N72 32182

NASA TECHNICAL MEMORANDUM

NASA TM X- 68135

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A DIGITAL SIMULATION OF MESSAGE TRAFFIC FOR NATURAL DISASTER WARNING COMMUNICATIONS SATELLITE

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E-7137

ABSTRACT

Various types of weather communications are required to alert industries and the general public about the impending occurrence of tornados, hurricanes, snowstorms, floods, etc. A natural disaster warning satellite system has been proposed for meeting the communications requirements of the National Oceanic and Atmospheric Administration. Message traffic for a communications satellite was simulated with a digital computer in order to determine the number of communications channels to meet system requirements. Poisson inputs are used for arrivals and an exponential distribution is used for service.

INTRODUCTION

The National Oceanic and Atmospheric Administration and the National Aeronautics and Space Administration have been jointly investigating various technologies in order to develop conceptual communications systems which meet requirements for a natural disaster warning system. The function of such a system would be to:

(1) Route disaster warnings to the general public.

(2) Provide disaster communications among national, regional and local weather service offices and affected areas.

(3) Provide environmental information to the general public.

(4) Provide a system for collecting decision information for warning to the public.

The natural disasters which would be monitored by the disaster warning system include tornados, severe thunderstorms, flash floods, tsunami, earthquakes, hurricanes, forest fires, winter storms, air pollution, etc.

The National Weather Service is organized to monitor and predict the weather locally, regionally and nationally. There are also national centers for particular types of weather, for example, the National Hurricane Center in Miami, Florida. The total number of offices and centers around the country is approximately 300.

The joint investigations by NOAA and NASA include terrestrial and satellite communication systems. This report is confined to a satellite system only. The problem is to determine the number of communications channels required for a satellite system. The information required for such a decision is difficult to generate since historical records show only the number and size of communications from various parts of the country. The exact time of transmissions cannot be determined and so it is impossible to determine instantaneous flows of message traffic thus precluding a deterministic analysis of any network. Because of the local and regional nature of many communications, no individual has an intuitive understanding of the total problem.

As will be demonstrated, the problem may be formulated as a multi-server queueing system. Simulation is frequently used to analyze unique queueing-type problems which defy direct analytical solution. This technique often provides more information than an analytical model because it is possible to formulate stochastic simulation models which reveal the system states during occurrences of events with small probabilities of happening, but which the system must be capable of handling. Such is the case of the natural disaster warning system. If messages are required to wait in a queue, a tornado may occur before the warning can be disseminated to the public. It is imperative that such a system would have minimum waiting times in a queue.

The simulation model discussed in this report was formulated to handle the local, regional and national disaster warning communications of NOAA. If a Disaster Warning System were developed, it would be designed as an interface with the many offices and centers throughout the country. The system would be used only to provide warnings to the public in the most expedient manner and to collect information from data collection platforms which would be located throughout the nation. The system would operate as an adjunct to the weather service rather than as a replacement for any present operation.

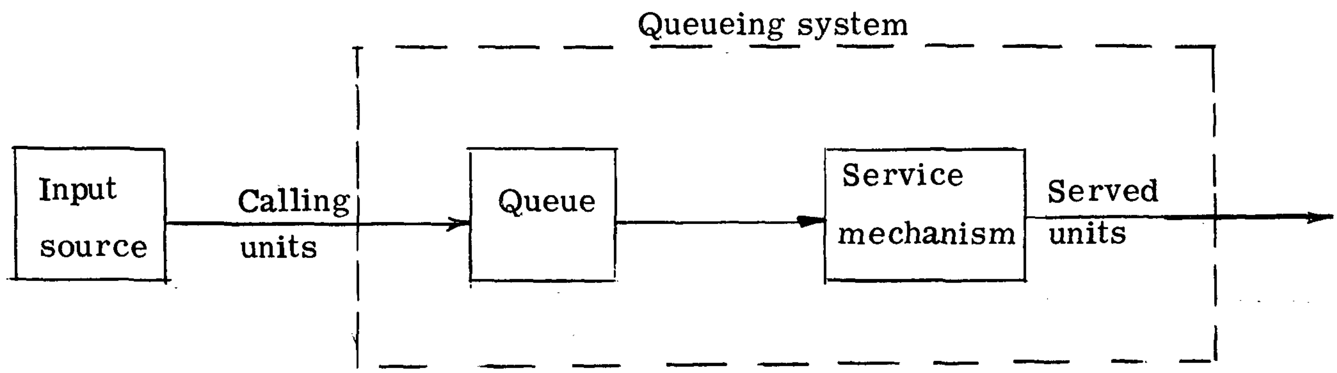
The data collection platforms would be designed to monitor the environment, for example, river and stream levels. This information would be relayed to a central area for data collection and then processed by the weather service. The channel allocation for such a system may be determined analytically and so will not be treated here. Communication channels required for data collection platforms and teletypes may also be added to those determined necessary for voice communication messages.

The classical queueing theory equations are discussed in this report in order to provide a framework for the development of a model; the equations are used to determine the expected values of certain parameters.

CLASSICAL QUEUEING EQUATIONS (REF. 1)

One of the most commonly encountered phenomena in the physical world is the waiting line process. The process occurs whenever a demand exceeds the capacity to provide service. In order to solve the waiting line problem, it is necessary to perform a trade-off between the "costs" of providing the service and the "costs" of not providing the service. Normally the goal is to achieve an economic balance between the two "costs" involved. Queueing theory and simulation models do not solve the problem directly, but the two approaches do provide the information required for decision making by predicting various characteristics of the queueing process.

In the usual formulations of the process, units are generated over time by an "input source". These units enter the system and join a "queue". At certain points in time, a member of the queue is selected for service by some rule called a "service discipline". The required service is then performed for the unit by the "service mechanism", and then the unit leaves the queueing system. The process is depicted in sketch (a).



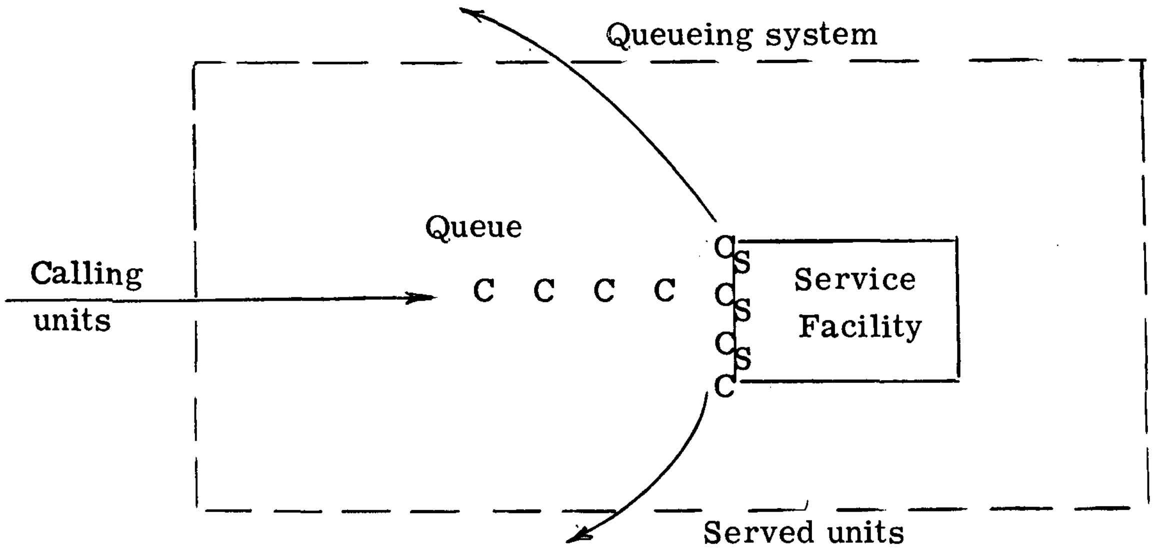
(a)

The size of the input source may be either finite or infinite. Since the calculations are easier for the infinite case, this assumption is often made even though the actual size is some relatively large finite number. The statistical pattern by which calling units are generated over time must also be specified. Usually it is assumed that this distribution is Poisson. An equivalent assumption is that the interarrival times form an exponential distribution since the cumulative distribution of the Poisson is of the exponential form $1\text{-}e^{-\lambda t}$.

The service discipline refers to the order in which members of the queue are selected for service. In this study it was assumed that the service discipline is first-come-first-served.

The service mechanism consists of one or more facilities, each of which contains one or more parallel service channels or servers. The time elapsed from the beginning of service to completion is referred to as the service time or holding time. The probability distribution of service must also be specified for a queueing model. Special cases of the gamma distribution, the exponential distribution and constant service times are frequently selected for the service mechanism.

Although many types of waiting line situations have been studied, queueing theory has been primarily concerned with one particular situation, namely, a single waiting line with one or more servers as seen in sketch (b).



(b)

The following is a listing of the standard notation and terminology used in queueing theory:

Line Length = number of calling units in the queueing system

Queue Length = number of calling units waiting for service

= line length minus number of units being served

E_n = state in which there are n calling units in the queueing system

P_n = probability that exactly n calling units are in the queueing system

S = number of servers or parallel service channels in the queueing system

λ_n = mean arrival rate (expected number of arrivals per unit time) of new calling units when n units are in the system

μ_n = mean service rate (expected number of units completing service per unit time) when n units are in the system

L = expected line length

L_q = expected queue length

W = expected waiting time in the system (includes service time)

W_q = expected waiting time in the queue (excludes service time)

A negligible function of Δt or zero order effect will be denoted $o(\Delta t)$.

Since interest usually lies in a steady-state processes, rather than initial or startup conditions, queueing theory deals primarily with processes which are assumed to have reached a steady state. In this case, when λ_n is a constant, λ, then

$$L = \lambda W$$

and

$$L_q = \lambda W_q$$

If the mean service time is assumed to be a constant, $1/\mu$ then

$$W = W_q + \frac{1}{\mu}$$

The term "birth" refers to the arrival of a new calling unit into the queueing system and "death" refers to the departure of a served unit. Three postulates form the basis of the birth-death process.

I. Birth Postulate: Given that the system is in state E_n at time t, the probability that exactly one birth will occur in the interval from t to $(t + \Delta t)$ is

$$\lambda_n \Delta t + o(\Delta t)$$

where λ_n is a positive constant.

II. Death Postulate: Given that the system is in state E_n at time t, the probability that exactly one death will occur during the interval from t to $(t + \Delta t)$ is

$$\mu_n \Delta t + o(\Delta t)$$

III. Multiple Jump Postulate: Given that the system is in state E_n at time t, the probability that the number of births and deaths combined will exceed one during the interval from t to $(t + \Delta t)$ is $o(\Delta t)$.

From the postulates it can be stated that one of four mutually exclusive events must occur during the interval from t to $(t + \Delta t)$:

1. Exactly one birth and no deaths.
2. Exactly one death and no births.
3. Number of births and deaths combined > one.
4. No births or deaths.

The sum of the four probabilities must equal one. The probability of event 4 equals 1- sum of probabilities for events 1 to 3, which during the interval from t to $(t + \Delta t)$ is equal to

$$1 - \lambda_n \Delta t - \mu_n \Delta t + o(\Delta t)$$

since the sum or difference of $o(\Delta t)$ terms can be written as $o(\Delta t)$. The probabilities of being in state E_n at time $t + \Delta t$ are developed from the possible states at time t and the events required to go from that state to the state E_n as follows:

State at t	Events from t to $(t + \Delta t)$	Probability of Occurrence
E_{n-1}	one birth	$P_{n-1} (\lambda_{n-1} \Delta t + o(\Delta t))$
E_{n+1}	one death	$P_{n+1} (\mu_{n+1} \Delta t + o(\Delta t))$
?	multiple events	$o(\Delta t)$
E_n	none	$P_n (1 - \lambda_n \Delta t - \mu_n \mu t + o(\Delta t)$

It is shown in reference 1 (p. 293) that

$$\frac{dP_n}{dt} = \lambda_{n-1} P_{n-1} + \mu_{n+1} P_{n+1} - (\lambda_n + \mu_n) P_n \text{ for } n > o$$

When $n = o$ $\lambda_{n-1} = o$ and $\mu_o = o$, so that

$$\frac{dP_o}{dt} = \mu_1 P_1 - \lambda_o P_o$$

This provides a set of differential equations which, if they could be solved, would provide the values for P_n. Unfortunately, a convenient general solution is not available and so the equations are used to obtain solutions for certain special cases.

The Pure Birth Process

Assume that $\lambda_n = \lambda$ and $\mu_n = o$ for all $n \geq o$. In this situation no deaths occur and the mean arrival rate is constant. The differential equations for this process are:

$$\frac{dP_o}{dt} = -\lambda P_o$$

$$\frac{dP_n}{dt} = \lambda P_{n-1} - \lambda P_n \quad \text{for } n = 1, 2, \ldots$$

If the system is in state E_o at time $t = o$, then the solution for the $n = o$ case is

$$P_o = e^{-\lambda t}$$

The general solution is

$$P_n = \frac{(\lambda t)^n e^{-\lambda t}}{n!}$$

This is the Poisson distribution with parameter λt. The mean and variance are both equal to λt and the mean arrival rate is λ.

Although the pure birth process is not very interesting by itself, it does form one component of the queueing process used in many models. One of the results of this solution leads to a property referred to previously. $P_o = e^{-\lambda t}$ implies that the probability that no births will occur during the time interval from o to t is $e^{-\lambda t}$. Thus, the probability that the first birth will occur in this time interval is $(1 - e^{-\lambda t})$. If the random variable T is the time of the first birth then the cumulative distribution function of T is

$$F(t) = P\{T \leq t\} = 1 - e^{-\lambda t}, \quad t \geq o$$

Therefore, the probability density function of T is

$$f(t) = \frac{dF(t)}{dt} = \lambda e^{-\lambda t}, \quad t \geq o$$

which is an exponential distribution.

This result verifies that the expected time between arrivals is

$$E(T) = \int_o^\infty t\lambda e^{-\lambda t}\, dt = \frac{1}{\lambda}$$

The Pure Death Process

Assume that $\lambda_n = o$ for all $n \geq o$ and that $\mu_n = \mu$ for $n \geq 1$. Also assume that the system is in state E_M at $t = o$. The first assumption implies that births never occur, and so this is a pure death process with a constant service rate until the process terminates at state E_o. The results are similar to the pure birth process except that this process is the opposite. The differential equations reduce to

$$\frac{dP_n}{dt} = \mu P_{n+1} - \mu P_n \quad \text{for } n = 0, 1, 2, \ldots M - 1$$

$$\frac{dP_M}{dt} = -\mu P_M$$

M-n is the number of events that have occurred in this proccess. The probability that no events have occurred by time t is

$$P_M = e^{-\mu t}$$

The probability that M-n events have occured

$$P_n = \frac{(\mu t)^{M-n}\, e^{-\mu t}}{(M-n)!} \quad \text{for } n = 1, 2, \ldots, M$$

The remaining possibility is that M events have occured, so that

$$P_o = 1 - \sum_{n=1}^{M} P_n$$

This is a truncated Poisson distribution with a parameter μt. The mean service rate is μ until the process terminates. The distribution of elapsed time between events is an exponential distribution.

Steady State Solution

The steady state solution for P_n may be obtained either by solving for P_n in the transient case and letting $t \to \infty$ or by setting $dP_n/dt = o$ in the differential equations and then solving for P_n. Since an elementary general transient solution is not available for the birth-death process, the second approach will be used and an assumption made that a steady-state solution exists, i.e.,

$$\lim_{t \to \infty} P_n(t) = P_n$$

and

$$\lim_{t \to \infty} \left\{ \frac{dP_n(t)}{dt} \right\} = 0$$

For the differential equations,

$$o = \lambda_{n-1} P_{n-1} + \mu_{n+1} P_{n+1} - (\lambda_n + \mu_n) P_n \quad \text{for } n > 0$$

$$o = \mu_1 P_1 - \lambda_o P_o \quad \text{for } n = 0$$

The equation for $n = 0$ yields

$$P_1 = \frac{\lambda_o}{\mu_1} P_o$$

When $n > o$ each equation yields

$$P_{n+1} = \frac{\lambda_n}{\mu_{n+1}} P_n + \frac{\mu_n P_n - \lambda_{n-1} P_{n-1}}{\mu_{n+1}}$$

Considering the numerator of the second term when $n > 1$,

$$\mu_n P_n - \lambda_{n-1} P_{n-1} = \mu_n \left[\frac{\lambda_{n-1}}{\mu_n} P_{n-1} + \frac{\mu_{n-1} P_{n-1} - \lambda_{n-2} P_{n-2}}{\mu_n} \right]$$

$$- \lambda_{n-1} P_{n-1} = \mu_{n-1} P_{n-1} - \lambda_{n-2} P_{n-2}$$

For successively smaller values of n this procedure must yield

$$\mu_n P_n - \lambda_{n-1} P_{n-1} = \mu_1 P_1 - \lambda_o P_o$$

From the solution to the $n = o$ equation

$$\mu_1 P_1 = \lambda_o P_o$$

so that

$$\mu_n P_n - \lambda_{n-1} P_{n-1} = 0$$

Then

$$P_n = \frac{\lambda_{n-1}}{\mu_n} P_{n-1}$$

$$= \frac{\lambda_{n-1}}{\mu_n} \left[\frac{\lambda_{n-2}}{\mu_{n-2}} P_{n-2} \right]$$

$$= \frac{\lambda_{n-1} \lambda_{n-2} \cdots \lambda_o}{\mu_n \mu_{n-1} \cdots \mu_1} P_o$$

or

$$P_n = \frac{\prod_{i=o}^{n-1} \lambda_i}{\prod_{i=1}^{n-1} \mu_i} P_o \quad \text{for } n = 1, 2, \ldots$$

To determine P_o, it is known that

$$\sum_{n=o}^{\infty} P_n = 1$$

so that

$$P_o = \frac{1}{1 + \sum_{n=1}^{\infty} \frac{\prod_{i=o}^{n-1} \lambda_i}{\prod_{i=1}^{n} \mu_i}}$$

For this information

$$L = \sum_{n=o}^{\infty} n\ P_n$$

and

$$L_q = \sum_{n=S}^{\infty} (n-S)\ P_n$$

The summations do have analytic solutions for special cases, one of which is the multiple server model with Poisson input and exponential service. No other types of output have been solved for the case when $S > 1$. The state probabilities for the Poisson input-exponential service will be used to approximate the state probabilities for the simulation model. The model assumes that arrivals occur according to a Poisson input with parameter λ and that the service time has an exponential distribution with mean $(1/\mu)$. The mean service rate for the system is dependent on the state of the system E_n. The mean service rate per busy server is μ. Therefore, the overall service rate must be $n\mu$ provided that $n \leq S$. If $n \geq S$, so that all servers are busy, $\mu_n = S\mu$. This is a special case of the birth death process with $\lambda_n = \lambda$ and

$$\mu_n = n_\mu \quad \text{if} \quad o \leq n \leq S$$

$$= S_\mu \quad \text{if} \quad n \geq S$$

If $\lambda < S\mu$, the mean arrival rate is less than the maximum mean service rate so that

$$P_o = \frac{1}{\sum_{n=o}^{S-1} \frac{\left(\frac{\lambda}{\mu}\right)^n}{n!} + \frac{\left(\frac{\lambda}{\mu}\right)^S}{S!} \sum_{n=S}^{\infty} \left(\frac{\lambda}{S\mu}\right)^{n-S}}$$

Since $\frac{\lambda}{S\mu} < 1$, the limit of the series

$$\sum_{n=S}^{\infty} \left(\frac{\lambda}{S\mu}\right)^{n-S} = \frac{1}{1 - \frac{\lambda}{S\mu}}$$

so that

$$P_o = \frac{1}{\sum_{n=o}^{n-S} \frac{\left(\frac{\lambda}{\mu}\right)^n}{n!} + \frac{\left(\frac{\lambda}{\mu}\right)^S}{S!} \left[\frac{1}{1 - \frac{\lambda}{S\mu}}\right]}$$

and

$$P_n = \frac{\left(\frac{\lambda}{\mu}\right)^n}{n!} P_o \qquad \text{if } o \leq n \leq S$$

$$= \frac{\left(\frac{\lambda}{\mu}\right)^n}{S!\ S^{n-S}} P_o \qquad \text{if } n \geq S$$

Let $\rho = \frac{\lambda}{S\mu}$. Then

$$L_q = \sum_{n=S}^{\infty} (n - S)\, P_n$$

$$= \sum_{j=o}^{\infty} j\, P_{S+j}$$

$$= \sum_{j=o}^{\infty} \frac{j\left(\frac{\lambda}{\mu}\right)^S}{S!} \rho^j\, P_o$$

$$= P_o \frac{\left(\frac{\lambda}{\mu}\right)^S}{S!} \rho \sum_{j=o}^{\infty} \frac{d}{d\rho} (\rho^j)$$

$$= P_o \frac{\left(\frac{\lambda}{\mu}\right)^S}{S!} \rho \frac{d}{d\rho} \sum_{j=o}^{\infty} \rho^j$$

Since $\rho < 1$ the limit of $\sum_{j=o}^{\infty} \rho^j = \frac{1}{1 - \rho}$, so that

$$Lq = \frac{P_o\left(\frac{\lambda}{\mu}\right)^S}{S!} \rho \frac{d}{d\rho}\left(\frac{1}{1 - \rho}\right)$$

$$= \frac{P_o\left(\frac{\lambda}{\mu}\right)^S \rho}{S!\, (1 - \rho)^2}$$

$$Wq = \frac{Lq}{\lambda}$$

$$W = Wq + \frac{1}{\mu}$$

$$L = Lq + \frac{\lambda}{\mu}$$

Weather Service Message Traffic and Distributions

The data for the message traffic was provided by the National Oceanic and Atmospheric Administration's Environmental Research Laboratories in Boulder, Colorado. The data were divided into three types of inputs in order to develop distributions which could be utilized in the simulation model: hurricanes reaching the east coast of the U.S.; weather warnings; and river forcasts and warnings.

The number of hurricanes reaching the east coast of the United States per year is a random variable having a Poisson distribution with $\lambda = 1.9$ (ref. 2). This information was used to develop a hurricane simulation for 100 years. A multiplicative congruential uniformly distributed random number generator was used to develop random numbers (ref. 3). These numbers were then mapped to a cumulative Poisson distribution in order to obtain the Poisson events. The hurricane simulation was used to develop a "worst case" as an input for the communication satellite simulation model. In the 40th year, two hurricanes reached the eastern part of the U.S. on July 13. On July 14, another hurricane reached the east coast. Finally, on October 3 of the 40th year, one more hurricane reached the east coast.

Using data from Hurricane Camille which occurred from August 12-14, 1969, a Poisson distribution was predicated for hurricane message traffic (for satellite simulator) with an estimated parameter of $\lambda = 0.019$ per minute during hurricanes. This assumption, if incorrect, will not affect the model appreciably because the traffic for a hurricane is very small relative to the other two types of message traffic. The effect is to increase the satellite channel requirements only during the periods mentioned above. The assumption also causes the results to be more conservative since the occurrence of three simultaneous hurricanes is a very remote possibility.

The weather warning data were provided for the 72 months from January 1966 to December 1972. The data included the categories: tornadoes and severe storms; hurricanes; small craft and gales; forecasts for inland lakes; winter storm warnings; and other.

A Poisson distribution was also predicated for the weather warnings. A Chi-square test was performed to determine the goodness of fit for a Poisson distribution with $\alpha = 0.05$. The 72 months of data yielded a parameter estimate of $\lambda = 0.1454$ per minute. In order to work with integral data, the test was performed on the expected number of messages per hour which yielded an estimate of $\lambda = 8.5$. The experimental value for the Chi-square statistic was 18.1. The value of $\chi^2_{0.05}$ with 11 degrees of freedom was 19.675 so that the hypothesis of a Poisson distribution for the weather warnings could not be rejected.

A time series analysis was performed on the weather warning data in order to determine trends and seasonal variations. The data are shown in figure 1. The trend was recovered by using linear regression. If x is the number of years from 1965, and y is the average number of messages per month for the year x, then the expression

$$y = 632\,x + 4163$$

may be used to estimate the value of the expected number of messages per month for a given year.[1] The correlation coefficient of the regression was $r = 0.96$. Table I shows the seasonal variation in percentage of deviation from trend and figure 2 is a graph of the irregular variations in percentage of deviation from trend.

The trend shows that the average number of monthly messages is in-

[1] x = 0, 1, 2, ... from base year 1966.

creasing at the rate of 632 per year. Therefore, the Poisson parameter should be increased in order to allow for a larger number of messages per month. It was not determined if there was actually more storms or whether there is a tendency to saturate the communications facilities, but the latter seems more likely. The Poisson parameter used for the simulation was based on the trend value for 1972 which yielded a value of $\lambda = 0.1923$ messages per minute.

The river forecast and warning data are treated in the same manner as the weather warning data. Data were obtained for the sixty months from January 1967 to December 1971. A Chi-square test was performed to determine the goodness of fit for a Poisson distribution with $\alpha = 0.05$. The data yielded an estimate of $\lambda = 0.5167$ messages per minute. This was converted to 31 messages per hour. The hypothesis of a Poisson distribution could not be rejected at the $\alpha = 0.05$ level.

A time series analysis was performed on the river forecast data to determine the trend and seasonal variations in the same manner as was done for the warning data. Using the same notation as previously the average number of messages per month for the year x is given by[2]

$$y = 2667\,x + 15665$$

The correlation coefficient for this regression was $r = 0.94$. Table II shows the seasonal variation in percentage of deviation from trend and figures 3 and 4 are graphs of the trend and irregular variations.

The trend shows that the average number of messages per month is increasing at the rate of 2667 per year. The Poisson parameter was adjusted to allow for a larger number of messages per month based on the year 1972 ($\lambda = 0.7224$ messages per minute).

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[2] $x = 0, 1, 2, \ldots$ from base year 1967.

Message Processing Times

A classification was made of 21 different types of weather service warnings and the average word length was provided by NOAA's Environmental Research Lab in Boulder. The average length of all 21 types was 136 words which also approximates the average speaking rate per minute. No data were given on the frequencies of the 21 message types but the average word length of each type was given.

Since the parallel-channel queueing equations require exponential service, this distribution was selected arbitrarily. The average processing time equals approximately one minute assuming a speaking of 137 words per minute. It seems plausible that the majority of messages would require 1 or 2 minutes to transmit, but that occasionally, messages would be on the order of 5 to 6 minutes. The exponential distribution allows for this possibility. If the parameter $\mu = 1$ is used for the distribution, then the cumulative distribution of $1\text{-}e^{-1t}$ where t is the processing time in minutes is

Minutes	Cumulative probability	Delta probability
1	0.632	0.632
2	.865	.233
3	.950	.085
4	.982	.032
5	.993	.011
6	.998	.005
7	.999	.001
8	1.000	.001

The delta probabilities may be interpreted to mean that 63.2 percent of all messages will have a processing time of 1 minute; 23.3 percent have times of 2 minutes; 8.5 percent have times of 3 minutes, etc. Only integral values were used for processing times to allow the computer program to perform most operations in integer arithmetic.

The Simulation Model and Computer Program

As stated previously, the simulation model was developed to utilize Poisson input and an exponential distribution for service. The computer program utilized integer data when possible to minimize the CPU time.

The queueing process input consisted of three types of message traffic: warning messages; river forecasts; disaster communications during and after hurricanes. The Poisson parameters used for these inputs were:

Warning messages	$\lambda = 0.1923$
River forecasts	$\lambda = 0.7224$
Disaster communication for hurricanes	$\lambda = 0.057$ from July 13 - 21
	$= 0.019$ from Oct. 3 - 11
	$= 0$ Otherwise

The exponential service parameter was the same for all three inputs ($\mu = 1.008$). The program organization consisted of a main routine and 12 subroutines. The source program names are:

Main Routine NOAA - Serves as an executive routine and initializes some parameters. Prompts user for satellite channel capacity and a seed for the random number generator. Also contains a report generator.

Subroutine MACHST - Sorting routine which determines the soonest available channel and then allocates that channel for use.

Subroutine FILL - Routine which calls the message distribution and service routines and converts each non-zero event into a message queue for one week in increments of one minute.

Subroutines NORDIS, RIVDIS, HURDIS - Routines which set Poisson parameters for each type of message. Each calls Poisson generator and then converts Poisson variable to an integral number of messages, (0, 1, 2, etc.). These integral events are then returned to subroutine FILL.

Subroutine MPROC - Routine which sets the parameter μ and calls the exponential distribution subroutine to obtain a service time.

Subroutine GSERV - Routine which updates channel times and accumulates idle channel times and waiting times for messages in the queue.

Subroutine AVTIM - Routine which calculates average time and number of messages in the system.

Subroutine AVUTIL - Routine which calculates average fractional channel utilization and the average time spent in the queue.

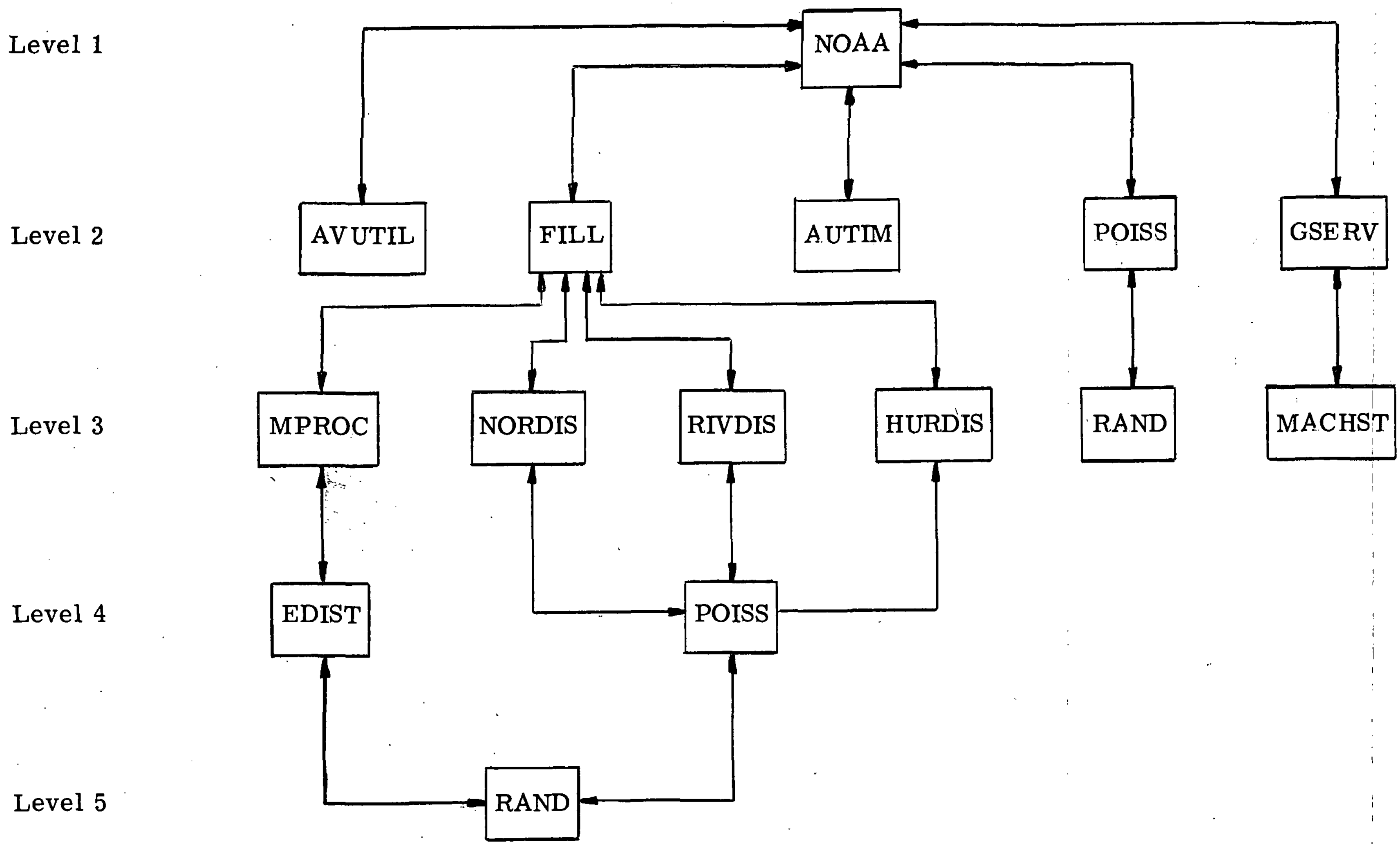
Subroutine POISS - Routine which converts a uniformly distributed random number to a Poisson distributed random number.

Subroutine EDIST - Routine which converts a uniformly distributed random number to an exponentially distributed random number.

Subroutine Rand - Routine which generates uniformly distributed random numbers between zero and one using a multiplicative congruential technique.

Using the convention that a given level may call only one subroutine at the next lower level and that control is always returned to the calling subroutine, the flow of the program is depicted in sketch (c).

A copy of the program appears in appendix A. Sample outputs are given in appendix B.


Level 1
Level 2
Level 3
Level 4
Level 5
NOAA
AVUTIL
FILL
AUTIM
POISS
GSERV
MPROC
NORDIS
RIVDIS
HURDIS
RAND
MACHST
EDIST
POISS
RAND

(c)

RESULTS OF SIMULATION AND CONCLUSIONS

The simulation program was used to simulate one week for channel numbers ranging from 1 to 20. The results are shown in table III and the utilization factors are plotted in figure 5.

Although the parameter used for the exponential distribution was 1.008, the average message processing time for all runs asymptotically approaches 1.6 because processing times less than 1 minute were not considered. The effect of this restriction was a reduction in μ to 0.625. Thus the data from the simulation runs is somewhat conservative.

One of the essential requirements of the Natural Disaster Warning System is that there be no delay in the transmission of warning messages. From the data in table III, this requirement means that the number of channels must be greater than eight if the average processing time is 1.6 minutes or more.

The queueing equations were used to analyze the sensitivity of the model to changes in the parameter μ. The probability of being in state zero was calculated for channels numbering from 3 to 20. Using P_0, the probability of being in state $(S + 1)$ was calculated for each number of channels from 3 to 20. This probability P_{S+1} is the probability of a message transmission being delayed. Table IV shows the probabilities for $\lambda = 0.9717$ per minute and $\mu = 1.008$ per minute. The value $\lambda = 0.9717$ occurs only during the period of 3 simultaneous hurricanes. Table V shows the probabilities P_0 and P_{S+1} for $\mu = 0.625$ per minute or a service time of approximately 1.6 minutes.

Although it is somewhat unrealistic to even consider such probabilities as 0.0000001, the concept may be employed to mean an almost virtual certitude that the event will not occur in practice. To ensure that the satellite system would never reach state $(S + 1)$ the arbitrary criterion was established that $P_{S+1} \leq 0.0000001$ would determine the number of channels sufficient to meet the no-delay requirement.

From tables IV and V it can be seen that $S = 9$ is sufficient for a service time which averages approximately one minute and $S = 11$ is sufficient for $\mu = 0.625$ or a service time which averages 1.6 minutes.

The probabilities P_o and P_{S+1} were also calculated for average service times of 2 and 3 minutes. The resulting estimates for S were 12 and 14, respectively.

As a verification of the model, there was no statistically significant difference between the calculated P_{S+1} and the number of delays occurring for $\lambda = 0.9717$ and $\mu = 0.625$ (service time = 1.6 minutes) for S = 3 to S = 8 (table III).

On the basis of the data used to establish the model a selection of S = 10 channels would offer a number sufficient to meet the requirements with a considerable safety margin. If such a choice were made table VI demonstrates the effects of power degradation on the accessibility of the satellite.

The information in table VI may be used to conclude that if 10 channels were selected, the satellite could operate and be used effectively even with a 50 percent degradation in power or transmission capability since delays would be expected to occur at the average rate of 6 per 10 000 messages transmitted. Moreover the maximum delay would probably not exceed 1 minute.

APPENDIX A

COMPUTER PROGRAM

The computer program was written in FORTRAN IV and executed on an IBM 360/67. The operating system TSS (Time Sharing System) allows terminal type interactive processing and so the program was written to be executed in a conversational mode.

```
C           MAIN ROUTINE FOR THE COMMUNICATIONS SATELLITE
C
C           SIMULATOR FOR THE DISASTER WARNING SYSTEM.
C
C
      DIMENSION ICHAN(200),IDLE(200),ITYPJ(3)
      INTEGER HI
      INTEGER*2 IJNO(30000),IJIND(30000),IMCHDX(30000),IWAIT(30000),-
     1IPROC(30000),IQUE(11000)
      DATA ITYPJ/'HURR','WARN','RIV.'/,ICHAN/200*1/
C
      WRITE(6,1032)
 1032 FORMAT(' ',T2,'IF WEEK = 1,HIT RETURN;OTHERWISE TYPE 111')
C
C
C           INITIALIZE TIME PARAMETERS
      READ(5,1001) IRND
      IF(IRND.NE.0) GO TO 50
C
      K=0
      IMINIT=0
      IWK=0
C
C
C           PROMPT FOR ENTRY OF NUMBER OF CHANNELS FOR SATELLITE
C
C
      WRITE (6,1000)
      READ (5,1001) NOCHAN
C
C
C           PROMPT FOR ENTRY OF A SEED TO START THE RANDOM
C           NUMBER GENERATOR.
C
C
      WRITE (6,1002)
      READ (5,1001) IGESS
      READ (5,1001) ISKIP
C
C           EVENTS WILL BE GENERATED TO SIMULATE ARRIVALS FOR
C           60 MINUTES PER HOUR, 24 HOURS PER DAY, FOR 7 DAYS.
C           THIS INFORMATION WILL THEN BE USED TO FORM A QUEUE
C           WHICH IS THEN PROCESSED. AFTER PROCESSING,SEVEN
C           MORE DAYS OF INFORMATION ARE GENERATED AND
C           PROCESSED. THIS PROCEDURE IS CONTINUED UNTIL
C           A YEAR HAS ELAPSED IN THE SIMULATION.
C
C
      GO TO 100
C
   50 READ(9,1030) K,IMINIT,IWK,NOCHAN,IGESS,ISKIP,Z,KKJ1,KKJ2,KJ1,KJ2
      READ(9,1031) (ICHAN(IJK),IJK=1,200)
      CALL RAND(Z,IGESS,KKJ1,KKJ2,KJ1,KJ2)
C
C
```

```
C
C          SUBROUTINE FILL GENERATES THE EVENTS AND TRANSFORMS
C          NONZERO EVENTS INTO MESSAGES FOR A QUEUE.
C
C
  100 CALL FILL(IJNO,IJIND,IPROC,K,IMINIT,IJOB,IGESS,KKJ1,KKJ2,KJ1,KJ2)
      K=1
C
C
C         SUBROUTINE GSERV PROCESSES THE QUEUE.
C
C
      DO 200 I=1,IJOB
      CALL GSERV(I,IJNO,MIN,ICHAN,NOCHAN,IMCHDX,IJIND,IDLE,IWAIT,-
     1IPROC,IQUE)
  200 CONTINUE
C
C
C         SIMULATION FOR 1 WEEK COMPLETED. BEGIN PROCESSING
C         OF QUEUE FOR PRINTING.
C
C

C
C         PRINT HEADING ROUTINE
C
      WRITE (7,1004)
      WRITE (7,1005)
      WRITE (7,1006)
      WRITE (7,1007)
      WRITE (7,1008) NOCHAN
C
  600 IWK=IWK+1
      WRITE (7,1009)
      WRITE (7,1010) IWK
      MAXWT=0
      NOMAX=0
      NOARRV=0
      NOFIN=0
      DO 650 KK=1,IJOB
      IF (IJIND(KK).LE.10080) NOARRV=NOARRV+1
      IFIN=IJIND(KK)+IWAIT(KK)+IPROC(KK)
      IF (IFIN.LT.10080) NOFIN=NOFIN+1
      IF ((IWAIT(KK).GT.MAXWT).AND.(IJIND(KK).LE.10080)) MAXWT=IWAIT(KK)
  650 CONTINUE
      WRITE (7,1011) NOARRV
      WRITE (7,1012) NOFIN
      PDMINS=10080
      LO=1
      HI=10080
      CALL AVTIM(IJIND,LO,HI,NOARRV,ARRV,SUM,IJOB,IQUE,PDMINS,SUMQUE,IWAIT,IPROC)
      CALL AVUTIL(IDLE,SUMIDL,NOCHAN,SUMWT,IJIND,IWAIT,ARRV,HI,LO,IJOB,PDMINS)
C
C
C         AVTIM AND AVUTIL ARE USED TO CALCULATE THE AVERAGE
```

```
C          TIME IN THE SYSTEM,AVERAGE NUMBER IN THE SYSTEM,
C          FRACTIONAL CHANNEL UTILIZATION AND THE AVERAGE TIME
C          IN THE QUEUE.  USING THIS INFORMATION, THE AVERAGE
C          PROCESSING TIME CAN BE DETERMINED BY SUBTRACTING THE
C          AVERAGE TIME IN THE QUEUE FROM THE AVERAGE TIME IN
C          THE SYSTEM.
C
C                   SUM    = AVERAGE TIME IN THE SYSTEM
C                   SUMQUE= AVERAGE NUMBER IN THE SYSTEM
C                   SUMIDL= AVERAGE FRACTIONAL CHANNEL UTILIZATION
C                   SUMWT  = AVERAGE TIME IN THE QUEUE
C                   AVPROC= SUM-SUMWT= AVERAGE PROCESSING TIME
C
C
      AVPROC=SUM-SUMWT
      WRITE (7,1024) SUM
      WRITE (7,1025) SUMQUE
      WRITE (7,1026) SUMIDL
      WRITE (7,1027) SUMWT
      WRITE (7,1028) AVPROC
C
C
C                   DETERMINE MAXIMUM WAITING TIME AND FREQUENCY
C
C
      DO 690 KK=1,IJOB
      IF (IWAIT(KK).LT.MAXWT) GO TO 690
      NOMAX=NOMAX+1
  690 CONTINUE
      WRITE (7,1029) MAXWT,NOMAX
      IF (ISKIP.EQ.1) GO TO 810
      IPAGE=1
      WRITE (7,1014) IWK,IPAGE
      WRITE (7,1016)
      WRITE (7,1017)
      WRITE (7,1018)
      WRITE (7,1016)
      IF (ISKIP.EQ.1) GO TO 810
      DO 800 KK=1,IJOB
      IF (IJIND(KK).GT.10080) GO TO 800
      IPG=MOD(KK,55)
      IF (IPG.NE.0) GO TO 700
      IPAGE=IPAGE+1
      WRITE (7,1014) IWK,IPAGE
      WRITE (7,1016)
      WRITE (7,1017)
      WRITE (7,1018)
      WRITE (7,1016)
C
C
C                   CONVERT ARRIVAL TIME TO DAY-HR-MIN FORMAT
C
C
  700 IART=IJIND(KK)
      IREM=MOD(IART,1440)
```

```
      IF (IREM.EQ.0) IDAY1=IART/1440
      IF (IREM.NE.0) IDAY1=IART/1440 + 1
      IREM=IART-(IDAY1-1)*1440
      IREM1=MOD(IREM,60)
      IF (IREM1.EQ.0) IHR1=IREM/60
      IF (IREM1.NE.0) IHR1=IREM/60 + 1
      MIN1=IART-(IDAY1-1)*1440 - (IHR1-1)*60
C
C
C                 CONVERT FINISH TIME TO SAME FORMAT
C
C
      IFIN=IJIND(KK) + IWAIT(KK) + IPROC(KK)
      IREM=MOD(IFIN,1440)
      IF (IREM.EQ.0) IDA2=IFIN/1440
      IF (IREM.NE.0) IDAY2=IFIN/1440 + 1
      IREM=IFIN-(IDAY2-1)*1440
      IREM1=MOD(IREM,60)
      IF (IREM1.EQ.0) IHR2=IREM/60
      IF (IREM1.NE.0) IHR2=IREM/60 + 1
      MIN2=IFIN-(IDAY2-1)*1440-(IHR2-1)*60
      KJTYP=IJNO(KK)
C
C
C                 PRINT MESSAGE LOG
C
C
      WRITE (7,1023) KK,IDAY1,IHR1,MIN1,IDAY2,IHR2,MIN2,ITYPJ(KJTYP),-
     1IMCHDX(KK),IPROC(KK),IWAIT(KK)
  800 CONTINUE
C
C
C                 IF WEEK IS 52, THE PROGRAM IS FINISHED;
C                 OTHERWISE ALL TABLES MUST BE CLEARED FOR
C                 THE NEXT WEEK.
C
C
C
  810 CONTINUE
      IF (IWK.EQ.52) GO TO 1500
      J=0
      DO 900 I=1,IJOB

  825 IJNO(I)=0
      IJIND(I)=0
      IMCHDX(I)=0
      IWAIT(I)=0
      IPROC(I)=0

  900 CONTINUE
C
C
                  CLEAR IQUE AND UPDATE ICHAN.
C
C
```

```
C
       DO 910 I=1,10080
910    IQUE(I)=0
       DO 940 I=1,200
       IDLE(I)=0
940    ICHAN(I)=1
       CALL RAND(Z,IGESS,KKJ1,KKJ2,KJ1,KJ2)
935    CONTINUE
       WRITE(8,1030) K,IMINIT,IWK,NOCHAN,IGESS,ISKIP,Z,KKJ1,KKJ2,KJ1,KJ2
       WRITE(8,1031) (ICHAN(IJK),IJK=1,200)
       GO TO 1500
C
C                     FORMAT STATEMENTS
C
C
1000   FORMAT (' ',T2,'ENTER NUMBER OF COMMUNICATION CHANNELS IN FORMAT I3')
1001   FORMAT (I3)
1002   FORMAT (' ',T2,'ENTER A RANDOM NUMBER BETWEEN 1 AND 999 IN FORMAT I3')
1004   FORMAT ('1',T2,'      ')
1005   FORMAT (' ',T56,'********************')
1006   FORMAT (' ',T56,'* COMM. SATELLITE  *')
1007   FORMAT (' ',T56,'*   SIMULATION     *')
1008   FORMAT ('0',T44,'NO. OF CHANNELS=',T61,I3,T75,'WEEKS SIMULATED=  52')
1009   FORMAT ('-',T2,'      ')
1010   FORMAT (' ',T25,'WEEK',T30,I2)
1011   FORMAT (' ',T52,'NO. OF ARRIVALS DURING PERIOD =',T84,I6)
1012   FORMAT (' ',T52,'NO. OF MSGS COMPLETED THIS PD.=',T84,I6)
1014   FORMAT ('1',T25,'WEEK=',I3,T100,'PAGE=',I4)
1016   FORMAT (' ',T25,'--------------------------------------------------------
      1-----------------------------------')
1017   FORMAT (' ',T25,'|  MSG  |  ARRIVAL TIME  |  FINISH TIME  |  MSG.  |-
      1  CHAN.  |  PROCESS  |  WAIT  |')
1018   FORMAT (' ',T25,'|  NO.  |  DAY HR. MIN.  |  DAY HR. MIN. |  TYPE  |-
      1  ASSGN.  |   MINS.   |  MINS. |')
1023   FORMAT (' ',T25,'|',I5,T33,'|',I4,I4,I5,T50,'|',I4,I4,I5,T66,'|',T69,A4,-
      1T75,'|',I6,T86,'|',I6,T98,'|',I5,3X,'|')
1024   FORMAT (' ',T52,'AVERAGE TIME IN SYSTEM         =',T84,F7.1)
1025   FORMAT (' ',T52,'AVERAGE NO. IN SYSTEM          =',T84,F7.1)
1026   FORMAT (' ',T52,'AVERAGE FRACTIONAL CHAN. UTIL.=',T84,F8.2)
1027   FORMAT (' ',T52,'AVERAGE TIME IN QUEUE          =',T84,F7.1)
1028   FORMAT (' ',T52,'AVERAGE PROCESSING TIME        =',T84,F7.1)
1029   FORMAT ('0',T52,'THE MAXIMUM DELAY OF',I5,' MINUTES OCCURRED',I5,' TIMES')
 1030 FORMAT(6I10,F15.12,4I10)
 1031 FORMAT(200I10)
C
C
C
1500   CONTINUE
       STOP
       END
```

```
      SUBROUTINE MACHST(MIN,IMACH,NOMACH)
      DIMENSION IMACH(200)
      MIN=1
      DO 100 J=2,NOMACH
      IF (IMACH(MIN).LE.IMACH(J)) GO TO 100
      MIN=J
  100 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE FILL(IJNO,IJIND,IPROC,K,IMINIT,IJOB,IGESS,KKJ1,KKJ2,KJ1,KJ2)
C
C            SUBROUTINE FILL GENERATES THE EVENTS AND TRANSFORMS
C            NONZERO EVENTS INTO MESSAGES FOR A QUEUE.
C
      INTEGER*2 IJNO,IJIND,IPROC
      DIMENSION  IJNO(30000),IJIND(30000),IPROC(30000)

      IF(K.EQ.1) GO TO 200
      IJOB=0
      DO 100 I=1,10080
      IMINIT=I
      CALL NORDIS(NOEVTS,IGESS,KKJ1,KKJ2,KJ1,KJ2)
      IF(NOEVTS.EQ.0) GO TO 25
   10 IJOB=IJOB+1
      IJNO(IJOB)=2
      IJIND(IJOB)=I
      CALL MPROC(MSERV,IGESS,KKJ1,KKJ2,KJ1,KJ2)
      IPROC(IJOB)=MSERV
      NOEVTS=NOEVTS-1
      IF(NOEVTS.GT.0) GO TO 10
C
   25 CONTINUE
C
      CALL RIVDIS(NOEVTS,IGESS,KKJ1,KKJ2,KJ1,KJ2)
      IF(NOEVTS.EQ.0) GO TO 100
   30 IJOB=IJOB+1

      IJNO(IJOB)=3

      IJIND(IJOB)=I
      CALL MPROC(MSERV,IGESS,KKJ1,KKJ2,KJ1,KJ2)
      IPROC(IJOB)=MSERV
      NOEVTS=NOEVTS-1
      IF(NOEVTS.GT.0) GO TO 30
  100 CONTINUE
  110 GO TO 400
  200 DO 300 I=1,10080
      IMINIT=IMINIT+1
      IF((IMINIT.LT.279360).OR.(IMINIT.GT.293760)) GO TO 210
      CALL HURDIS(NOEVTS,IMINIT,IGESS,KKJ1,KKJ2,KJ1,KJ2)
      IF(NOEVTS.EQ.0) GO TO 210
  205 IJOB=IJOB+1
      IJNO(IJOB)=1
      IJIND(IJOB)=I
      CALL MPROC(MSERV,IGESS,KKJ1,KKJ2,KJ1,KJ2)
      IPROC(IJOB)=MSERV
      NOEVTS=NOEVTS-1
      IF(NOEVTS.GT.0) GO TO 205
  210 IF((IMINIT.LT.397440).OR.(IMINIT.GT.411840)) GO TO 220
      CALL HURDIS(NOEVTS,IMINIT,IGESS,KKJ1,KKJ2,KJ1,KJ2)
      IF(NOEVTS.EQ.0) GO TO 220
  215 IJOB=IJOB+1
      IJNO(IJOB)=1
      IJIND(IJOB)=I
```

```
      CALL MPROC(MSERV,IGESS,KKJ1,KKJ2,KJ1,KJ2)
      IPROC(IJOB)=MSERV
      NOEVTS=NOEVTS-1
      IF(NOEVTS.GT.0) GO TO 215
  220 CALL NORDIS(NOEVTS,IGESS,KKJ1,KKJ2,KJ1,KJ2)
      IF(NOEVTS.EQ.0) GO TO 230
  225 IJOB=IJOB+1
      IJNO(IJOB)=2
      IJIND(IJOB)=I
      CALL MPROC(MSERV,IGESS,KKJ1,KKJ2,KJ1,KJ2)
      IPROC(IJOB)=MSERV
      NOEVTS=NOEVTS-1
      IF(NOEVTS.GT.0) GO TO 225
C
  230 CONTINUE
C
      CALL RIVDIS(NOEVTS,IGESS,KKJ1,KKJ2,KJ1,KJ2)
      IF(NOEVTS.EQ.0) GO TO 250
  235 IJOB=IJOB+1
      IJNO(IJOB)=3
      IJIND(IJOB)=I
      CALL MPROC(MSERV,IGESS,KKJ1,KKJ2,KJ1,KJ2)
      IPROC(IJOB)=MSERV
      NOEVTS=NOEVTS-1
      IF(NOEVTS.GT.0) GO TO 235
  250 CONTINUE
  300 CONTINUE
  400 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE RIVDIS(NOEVTS,IGESS,KKJ1,KKJ2,KJ1,KJ2)
C
C
C

C     THIS SUBROUTINE CALLS A POISSON DISTRIBUTED GENERATOR
C     WHICH DEVELOPS THE NUMBER OF SIMULTANEOUS RIVER
C     WARNING MESSAGES
C
      REAL LAMDA
      LAMDA=0.7224
      CALL POISS(LAMDA,NOEVTS,IGESS,KKJ1,KKJ2,KJ1,KJ2)
      CONTINUE
      RETURN
      END
```

```
      SUBROUTINE HURDIS(NOEVTS,IMINIT,IGESS,KKJ1,KKJ2,KJ1,KJ2)
C
C
C
C     THIS SUBROUTINE CALLS A POISSON DISTRIBUTED GENERATOR WHICH
C     DEVELOPS THE SIMULTANEOUS NUMBER OF HURRICANE WARNING
C     MESSAGES
C
C
      REAL LAMDA
      IF(IMINIT.GT.293760) GO TO 1
      LAMDA=0.057
      GO TO 2
    1 LAMDA=0.019
    2 CALL POISS(LAMDA,NOEVTS,IGESS,KKJ1,KKJ2,KJ1,KJ2)
      CONTINUE
      RETURN
      END
```

```
      SUBROUTINE NORDIS(NOEVTS,IGESS,KKJ1,KKJ2,KJ1,KJ2)
C
C
C
C       THIS SUBROUTINE CALLS A POISSON DISTRIBUTED GENERATOR
C       WHICH DEVELOPS THE NUMBER OF SIMULTANEOUS MESSAGES OR
C       EVENTS FOR A PROCESS WHICH HAS A PROBABILITY DENSITY
C       FUNCTION WHICH IS DISTRIBUTED AS A POISSON DENSITY
C       FUNCTION.
C
      REAL LAMDA
      LAMDA=0.1923
      CALL POISS(LAMDA,NOEVTS,IGESS,KKJ1,KKJ2,KJ1,KJ2)
      CONTINUE
      RETURN
      END
```

```
      SUBROUTINE MPROC(MSERV,IGESS,KKJ1,KKJ2,KJ1,KJ2)
C
C
C
C       THIS SUBROUTINE IS USED TO DEVELOP A PROCESSING TIME FOR
C       MESSAGES.  THE DISTRIBUTION TIME IS EXPONENTIAL AND
C       BASED ON HISTORICAL VALUES FOR MESSAGE PROCESSING TIMES.
C
C
      REAL MU
      MU=1.008
      CALL EDIST (MU,MSERV,IGESS,KKJ1,KKJ2,KJ1,KJ2)
      CONTINUE
      RETURN
      END
```

```
      SUBROUTINE GSERV(I,IJNO,MIN,ICHAN,NOCHAN,IMCHDX,IJIND,IDLE,IWAIT,IPROC,IQUE)
C
C       SUBROUTINE GSERV PROCESSES THE QUEUE.
C
C
      DIMENSION ICHAN(200), IDLE(200)
      INTEGER*2 IJNO,IMCHDX,IJIND,IWAIT,IPROC,IQUE
C
      DIMENSION IJNO(30000),IMCHDX(30000),IWAIT(30000)
      DIMENSION IPROC(30000), IQUE(11000),IJIND(30000)

      CALL MACHST(MIN,ICHAN,NOCHAN)
      IMCHDX(I)=MIN
      IF(ICHAN(MIN).GT.IJIND(I)) GO TO 1105
      IWAIT(I)=0




      IDLE(MIN)=IDLE(MIN)+IJIND(I)-ICHAN(MIN)
      ICHAN(MIN)=IJIND(I)
      GO TO 1110
1105  IWAIT(I)=ICHAN(MIN)-IJIND(I)
 1110 IFIN=IJIND(I)+IWAIT(I)+IPROC(I)
      IFIN1=IFIN
      IFIN2=IJIND(I)
      DO 1115 ITIND=IFIN2,IFIN1
1115  IQUE(ITIND)=IQUE(ITIND)+1
      ICHAN(MIN)=ICHAN(MIN)+IPROC(I)





1120  CONTINUE
      RETURN
      END
```

```
      SUBROUTINE AVTIM(IJIND,LO,HI,NOARRV,ARRV,SUM,IJOB,IQUE,PDMINS,SUMQUE,IWAIT,IPROC)
C
C       THIS SUBROUTINE CALCULATES THE AVERAGE TIME IN THE SYSTEM
C       AND THE AVERAGE NUMBER OF MESSAGES IN THE SYSTEM.
C
      DIMENSION IJIND(30000),IQUE(11000),IWAIT(30000),IPROC(30000)
      INTEGER*2 IJIND,IQUE,IWAIT,IPROC
      INTEGER HI
      SUMQUE=0.
      SUM=0.
      DO 100 KKK=1,IJOB
      IF (IJIND(KKK).LT.LO) GO TO 100
      IF (IJIND(KKK).GT.HI) GO TO 100
      SUM=SUM+IWAIT(KKK)+IPROC(KKK)
  100 CONTINUE
      ARRV=NOARRV
      SUM=SUM/ARRV
      DO 200 I=LO,HI
  200 SUMQUE=SUMQUE+IQUE(I)
      SUMQUE=SUMQUE/PDMINS
      RETURN
      END
```

```
      SUBROUTINE AVUTIL(IDLE,SUMIDL,NOMACH,SUMWT,IJIND,IWAIT,ARRV,HI,LO,IJOB,PDHRS)
C       THIS SUBROUTINE IS USED TO CALCULATE THE FRACTION OF
C       TIME THE COMMUNICATION CHANNELS ARE USED AND THE AVERAGE .
C       WAITING TIME IN THE QUEUE.
C
      INTEGER*2 IJIND,IWAIT
      DIMENSION IDLE(200),IJIND(30000),IWAIT(30000)
      INTEGER HI
      SUMIDL=0.
      SUMWT=0.
      DO 100 KKK=1,NOMACH
100    SUMIDL=SUMIDL+IDLE(KKK)
      DMACH=NOMACH
      SUMIDL=(PDHRS-SUMIDL/DMACH)/PDHRS
      DO 200 I=1,IJOB
      IF (IJIND(I).LT.LO) GO TO 200
      IF (IJIND(I).GT.HI) GO TO 200
      SUMWT=SUMWT+IWAIT(I)
200   CONTINUE
      SUMWT=SUMWT/ARRV
      RETURN
      END
```

```
      SUBROUTINE POISS(LAMDA,NOEVTS,IGESS,KKJ1,KKJ2,KJ1,KJ2)
C
C        THIS SUBROUTINE MAPS A UNIFORMLY DISTRIBUTED RANDOM NUMBER ONTO
C        A CUMULATIVE POISSON DISTRIBUTION IN ORDER TO OBTAIN A POISSON
C        DISTRIBUTED RANDOM NUMBER.
C
      DIMENSION PROB(10)
      REAL NFACT,LAMDA
      NFACT=1.0
      PZERO=EXP(-LAMDA)
      DO 100 N=1,10
      NFACT=NFACT*N
      PROB(N)=(LAMDA**N)*EXP(-LAMDA)/NFACT
100   CONTINUE
      CALL RAND(Z,IGESS,KKJ1,KKJ2,KJ1,KJ2)
      NOEVTS=0
      Z=Z-PZERO
      IF (Z.LT.0.0) GO TO 300
      NOEVTS=NOEVTS+1
      DO 200 N=1,10
      Z=Z-PROB(N)
      IF (Z.LT.0.0) GO TO 300
      NOEVTS=NOEVTS+1
200   CONTINUE
300   CONTINUE
      RETURN
      END
```

```
      SUBROUTINE EDIST(MU,MSERV,IGESS,KKJ1,KKJ2,KJ1,KJ2)
C
C       THIS SUBROUTINE MAPS A UNIFORMLY DISTRIBUTED RANDOM NUMBER ONTO
C       A CUMULATIVE EXPONENTIAL DISTRIBUTION IN ORDER TO OBTAIN AN
C       EXPONENTIALLY DISTRIBUTED RANDOM NUMBER.
C
      DIMENSION PROB(150)
      REAL MU
      DATA I/1/
      IF (I.EQ.0) GO TO 200
      I=0
      DO 100 N=1,50
100   PROB(N)=1.0-EXP(-MU*N)
200   CONTINUE
      MSERV=1
      CALL RAND(Z,IGESS,KKJ1,KKJ2,KJ1,KJ2)
      DO 300 N=1,50
      IF (Z.LT.PROB(N)) GO TO 300
      MSERV=MSERV+1
300   CONTINUE
      RETURN
      END
```

```
      SUBROUTINE RAND(Z,IGESS,A,X,I,ISW)
C
C       SUBROUTINE RAND GENERATES UNIFORMLY DISTRIBUTED RANDOM NUMBERS.
C
      INTEGER A,X
      M=2**20
      FM=M
      IF (I.EQ.1) GO TO 100
      I=1
      X=566387
      A=2**10+3
100   X=MOD(A*X,M)
      FX=X
      Z=FX/FM
      IF (ISW.EQ.1) GO TO 300
      DO 200 K=1,IGESS
      X=MOD(A*X,M)
      FX=X
      Z=FX/FM
200   CONTINUE
      ISW=1
300   CONTINUE
      RETURN
      END
```

APPENDIX B

SAMPLE COMPUTER OUTPUTS

The output from the computer program consists of statistics and a message log. The first example consists of statistics and one page of the message log for week one of a simulation of 4 communication channels. The second example consists of only the statistics for week 43 of a simulation of 10 communication channels. The message log may be printed or suppressed at the users option.

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* COMM. SATELLITE    *
*   SIMULATION       *
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NO. OF CHANNELS= 4 WEEKS SIMULATED= 52

WEEK 1

NO. OF ARRIVALS DURING PERIOD	=	9345
NO. OF MSGS COMPLETED THIS PD.	=	9343
AVERAGE TIME IN SYSTEM	=	1.6
AVERAGE NO. IN SYSTEM	=	2.4
AVERAGE FRACTIONAL CHAN. UTIL.	=	0.37
AVERAGE TIME IN QUEUE	=	0.0
AVERAGE PROCESSING TIME	=	1.6

THE MAXIMUM DELAY OF 4 MINUTES OCCURRED 1 TIMES

WEEK= 1 PAGE= 1

MSG NO.	ARRIVAL TIME DAY	HR.	MIN.	FINISH TIME DAY	HR.	MIN.	MSG. TYPE	CHAN. ASSGN.	PROCESS MINS.	WAIT MINS.
1	1	1	1	1	1	2	WARN	1	1	0
2	1	1	1	1	1	2	RIV.	2	1	0
3	1	1	1	1	1	2	RIV.	3	1	0
4	1	1	2	1	1	3	RIV.	4	1	0
5	1	1	4	1	1	7	WARN	1	3	0
6	1	1	4	1	1	6	RIV.	2	2	0
7	1	1	5	1	1	6	RIV.	3	1	0
8	1	1	8	1	1	9	RIV.	4	1	0
9	1	1	9	1	1	11	RIV.	2	2	0
10	1	1	12	1	1	13	RIV.	3	1	0
11	1	1	13	1	1	14	WARN	1	1	0
12	1	1	13	1	1	14	RIV.	4	1	0
13	1	1	14	1	1	15	RIV.	2	1	0
14	1	1	15	1	1	16	WARN	3	1	0
15	1	1	15	1	1	16	RIV.	1	1	0
16	1	1	15	1	1	16	RIV.	4	1	0
17	1	1	16	1	1	18	WARN	2	2	0
18	1	1	18	1	1	19	WARN	1	1	0
19	1	1	18	1	1	19	RIV.	3	1	0
20	1	1	19	1	1	20	RIV.	4	1	0
21	1	1	20	1	1	21	RIV.	2	1	0
22	1	1	22	1	1	23	RIV.	1	1	0
23	1	1	24	1	1	25	RIV.	3	1	0
24	1	1	28	1	1	29	RIV.	4	1	0
25	1	1	31	1	1	32	RIV.	2	1	0
26	1	1	32	1	1	34	RIV.	1	2	0
27	1	1	35	1	1	36	RIV.	3	1	0
28	1	1	36	1	1	39	WARN	4	3	0
29	1	1	37	1	1	40	RIV.	2	3	0
30	1	1	38	1	1	39	RIV.	1	1	0
31	1	1	39	1	1	42	WARN	3	3	0
32	1	1	44	1	1	48	RIV.	1	4	0
33	1	1	46	1	1	49	RIV.	4	3	0
34	1	1	46	1	1	47	RIV.	2	1	0
35	1	1	46	1	1	47	RIV.	3	1	0
36	1	1	47	1	1	48	RIV.	2	1	0
37	1	1	51	1	1	54	WARN	3	3	0
38	1	1	51	1	1	54	RIV.	1	3	0
39	1	1	52	1	1	53	RIV.	2	1	0
40	1	1	52	1	1	53	RIV.	4	1	0
41	1	1	53	1	1	54	WARN	2	1	0
42	1	1	54	1	1	57	WARN	4	3	0
43	1	1	56	1	1	57	RIV.	1	1	0
44	1	1	57	1	1	58	RIV.	2	1	0
45	1	1	58	1	1	59	WARN	3	1	0
46	1	1	58	1	1	59	WARN	1	1	0
47	1	1	58	1	1	59	RIV.	4	1	0
48	1	1	59	1	1	60	RIV.	2	1	0
49	1	1	60	1	2	4	RIV.	1	4	0
50	1	2	4	1	2	5	RIV.	3	1	0
51	1	2	5	1	2	9	WARN	4	4	0
52	1	2	5	1	2	7	RIV.	2	2	0
53	1	2	5	1	2	6	RIV.	1	1	0
54	1	2	6	1	2	7	WARN	3	1	0

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* COMM. SATELLITE    *
*   SIMULATION       *

NO. OF CHANNELS=  10          WEEKS SIMULATED=  52


WEEK 43

           NO. OF ARRIVALS DURING PERIOD =    9193
           NO. OF MSGS COMPLETED THIS PD.=    9192
           AVERAGE TIME IN SYSTEM        =     1.6
           AVERAGE NO. IN SYSTEM         =     2.4
           AVERAGE FRACTIONAL CHAN. UTIL.=     0.14
           AVERAGE TIME IN QUEUE         =     0.0
           AVERAGE PROCESSING TIME       =     1.6

           THE MAXIMUM DELAY OF    0 MINUTES OCCURRED 9193 TIMES
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REFERENCES

1. Hillier, Frederick S.; and Lieberman, Gerald J.: Introduction to Operations Research. Holden-Day, Inc., 1967.

2. Miller, Irwin; and Freund, John E.: Probability and Statistics for Engineers. Prentice-Hall, Inc., 1965.

3. Carnahan, Brice; Luther, H. A.; and Wilkes, James O.: Applied Numerical Methods. John Wiley & Sons, Inc., 1969.

TABLE I. - TABLE OF SEASONAL VARIATIONS OF DISASTER WARNING MESSAGES FROM 1966 - 1971

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1966	103.82	76.25	73.85	102.94	109.72	119.50	111.70	82.99	96.54	109.68	97.93	115.06
1967	98.35	93.59	79.65	105.71	120.16	123.28	96.33	85.86	99.15	91.91	77.64	128.27
1968	91.82	73.79	82.42	108.24	138.35	115.53	100.85	85.38	80.80	99.05	98.21	125.60
1969	109.85	88.27	80.80	98.72	123.88	115.38	92.60	86.18	81.77	99.96	101.47	121.11
1970	74.99	83.41	98.93	119.17	89.23	105.14	118.01	96.38	96.98	105.17	97.22	115.37
1971	90.52	102.56	102.74	103.74	112.13	93.12	89.53	99.07	94.14	85.61	112.16	114.67
Total	569.35	517.87	518.39	638.52	693.47	671.95	609.02	535.86	549.41	591.38	584.63	720.18
Mean	94.89	86.31	86.40	106.42	115.58	111.99	101.50	89.31	91.57	98.56	97.44	120.03

TABLE II. - TABLE OF SEASONALLY ADJUSTED DATA FOR

DISASTER WARNING MESSAGES FROM 1966 - 1971

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1966	5103.8	4121.2	3987.2	4512.3	4428.1	4977.2	5133.0	4334.3	4917.5	5190.7	4688.0	4471.3
1967	6010.1	6287.8	5346.0	5760.2	6028.7	6383.6	5503.4	5574.9	6279.3	5407.8	4620.3	6201.8
1968	5918.4	5228.8	5834.5	6220.6	7321.3	6309.5	6076.8	5843.7	5397.0	6146.5	6164.8	6400.0
1969	7349.5	6492.9	5937.5	5888.9	6804.8	6540.7	5792.1	6125.8	5668.9	5266.8	6611.2	6405.9
1970	5536.9	6770.9	8023.1	7846.2	5409.2	6578.2	8146.8	7561.3	7420.6	7476.7	6991.0	6735.0
1971	7935.5	9884.1	9891.2	8108.4	8069.7	6916.7	7376.9	9227.4	8554.1	7225.0	9575.1	7947.2

FOR CHANNELS NUMBERING 1 TO 20

Number channels	Average time in system	Average number in system	Average fraction channel utilization	Average time in queue	Average processing time	Maximum delay	Number times delay occurred
1	2.9	3.7	0.77	1.4	1.6	13	1
2	2.9	3.7	0.74	1.4	1.6	13	1
3	1.8	2.6	0.49	0.2	1.6	5	19
4	1.6	2.4	.37	.0	1.6	4	1
5	1.6	2.4	.30	.0	1.6	2	4
6	1.6	2.4	.25	.0	1.6	1	26
7	1.6	2.4	.21	.0	1.6	1	5
8	1.6	2.4	.19	.0	1.6	1	1
9	1.6	2.4	.16	.0	1.6	0	0
10	1.6	2.4	.15	.0	1.6	0	0
11	1.6	2.4	.13	.0	1.6	0	0
12	1.6	2.4	.12	.0	1.6	0	0
13	1.6	2.4	.11	.0	1.6	0	0
14	1.6	2.4	.11	.0	1.6	0	0
15	1.6	2.4	.10	.0	1.6	0	0
16	1.6	2.4	.09	.0	1.6	0	0
17	1.6	2.4	.09	.0	1.6	0	0
18	1.6	2.4	.08	.0	1.6	0	0
19	1.6	2.4	.08	.0	1.6	0	0
20	1.6	2.4	.07	.0	1.6	0	0

Random number seed = 8

Number of arrivals = 9357

Number of messages completed = 9355

TABLE IV. - PROBABILITIES OF BEING

IN STATE ZERO AND STATE (S+1)

FOR $\lambda = 0.9717$ AND $\mu = 1.008$

S	P_o	P_{S+1}
3	0.377555668	0.026689434
4	.380904197	.004351790
5	.381315291	.000632013
6	.381363153	.000081526
7	.381368398	.000009239
8	.381368994	.000000623
9	.381369114	<.0000001
10	.381369114	<.0000001
11	.381369114	<.0000001
12	.381369114	<.0000001
13	.381369114	<.0000001
14	.381369114	<.0000001
15	.381369114	<.0000001
16	.381369114	<.0000001
17	.381369114	<.0000001
18	.381369114	<.0000001
19	.381369114	<.0000001
20	.381369114	<.0000001

TABLE V. - PROBABILITIES OF BEING

IN STATE ZERO AND STATE (S+1)

FOR $\lambda = 0.9717$ AND $\mu = 0.625$

S	P_o	P_{S+1}
3	0.197496175	0.106376171
4	.208861827	.027976811
5	.210840284	.006570279
6	.211182415	.001367569
7	.211238622	.000253737
8	.211247265	.000042796
9	.211248517	.000006914
10	.211248695	.000001430
11	.211248755	<.0000001
12	.211248755	<.0000001
13	.211248755	<.0000001
14	.211248755	<.0000001
15	.211248755	<.0000001
16	.211248755	<.0000001
17	.211248755	<.0000001
18	.211248755	<.0000001
19	.211248755	<.0000001
20	.211248755	<.0000001

TABLE VI. - PROBABILITIES P_{S+1} FOR VARIOUS

PERCENTAGES OF DEGRADATION FOR

$S = 10,\ \lambda = 0.9717,\ \mu = 1.008$

Degradation (90)	P_{S+1}
0	<0.0000001
10	<0.0000001
20	.0000006
30	.0000092
40	.0000815
50	.0006320
60	.0043518
70	.0266894
80	.1511115
90	.9292730
100	1.0000000

FIG. 1 DISASTER WARNING MESSAGES ISSUED BY THE NATIONAL WEATHER SERVICE FOR THE YEARS 1966 - 1971

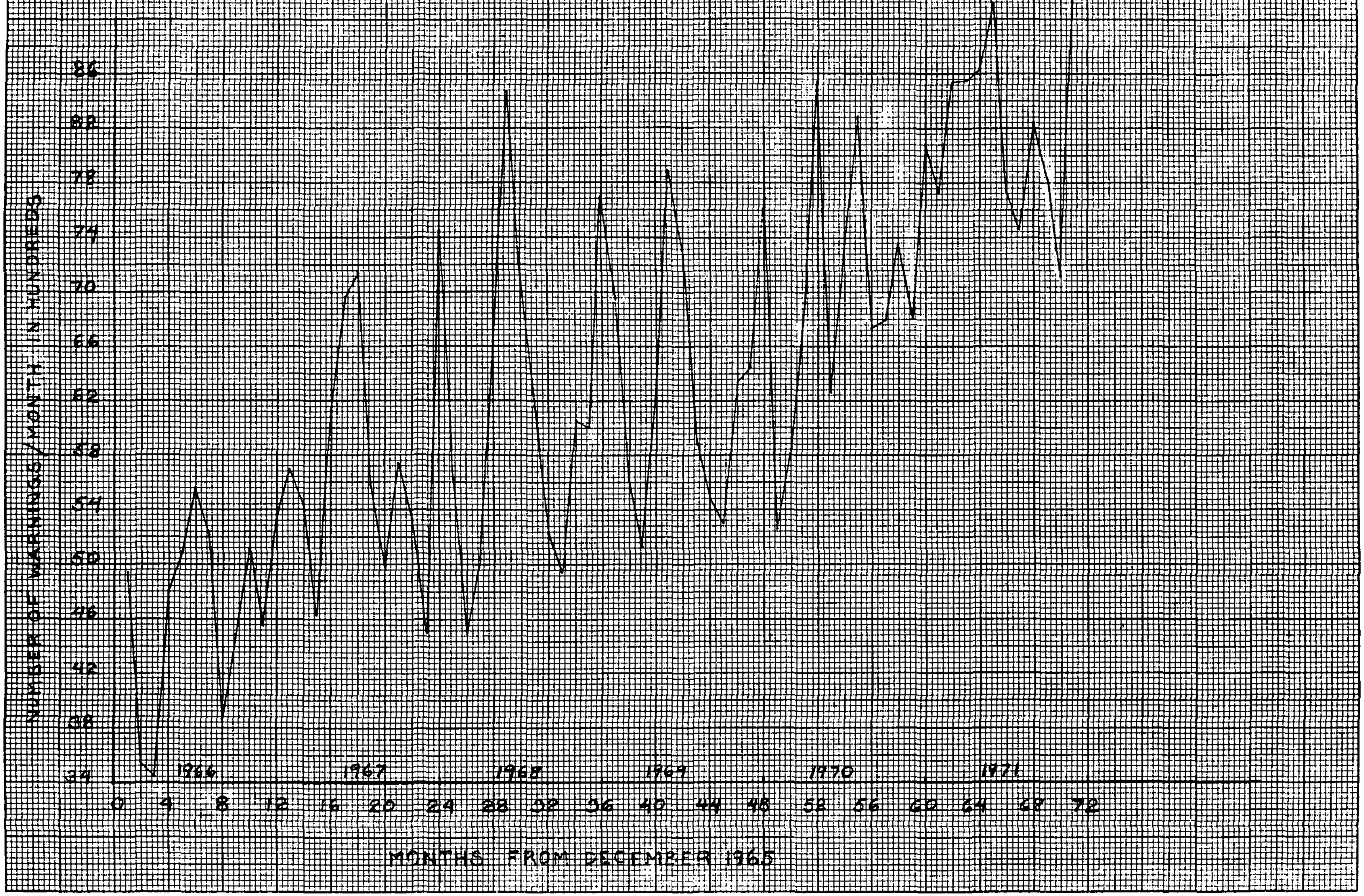


FIG. 2. IRREGULAR VARIATIONS OF MESSAGES FROM TREND IN PERCENT

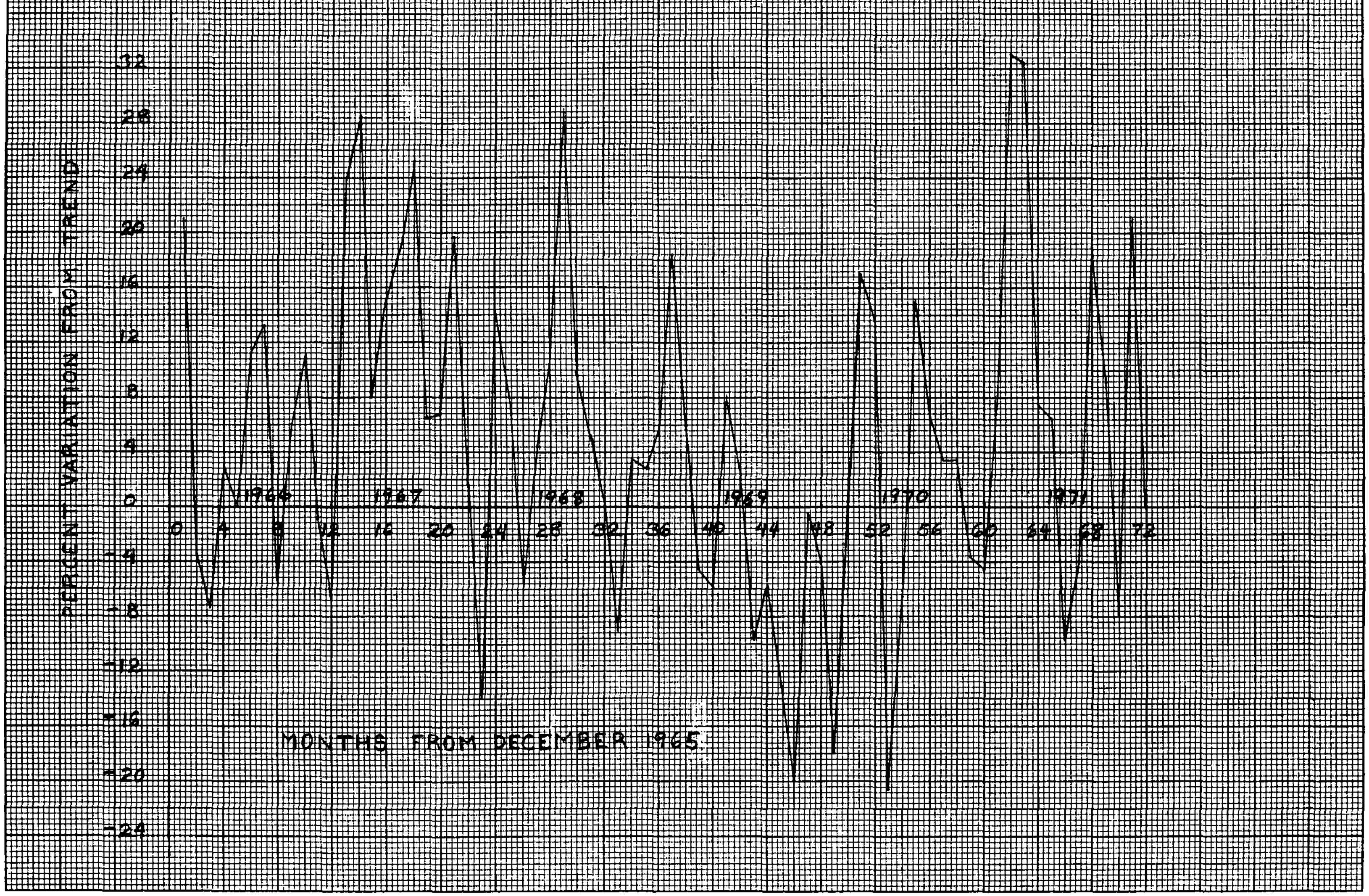


FIG. 3 RIVER FORECASTS AND WARNING MESSAGES ISSUED BY THE NATIONAL WEATHER SERVICE FOR THE YEARS 1967–1971

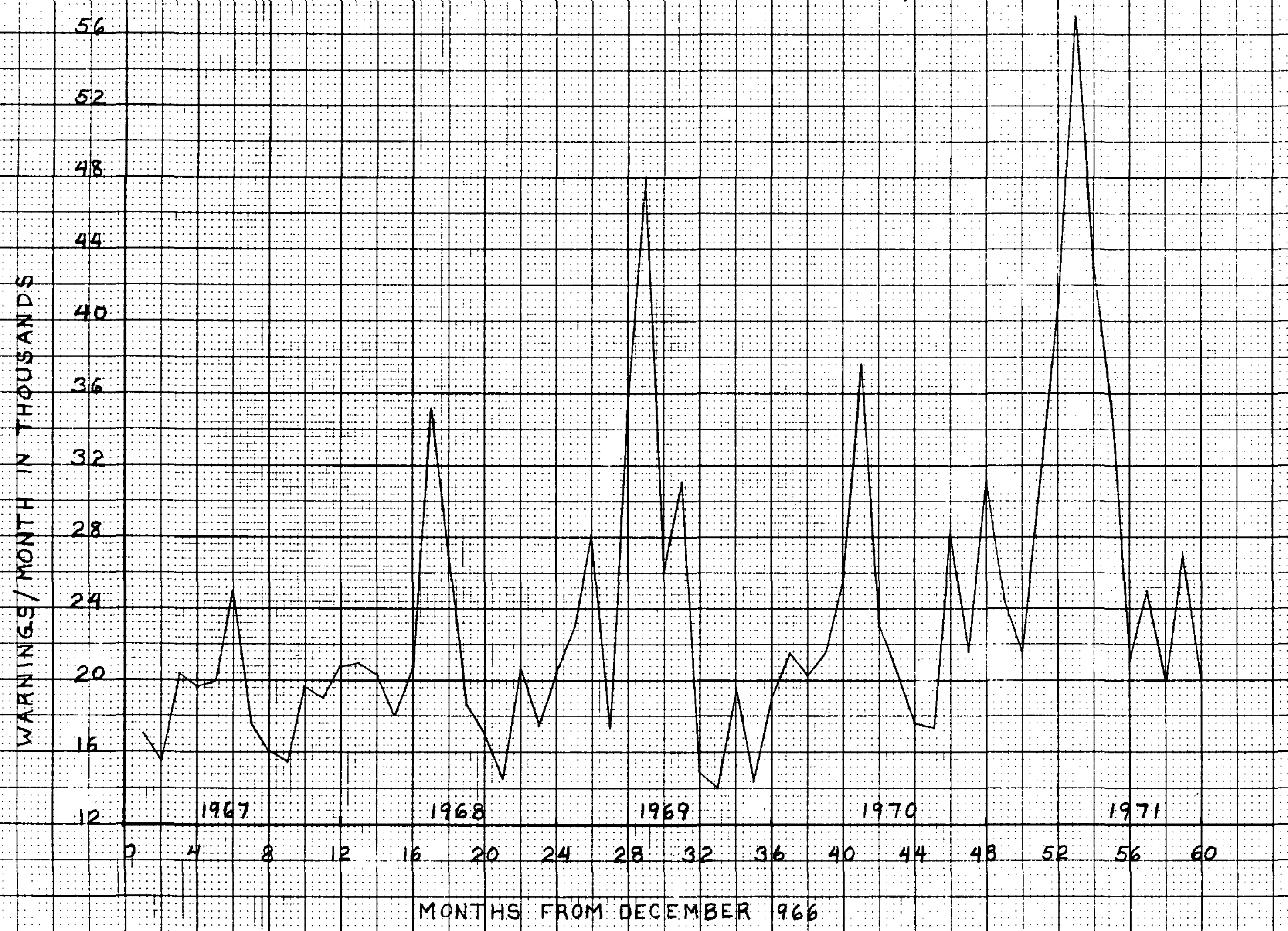
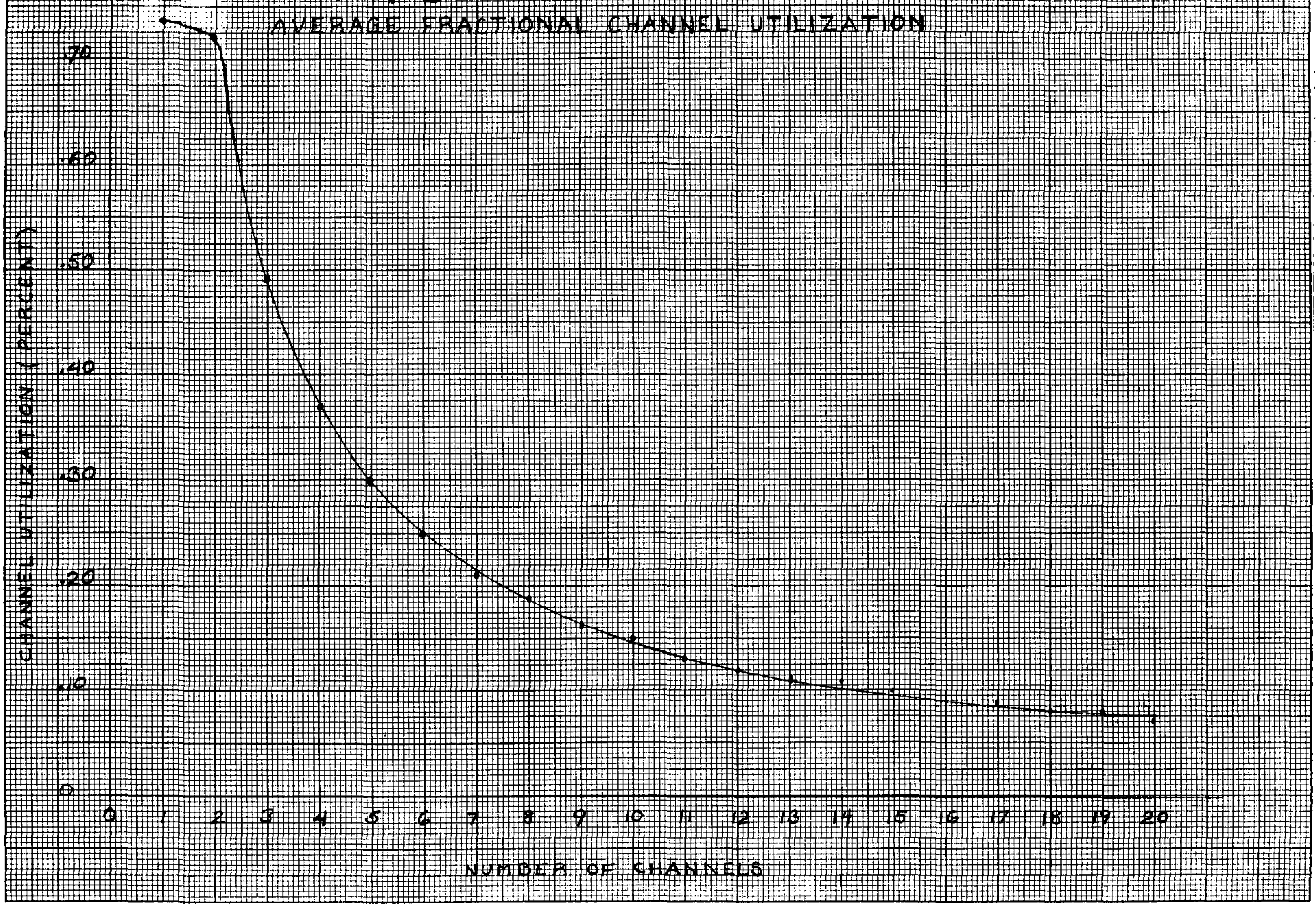


FIG. 4 IRREGULAR VARIATIONS OF RIVER FORECASTS AND WARNINGS FROM TREND IN PERCENT

FIG. 5


AVERAGE FRACTIONAL CHANNEL UTILIZATION
CHANNEL UTILIZATION (PERCENT)
.70
.60
.50
.40
.30
.20
.10
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
NUMBER OF CHANNELS