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ANALYSIS OF TRANSMISSION ERROR EFFECTS ON THE TRANSFER OF REAL-TIME SIMULATION DATA

by Leonard Credeur

April 1977

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16. Abstract

An analysis was made to determine the effect of transmission errors on the quality of data transferred from the Terminal Area Air Traffic Model to a remote site. Data formating schemes feasible within the operational constraints of the commercial Bell System data link were proposed and their susceptibility to both random bit error and to noise burst were investigated. It was shown that satisfactory reliability is achieved by a scheme formating the simulation output into three data blocks which has the priority data triply redundant in the first block in addition to having a retransmission priority on that first block when it is received in error.

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INTRODUCTION

A two way real-time communication link is being established between the central computer facility at Langley Research Center and the Wallops Flight Center. Its purpose is to connect the Terminal Area Air Traffic Model (TAATM) to Wallops thereby providing a representative Air Traffic Control (ATC) environment for research using NASA's B737 aircraft which is managed by the Terminal Configured Vehicle Program Office. Figure 1 is a pictorial view of the facilities to be serviced by this data link. In order to use these facilities in the manner intended, an investigation was needed to determine the effect transmission errors would have on the quality of the received data. The goal of this discussion is to propose simple data formating schemes operationally permitted by the tie-line and to analyze their susceptability to random bit error and also to noise burst disturbance.

DESCRIPTION AND ANALYSIS

The TAATM simulation provides a computer generated radar display, updated every four seconds, of aircraft movement within a 40 nautical mile radius of a selected terminal area. It controls aircraft in accordance with specified ATC procedures, the navigation capabilities available, and the aircraft flight performance characteristics of the traffic. The exact information transferred from TAATM to Wallops will depend on the particular

flight experiment. However, a tentative list of the possible data is shown in table 1. This consist of information required for up to 10 controller messages and also aircraft data for up to 40 aircraft active in the terminal.

Normally the critical information will be controller instructions to the aircraft. Thus, we seek to determine how to protect against errors or loss of this information within the normal operating capability of the Bell System 3002-type four-wire leased channel. The protocol or operational procedure agreed to will provide for half-duplex operation over the channel at 4800 bits per second and will not permit the simultaneous transmission of data in both directions. Communication between the Langley central computer system and Wallops Flight Center are bit serial, byte serial. Each byte or character consist of 8 bits of which 6 are data bits and the other 2 bits serve protocol requirements. Data characters are sent in blocks with a maximum block length of 1040 data characters (8-bit bytes). Protocol procedures in order to identify stations, sync transmissions, signal or acknowledge correct transmission, etc., require an additional 22 characters each time a block of data is transmitted. (For protocol details see references 5 and 6.) Thus, the total bits per data block are

$$8[(\#\text{ of data characters}) + (22\text{ overhead protocol characters})]$$

The information which may be needed by the TAATM simulation from Wallops is contained in table 2. Sending this data requires a block of 39 data characters plus an overhead of 22 characters for a total of 61 characters. The Wallops to Langley transmission time allowing for one retransmission is

$$(2\text{ transmission})\ (61\text{ characters})\ (8\text{ bits/character})\ (1/4800\text{ sec/bit}) = 0.203\text{ sec}$$

This leaves for Langley to Wallops transmission, if we ignore for now the internal computer "turnaround time" at each end

4 sec. scan time - 0.203 sec = 3.797 sec.

Constraints on our transmission scheme then are that we have somewhat less than 3.797 sec allowed for TAATM to Wallops output during a radar scan, as well as the standard protocol which has an error detection but not error correction code. From the data in table 1, we will consider the controller messages as the critical information which we will attempt to protect from transmission error to a greater degree than the balance of the information. Another consideration is the ease of reconstructing the transmitted data at the Wallops Complex. We will consider three data arrangement schemes which conveniently break down a TAATM frame of transmission data into progressively smaller blocks of characters for redundance and yet remain within the time limits required, as well as achieving higher reliability for the high priority data. These schemes are described as follow:

I. This scheme consist of 1 data block (A) per simulation scan which contains 3 copies of the controller messages as well as the balance of the scan data. If there is an error in the first attempt at transmitting the data, there is the capability of 1 more attempt during a scan time. The character format is shown in Figure 2. There are 1014 data characters and 22 overhead characters per block for a total of 1036 characters.

II. This scheme consist of 2 data blocks (A,B) per simulation scan, with 3 copies of the controller messages in block A as shown in Figure 3. It has the ability of trying to transmit block A error free for up to four times if necessary and to transmit block B up to (4 minus the number of

transmissions of block A). There are 511 data characters and 22 overhead characters for a total of 533 characters per block for each transmission.

III. This scheme consist of 3 data blocks (A,B,C) per simulation scan with 3 copies of the controller messages in block A as shown in Figure 4. It will attempt to transmit block A without error up to six times if necessary, and to transmit block B up to (6 minus the number of transmissions of block A), and to transmit block C up to (6 minus the sum of number of transmissions of block A and B). There are 341 data characters and 22 overhead characters for a total of 363 characters per block for each transmission.

Random Bit Error Performance

The number of bit errors after transmission for the equipment and data rates we are dealing with are typically in the range of one in 10^5 to 10^4 bits. In the following development we shall assume that the errors occur at random and are independent of each other. It should be recognized that in some cases errors occur from noise burst affecting more than one bit, but we shall treat that case in the following section. If we define the following:

P_{bit} = the bit error probability of an independent bit

A,B,C = block identifiers

N_c = number of characters per block

N = number of bits per block, in our case $8\ N_c$

A_C = event that block A received correctly

A_E = event that block A received in error

P(event) = probability of event occurring

Then the probability that block A, B, or C is correctly received after transmission is

$$P(A_C) = (1 - P_{bit})^N \tag{1}$$

and the probability of block A, B, or C being in error is

$$P(A_E) = 1 - P(A_C) \tag{2}$$

If we define

n = number of possible transmissions of block A, B, or C

A_{TE} = event that block A in error after all n transmissions

then the probability of block A, B, or C being in error after transmission n times is

$$P(A_{TE}) = [P(A_E)]^n \tag{3}$$

Since there are three copies of the controller messages in block A, then even if block A has been received in error it is possible that two of the three copies of the messages have been received correctly. If we do a simple bit-by-bit comparison at Wallops of the last block A sent in the four second limit and determine that two of the three copies agree perfectly, then they almost certainly have been received correctly under the independent bit error assumption. If we define

a,b,c = 1st, 2nd and 3rd copy of the priority data in block A

a_C = event that copy was received correctly

a_E = event that copy was received in error

then for our case with a single message length being 110 characters

$$P(a_C) = (1 - P_{bit})^{880} \tag{4}$$

and

$$P(a_E) = 1 - P(a_C) \tag{5}$$

If we let the event (M_C) be defined as the correct determination of the priority data from the comparison procedure at Wallops operating on the last block A incorrectly received during the scan then we can write

$$(M_C) = (a_C b_C c_E \cup a_C b_E c_C \cup a_E b_C c_C) \tag{6}$$

Similiarly if we define event (M_E) as the incorrect determination of priority data from the comparison procedure at Wallops then

$$(M_E) = (a_E b_E c_E \cup a_C b_E c_E \cup a_E b_C c_E \cup a_E b_E c_C) \tag{7}$$

Since these individual possible outcomes of the comparison procedure are mutually exclusive or disjoint we can say

$$P(M_C) = 3P(a_C)^2 P(a_E) \tag{8}$$

and

$$P(M_E) = P(a_E)^3 + 3P(a_E)^2 P(a_C) \tag{9}$$

Remember what we seek to formulate is the probability that block A has been received in error and after a comparison procedure at Wallops we are still not able to obtain an error free sample of the priority data. Using the conditional probability rule, this can be written as

$$P(A_{TE} \cap M_E) = P(M_E | A_{TE})\ P(A_{TE}) \tag{10}$$

Given that we have not received block A correctly even after all possible transmissions for the scheme considered, we know that the outcome must be either event (M_E) or (M_C). The probability that it will be (M_E) is

$$P(M_E | A_{TE}) = \frac{P(M_E)}{P(M_E) + P(M_C)} \tag{11}$$

Therefore, even after utilization of the comparison procedure at Wallops when not receiving block A correctly, the probability that the priority data will be in error is

$$P(A_{TE} \cap M_E) = \frac{P(M_E)P(A_{TE})}{P(M_E) + P(M_C)} \tag{12}$$

So far we have analyzed the effect of random bit error on the high priority data but for completeness we should also consider its effect on the total information transmitted during a scan of the terminal area simulation. If we define

S_C = the event that a total scan of data was received correctly (all the blocks in the scan received without error)

S_E = the event that a total scan of data was not received correctly

then we can write the probability of some data in the scan being in error simply as

$$P(S_E) = 1 - P(S_C) \tag{13}$$

For scheme I we have already solved our problem since the total scan information is contained in the first and only block A whose probability of error after retransmission we have already formulated (equation 3). The task for the other two schemes will be to determine the probability of the combinations possible to get all the blocks of that scheme transmitted correctly. Recalling that scheme II consist of two blocks (A,B), we can write the event that a correct scan of data was received from that scheme as

$$S_C = (A_C B_C \cup A_C B_E B_C \cup A_E A_C B_C \cup A_C B_E B_E B_C \cup A_E A_E A_C B_C \cup A_E A_C B_E B_C) \tag{14}$$

Since $P(A_C) = P(B_C)$ and $P(A_E) = P(B_E)$ for A and B the same character size, also these individual outcomes are disjoint events in the universe of possible outcomes for scheme II, then the probability of a correct scan transmission is

$$P(S_C) = P(A_C)^2 \, [1 + 2P(A_E) + 3P(A_E)^2] \tag{15}$$

Scheme III is more complex. Since it consist of three blocks (A,B,C), we can write the event that a correct scan of data was received as

$$
\begin{aligned}
(S_C) = (&A_C B_C C_C \cup \\
&A_C B_C C_E C_C \cup A_C B_E B_C C_C \cup A_E A_C B_C C_C \cup \\
&A_C B_C C_E C_E C_C \cup A_C B_E B_E B_C C_C \cup A_E A_E A_C B_C C_C \cup \\
&A_C B_C C_E C_E C_E C_C \cup A_C B_E B_E B_E B_C C_C \cup A_E A_E A_E A_C B_C C_C \cup \\
&A_C B_E B_C C_E C_E C_C \cup A_C B_E B_E B_C C_E C_C \cup A_E A_C B_C C_E C_E C_C \cup \\
&A_E A_E A_C B_C C_E C_C \cup A_E A_C B_E B_E B_C C_C \cup A_E A_E A_C B_E B_C C_C \cup \\
&A_C B_E B_C C_E C_C \cup A_E A_C B_C C_E C_C \cup A_E A_C B_E B_C C_C \cup \\
&A_E A_C B_E B_C C_E C_C)
\end{aligned}
\tag{16}
$$

Since $P(A_C) = P(B_C) = P(C_C)$ and $P(A_E) = P(B_E) = P(C_E)$ for A, B and C the same size and the above individual outcomes are disjoint events, then the probability of a correct scan transmission for scheme III is

$$P(S_C) = P(A_C)^3 \, [1 + 3P(A_E) + 6P(A_E)^2 + 10P(A_E)^3] \tag{17}$$

In review, we have developed (1) the probability of error for the total scan of information, (2) the probability of error for block a containing the high priority data, and (3) the probability of error for both block A and the comparison procedure of the individual copies of the high priority data within block A. If we let a generalized probability of error, P(E), represent any of the above it is easier to visualize its effect on our data transmission by saying that on the average 1 out of every $[1|P(E)]$ scans will be in error. Since a scan of data is four seconds long, then we will average an error in the particular information referred to every $4[1|60P(E)]$ minutes of real time operation. Table 3 contains examples of these calculations in convenient time units for the three schemes analyzed at various bit error probabilities.

Noise Burst or Line Outage Performance

It was pointed out in the random bit error analysis that in may cases errors result not from isolated random bit mistakes but from noise burst or even line outages occurring for a period of time. In order to analyze this problem we will assume that we have an entire four seconds to transmit a scan of information. As shown in Figure 5, this time will be broken up to 2, 4, or 6 segments to accommodate 1, 2, or 3 blocks with retransmissions as described in schemes I, II, or III. This ideal time breakdown while not accounting for Wallops transmission, error acknowledgements, etc., will be sufficiently representative for the results to apply to our case.

We will determine the probability of having an error in: (1) the total scan information, (2) block A, and (3) the high priority data after the comparison procedure caused by either line outage or extended noise burst lasting for various periods of time. In this manner the burst susceptibility of the proposed block coding schemes can be compared.

For illustration, Figure 6 shows the situation where there is a disturbance of three seconds duration occurring for scheme II (2 blocks/scan). If the three seconds disturbance starts at 2.5 seconds from the beginning of the reference scan 1, we see that the scan information for both scan 1 and scan 2 can be correctly sent. However, if the 3 seconds noise starts in the interval between time 0 and 2 seconds, we will not be able to correctly transmit scan 1. Likewise, it it starts in the interval between 3 seconds and 4 seconds we will not be able to correctly transmit scan 2. Since the starts of the disturbances are uniformly distributed in the 4 second interval, we can say that a 3 second noise disturbance has a probability of 0.75 of causing a scan of data to be incorrectly received. Similiarly, we see that a 3 second

noise occurring in the interval between 0 and 1 second will result in even block A being incorrectly received. Thus, a noise burst of 3 seconds has a 0.25 probability of causing block A to be in error. Using this procedure the probability of error of: (1) the total scan information, (2) block A, and (3) the high priority data after the comparison procedure, resulting from disturbances of various lengths were determined for the three data block schemes proposed. These results are plotted in Figures 7 and 8.

DISCUSSION AND CONCLUSION

Since real time experiments are to be conducted with the Terminal Area Air Traffic Model at Langley providing a representative ATC environment, it is essential that we investigate to what extent transmission errors would affect the quality of the data provided to Wallops. We proposed three data formating schemes which were feasible within the operational constraints of the commercial Bell System tie line and the time requirements of the Terminal Area simulation. The performance of these schemes submitted to both random bit error and to noise burst disturbance were investigated.

The data in Table 3 indicates that the three block per scan (scheme III) data formating was considerably superior at all levels of random bit error considered for both the total scan information and particularly for the high priority data. Consider the fact that it takes approximately twenty minutes for an aircraft to fly from the perimeter of a large terminal to the runway. Even for the worst bit error probability assumed, the result in table 3c for scheme III indicates that we could average 150 flights between errors for the high priority data. In fact, depending on the bit error characteristics of our particular tie-line it may be possible that the errors shown in table 3b for scheme III are such that we will not need to encode three copies of the

high priority data in block A. This will leave room in block A for other data for which we may want a higher reliability. If the random bit error for our link are in the mid-range assumed, then from table 3a we see that for scheme III we can expect to operate 8 hours of real time without any errors even for the low priority data.

Figure 8 indicates that for both block A and for the high priority data after comparison, scheme III has less probability of error than the other schemes for noise burst of up to about 6.6 seconds in length. In fact scheme III completely protects the high priority data from noise burst of up to about 2.6 seconds duration. The advantage of scheme III for the total scan information is less pronounced. Figure 7 indicates that this scheme will give the total scan information complete immunity from noise burst of less than about 1.3 seconds, however, its advantage for noise of longer duration rapidly disappears.

If the performance of the tie-line used is within the bounds assumed in our analysis, it appears that data formating scheme III (three data blocks/scan) will grant us the transmission reliability necessary for the successful conduct of experiments using the Terminal Area Air Traffic Model (TAATM) at Langley to simulate a terminal for an aircraft flying at the Wallops Flight Center.

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TABLE 1.- TENTATIVE LIST OF DATA TRANSMITTED FROM LANGLEY TO WALLOPS

DATA	NO. OF CHARACTERS	
1. For 10 controller messages	110	
a. Aircraft I.D.		2
b. Message type		1
c. Information 1		2
d. Information 2		2
e. Information 3		2
f. Information 4		2
2. Controller number for controller handling the TCV-B737 A/C	1	
3. Scan number	2	
4. Number of aircraft	1	
5. Active traffic for 40 A/C	680	
a. X-position		3
b. Y-position		3
c. Heading		2
d. Velocity		2
e. Identification		2
f. Altitude/100		2
g. Flight status		1
h. Bank angle		2

TABLE 2.- TENTATIVE LIST OF DATA TRANSMITTED FROM WALLOPS TO LANGLEY

DATA	NO. OF CHARACTERS	
1. Scan number	2	
2. Aircraft data	26	
a. X-position		3
b. Y-position		3
c. Altitude		3
d. Radar ground speed		2
e. Indicated airspeed		2
f. Heading		2
g. Rate of change in X		3
h. Rate of change in Y		3
i. Rate of change in heading		3
j. Bank angle		2
3. Controller message verification	11	
a. Aircraft I.D.		2
b. Message type		1
c. Information 1		2
d. Information 2		2
e. Information 3		2
f. Information 4		2

TABLE 3a.- EFFECT OF RANDOM BIT ERRORS ON TRANSMITTING A COMPLETE SCAN OF SIMULATION DATA.

Transmission scheme	The average time without an error in transmitting 4 sec. scans of terminal area data (all blocks in scan received correctly) for various probabilities of error per transmitted bit.		
	$P_{bit} = \frac{1}{10,000}$	$P_{bit} = \frac{1}{50,000}$	$P_{bit} = \frac{1}{100,000}$
I, 1 block (A)	12.60 sec 0.21 min	171.43 sec 2.86 min	632.28 sec 10.54 min
II, 2 blocks (A,B)	32.31 sec 0.54 min	1,950.22 sec 32.50 min	14,191.94 sec 236.53 min
III, 3 blocks (A,B,C)	103.39 sec 1.72 min	28,848.96 sec 480.82 min 8.01 hr	416,163.80 sec 6,936.06 min 115.60 hr 4.82 day

TABLE 3b.- EFFECT OF RANDOM BIT ERROR ON TRANSMITTING BLOCK A (FIRST BLOCK IN FORMAT) OF THE SIMULATION SCAN DATA.

Transmission scheme	The average time without error in transmitting at least block A (the first block in format), using all transmission slots for that block if necessary, for various probabilities of error per transmitted bit.		
	$P_{bit} = \frac{1}{10,000}$	$P_{bit} = \frac{1}{50,000}$	$P_{bit} = \frac{1}{100,000}$
I, 1 block (A)	12.60 sec 0.21 min	171.43 sec 2.86 min	632.28 sec 10.54 min
II, 2 blocks (A,B)	275.39 sec 4.59 min	1,492.97 min 24.88 hr	21,955.58 min 365.92 hr 15.25 day
III, 3 blocks (A,B,C)	260.03 min 4.33 hr	2,065,518.16 min 34,425.30 hr 1,434.39 day 3.93 yr	1.212×10^8 min 2,020,793.77 hr 84,199.74 day 230.53 yr

TABLE 3c.- EFFECT OF RANDOM BIT ERROR ON THE RECOVERY OF THE SIMULATION SCAN HIGH PRIORITY DATA.

Transmission scheme	The average time without error in the recovery of the high priority data after utilization of comparison procedure at Wallops for cases when block A is incorrectly received, even after all possible transmissions, for various probabilities of error per transmitted bit.		
	$P_{bit} = \frac{1}{10,000}$	$P_{bit} = \frac{1}{50,000}$	$P_{bit} = \frac{1}{100,000}$
I, 1 block (A)	145.49 sec	9,769.41 sec	71,955.93 sec
	2.42 min	162.82 min	1,199.27 min
		2.71 hr	19.99 hr
II, 2 blocks (A,B)	3,179.92 sec		
	53.00 min	85,080.77 min	2,498,649.59 min
	0.88 hr	1,418.01 hr	41,644.16 hr
		59.08 day	1,735.17 day
			4.75 yr
III, 3 blocks (A,B,C)	3,002.57 min		
	50.04 hr		
	2.09 day	81,742.46 day	9,582,329.83 day
		223.80 yr	26,234.99 yr

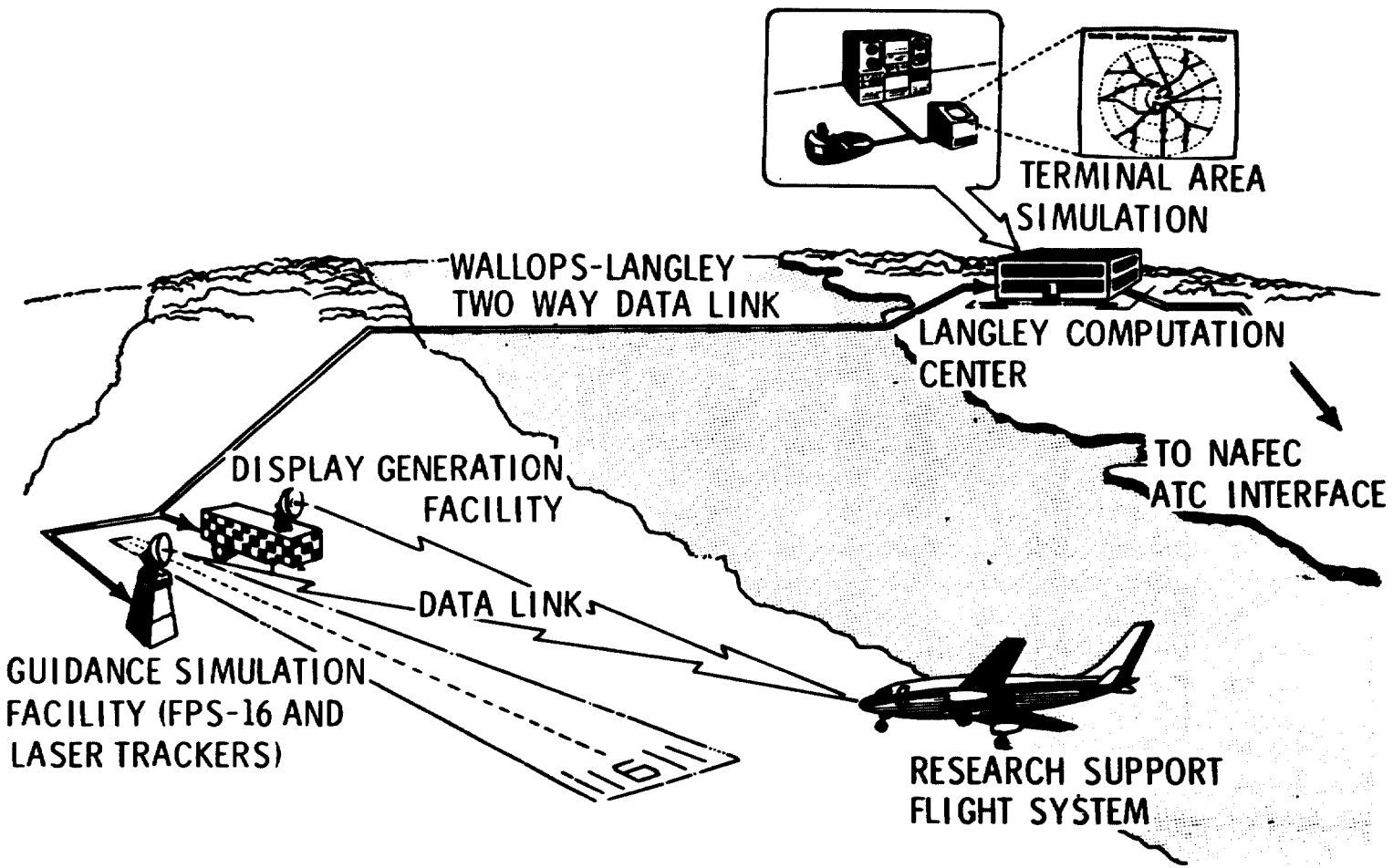

Figure 1. Wallops-Langley aircraft research facilities.

	Protocol	Controller #	Copy 1 Controller Messages	Copy 2 Controller Messages	Copy 3 Controller Messages	Scan #	# of A/C	40 Active A/C Traffic Data	Protocol	Protocol
Block A	8	1	110	110	110	2	1	680	4	10

Figure 2. The character format for scheme I which has one data block per scan of information.

	Protocol	Block #	Controller #	Copy 1 Controller Messages	Copy 2 Controller Messages	Copy 3 Controller Messages	Scan #	# of A/C	10 Active A/C Traffic Data	Blank	Protocol
Block A	8	1	1	110	110	110	2	1	170	6	14

	Protocol	Block #	30 Active A/C Traffic Data	Protocol	Protocol
Block B	8	1	510	4	10

Figure 3. The character format for scheme II which has two data blocks per scan of information.

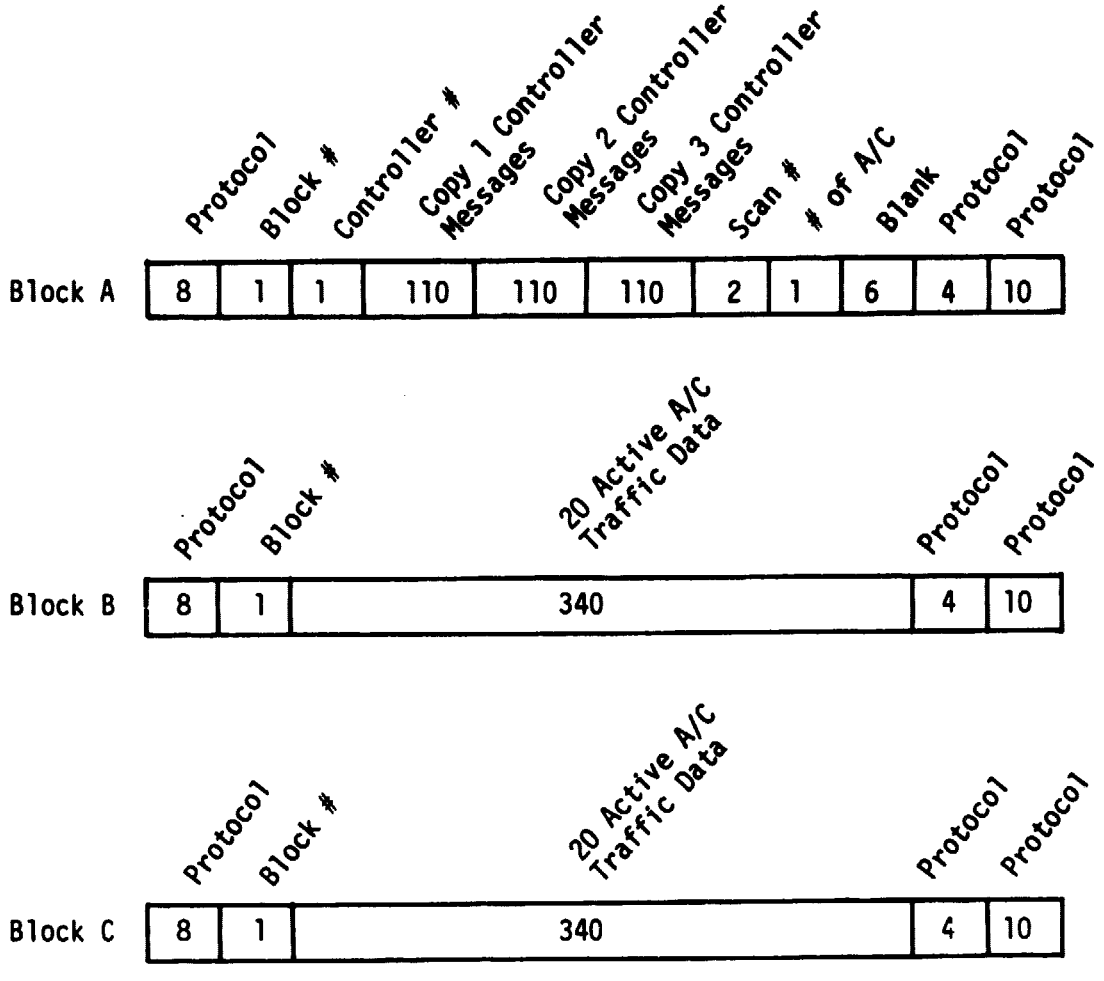

Figure 4. The character format for scheme III which has three data blocks per scan of information

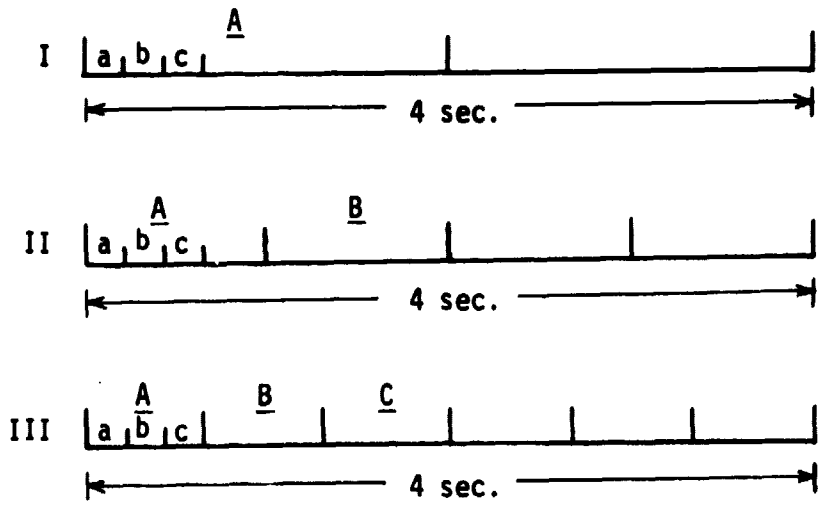

Figure 5. Idealized timing to transmit scan of data for the various blocks per scan schemes proposed.

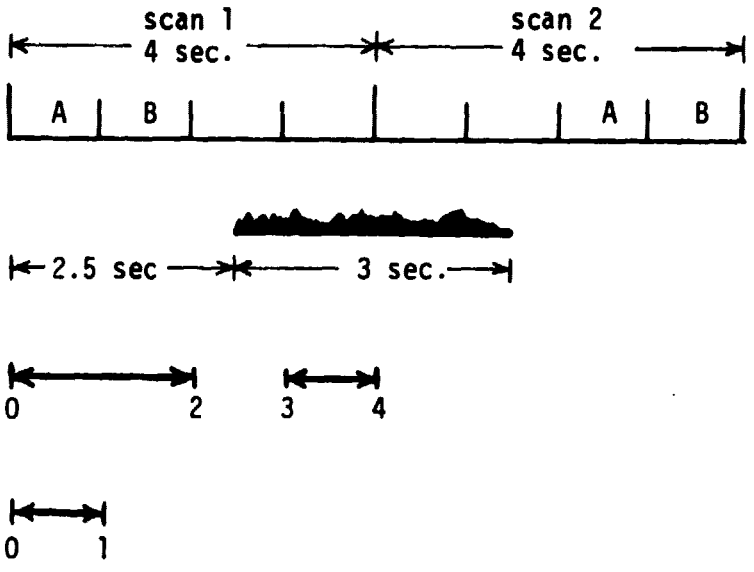

Figure 6. Illustration of the effect of a three second loss of information for the two block per scan (II) data block scheme.

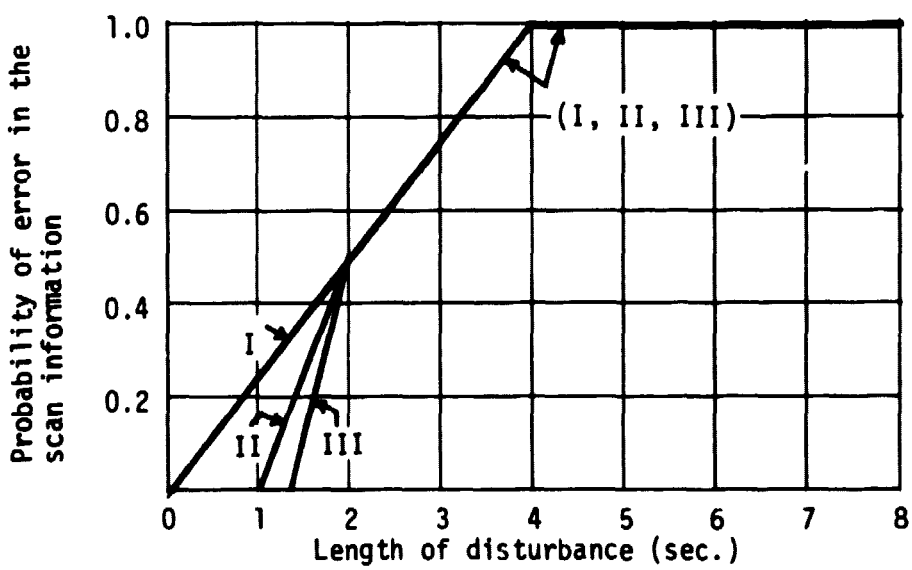

Figure 7. Probability of error in scan information versus time of disturbance for data block schemes I, II, III.

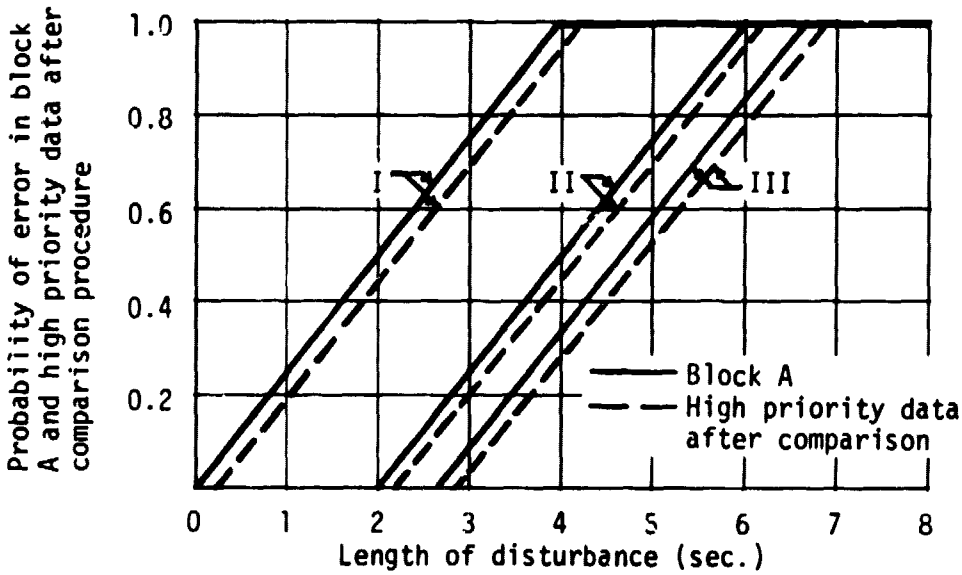

Figure 8. Probability of error in information of block A and of the high priority data after the comparison procedure versus time of disturbance for data block schemes I, II, III.