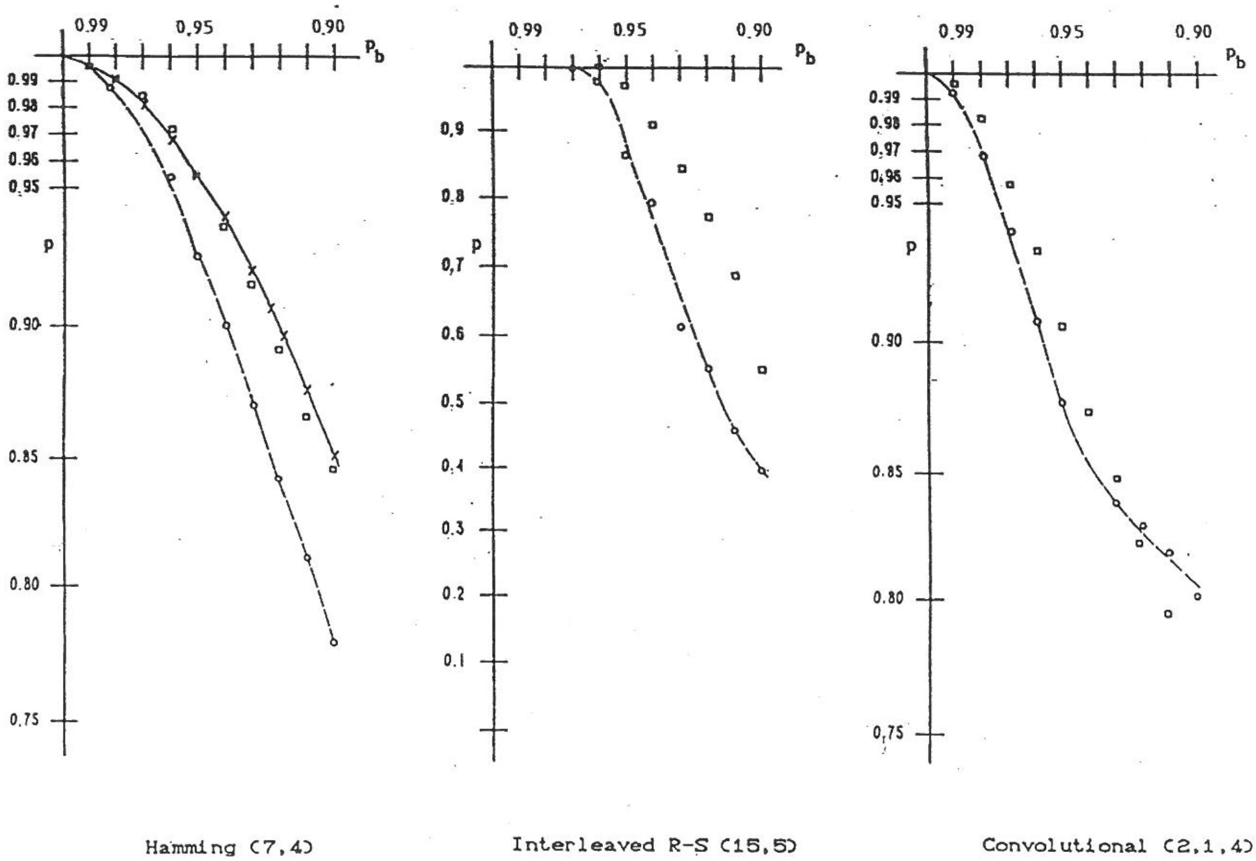

Fig. 8. Performance for some codes when acoustic channel error patterns were applied in comparison with random error channel

good states are denoted by $G1$ and $G2$ and error states by $B1$ and $B2$. From Fig. 7. it can be observed that the $B1$ state will be followed by a good one ($p_{b1b} = 0$, generating random errors) and $B2$ could generate bursts of errors. For each average bit error p_b in the channel, a different set of matrix coefficients was obtained. For an average bit error $p_b = 0.99$, p_{g1b2} and p_{g2b2} become 0, leaving only random errors in the channel model.

The probability transition matrix for the model is given by:

$$P = \begin{bmatrix} 0 & 0 & p_{bg1} & p_{bg2} \\ 0 & p_{b2b2} & p_{bg1} & p_{bg2} \\ p_{gb1} & p_{gb2} & p_{g1g1} & 0 \\ p_{gb1} & p_{gb2} & 0 & p_{g2g2} \end{bmatrix}$$

Statistical characteristics were separately tested for error and for "good" states. As for the error state, in 65% of tests, hypotheses were confirmed by the experimental data with $\alpha > 0.98$, and in the worst case $\alpha = 0.817$.

For the "good" channel model, the results were compared to the experimental data for the average bit error in channel $p = 0.90$ and the hypotheses were confirmed with a probability ranging from $\alpha = 0.417$ to $\alpha > 0.99$ [9].

5. Computer simulation

During computer simulation, different codes were tested against the error patterns generated by the hydroacoustical channel model and the random error generator. The error patterns were generated for expected typical channel bit error rates (p between 0.9 and 0.99). Some of the results are presented in Fig. 8., where the data for the random channel are represented by squares and the hydroacoustical channel model by circles. The data from theoretical calculations for the random channel, where performed, are marked by +.

In Fig. 8. the average bit error rate in the channel is given on the vertical axis and the bit error rates after the error correction with applied code are given on the horizontal axis.

The examples for convolutional burst error correcting codes were chosen from Volkov [10].

The compound nature of the hydroacoustical channel, having random errors and bursts of errors, selectively degrades the performance of different codes.

6. Experimental verification

The computer simulation results were compared to the code performance in shallow water environment. For experimental verification, a communication device DU 03 [8] was used. Because of the device limitations, only a simple Hamming code was used for testing.

A projector and a hydrophone, some 120 m apart from each other, were located at the sea bottom, at a depth of about 18 m. The location and its parameters were the same as in earlier experiments and are presented in Figs. 1. and 2.

In order to obtain different signal to noise ratios (and different bit error probability's p) in the channel, the data were transmitted at an appropriate amplitude level calculated from the previous experiments, using an analogue amplifier (BK 2713) added to the transmitter part of the DU 03. Due to the efficiency in error correction, it was possible to find out whether the errors in the channel were randomly distributed, or they followed expected values calculated from the model. The results are presented in Fig. 9.

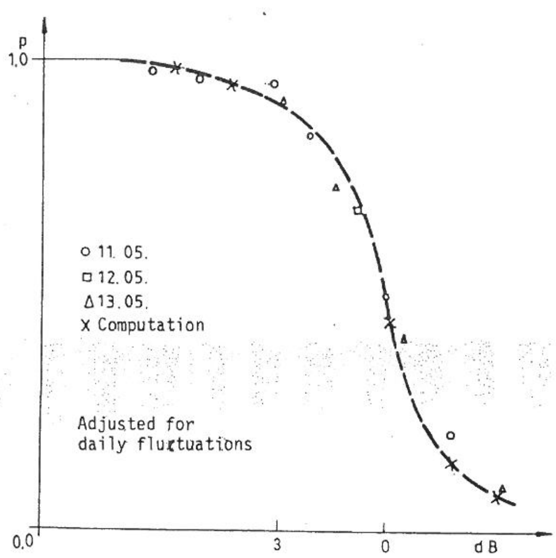

Fig. 9. Code performance in shallow water enviroment

7. Conclusion

A shallow water hydroacoustical channel model was developed as a simple Markov_chain model of the first order. The model has two types of states, an error free state and an error state. The probability transition matrix parameters of the model were chosen to match the experimental data measured at a shallow water location in the Adriatic Sea. The model can be used for performance prediction of the data protection codes in underwater acoustic communication.

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