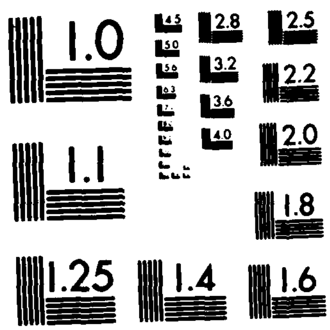
AD-A146 656 PRELIMINARY ANALYSIS OF LORAN-C SYSTEM RELIABILITY FOR CIVIL AVIATION(U) MITRE CORP MCLEAN VA G A WONG SEP 81 DOT/FAA/PM-81/110 1/1

UNCLASSIFIED F/G 17/7 NL

END



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

DOT/FAA/PM-81/110

Program Engineering &
Maintenance Service
Washington, D.C. 20591

Preliminary Analysis of LORAN-C System Reliability for Civil Aviation

Gene A. Wong

The MITRE Corporation
1820 Dolley Madison Boulevard
McLean, Virginia 22102

September 1981
Published September 1983

Final Report

This document is available to the U.S. public through the *National Technical Information* Service, Springfield, Virginia 22161.

US Department of Transportation
Federal Aviation Administration

NOTICE

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof.

Technical Report Documentation Page

1. Report No. DOT/FAA/PM-81/110	2. Government Accession No. AD-A146656	3. Recipient's Catalog No.
4. Title and Subtitle Preliminary Analysis of LORAN-C System Reliability for Civil Aviation		5. Report Date September 1981
		6. Performing Organization Code
7. Author(s) Gene A. Wong		8. Performing Organization Report No.
9. Performing Organization Name and Address The MITRE Corporation 1820 Dolley Madison Boulevard McLean, Virginia 22102		10. Work Unit No. (TRAIS)
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Program Engineering & Maintenance Service Washington, D.C. 20591		13. Type of Report and Period Covered Final
		14. Sponsoring Agency Code APM-400
15. Supplementary Notes		

16. Abstract

The LORAN-C system is one of the radionavigation systems currently under evaluation by the FAA with regard to its suitability as the primary or supplemental domestic navigation system for civil aviation during the post 1995 time period. Reliability of a candidate system to provide continuous navigation signals for airborne applications has been adopted as one of the evaluation criteria. The key consideration in the system reliability assessment is the impact of station outages and the resultant loss of navigation signals to the aviation users.

This paper presents an analytical technique for evaluating the reliability of the LORAN-C system over the conterminous United States (CONUS). Emphasis is placed on the technique itself and not the specific reliability statistics. The technique is applicable to the analysis of the existing USCG ground station configuration, as well as any proposed full-CONUS coverage station configuration.

The technique is based on the use of a Markov Chain model to provide a probabilistic measure of system unreliability and incorporates signal strength, relative geometry, and receiver configuration which define system coverage. A simplified analytic procedure is employed to bound the system unreliability and a numerical example is presented based on preliminary LORAN-C station reliability statistics for solid-state ground stations and a simple receiver model.

17. Key Words LORAN-C Navigation Reliability Civil Aviation Radionavigation	18. Distribution Statement Document is available to the public through the National Technical Information Service, Springfield, Virginia 22151.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
UNCLASSIFIED	UNCLASSIFIED	36	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ACKNOWLEDGMENT

The author wishes to acknowledge the technical advices provided by Mr. George Quinn of the FAA and Messrs. Melvin Zeltser and Ron Braff of the MITRE Corporation.

FOREWORD

This document is based on a paper presented at the thirty-seventh annual meeting of the Institute of Navigation, June 9-11, 1981, at Annapolis, Maryland. This paper is based upon navigation system engineering studies performed by MITRE for the FAA's Systems Research and Development Service. The contents of this paper reflect the views of the author and do not necessarily reflect the official views or policy of the FAA.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

1. INTRODUCTION

The Federal Aviation Administration is evaluating alternative radio navigation systems for civil aviation in the post-1995 time period. The systems under consideration for CONUS navigation are LORAN-C, VOR/DME, and NAVSTAR GPS. Reliability of a candidate system has been adopted as one of the evaluation criteria. This paper describes a technique for evaluating the reliability of LORAN-C over the CONUS.

The reliability analysis of the network of LORAN-C ground stations for civil aviation is concerned with the ability of the LORAN-C system to provide continuous and usable navigation signals for airborne applications. Coverage is defined by transmitted signal strength, geometric relationship between the user and the ground stations, and the receiver capabilities. In the event of failure of one or more of the ground stations, there would be an outage if there are not enough remaining stations satisfying the coverage criterion.

There are several aspects to LORAN-C system reliability that affect the interpretation of results. These include the size of the area affected by an outage, location of the user, and receiver design capabilities. LORAN-C is a long-range navigation system and therefore an outage of a single critical station may diminish the system coverage area significantly. If there are a large number of users of LORAN-C, the operation of the civil air traffic control system would be adversely affected. Another aspect of the LORAN-C system reliability is that it is location dependent, due to the variation of coverage across the CONUS. The LORAN-C system reliability also depends heavily on the operational capabilities of the receiver set since receiver capabilities, such as the master independent mode and low acquisition SNR, affect system coverage directly. For example, a receiver that acquires at a lower SNR generally yields a wider selection of usable triads and therefore better system reliability through ground station redundancy. Furthermore, a receiver capable of master independent mode can usually reconfigure itself to provide navigation in the event that the master station currently used by the receiver for position determination fails.

Previous analyses on the system reliability of navigation systems have been presented for LF/VLF navaids (Reference 1), LORAN-C (Reference 1, 2) and GPS (Reference 3). In Reference 1, a probabilistic method is given to analyze the risk associated with the loss of transmission of the LF/VLF navaids. However, signal strengths and geometric properties of the LF/VLF navaids are not considered. The applicability of the method in Reference (1) is also limited to certain flight durations. Reference (2) is concerned with the estimation of the number of additional CONUS stations needed for providing redundant coverage. The probabilistic measure of system reliability is not included. The reliability model presented herein is similar to that for GPS, given in Reference (3), in that a Markov Chain model is utilized. The formulation of the model is different since the receiver designs and coverage criteria for the two systems are different.

Section 2 presents an overview of the analysis technique. Section 3 describes the computerized LORAN-C coverage model which is used extensively in the reliability analysis. Section 4 describes the probabilistic approach to reliability analysis. The overall methodology for the analysis of LORAN-C system reliability in the CONUS is illustrated in Section 5 by an example using a previously proposed station configuration for full-CONUS coverage, a simplified low-cost airborne receiver model, and the station reliability statistics based on a preliminary analysis of the ground station data.*

* Presently, detailed analysis is being performed on the actual ground station reliability data, to be used in the reliability analysis.

2. OVERVIEW OF ANALYSIS TECHNIQUE

Figure 1 depicts the overall technique and the required inputs for the analysis of LORAN-C system reliability in the CONUS. Three major inputs are required for this analysis; namely, the LORAN-C station configuration for full CONUS coverage, receiver model, and station reliability parameters in the form of MTBF (Mean-Time-Between-Failures) and MTTR (Mean-Time-To-Restore). The station configuration is specified by the locations, radiated powers, chain identification, and master/secondary categorization of the stations.

The receiver model shown in Figure 1 is used to represent those features of the receiver which have a significant impact on the system coverage. The description of the receiver model includes the following:

- Hyperbolic or multi-rho navigation mode
- Master independent/dependent for the hyperbolic mode
- Cross-chain capability
- Minimum receiver signal-to-noise ratio (SNR)
- Back-up navigation mode.

The first step in the analysis is to identify the coverage, in terms of the set of usable triads, at regularly-spaced locations throughout the CONUS, based on a particular receiver model and station configuration. This is accomplished by means of a computerized coverage model (Section 3).

The next step is to examine the geographic impact of station outages on LORAN-C coverage area for the specified station configuration and receiver model. This is shown in Figure 1 as the deterministic component of the reliability analysis. In this approach, the effect of an outage of a single station is first evaluated. Since the areas of redundant coverage result in higher system reliability, areas of redundant and nonredundant coverage in the CONUS are also identified.

The probabilistic analysis of LORAN-C system reliability is concerned mainly with the assessment of the risk of the loss of LORAN-C coverage over various time intervals. The reliability and maintainability performance of the ground stations are accounted for in the analysis by the parameters MTBF and MTTR of the stations. The evaluation technique is based on the Markov

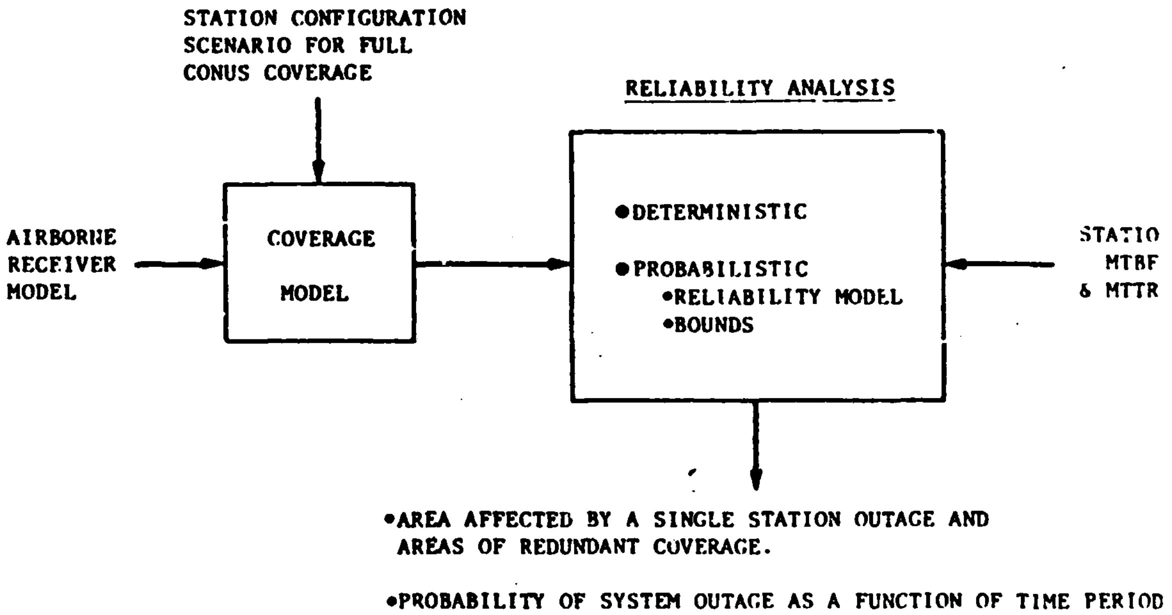


FIGURE 1
OVERVIEW OF LORAN-C SYSTEM RELIABILITY ANALYSIS TECHNIQUE

Chain model. Usually one model needs to be developed at each location because LORAN-C coverage varies from one location to another. However, an alternative procedure is developed in this paper to simplify the overall system reliability calculations.

3. LORAN-C COVERAGE MODEL

A computerized coverage model has been developed to analyze the adequacy of LORAN-C coverage for arbitrary station configurations, receiver capabilities, and system parameters. This model essentially evaluates the coverage at regularly-spaced geographic points throughout the CONUS. For a geographic location to have LORAN-C coverage, a minimum of three stations* must be available that meets the following conditions:

(1) Signal strength from each of the three stations yields at least a specified minimum signal-atmospheric noise-ratio at the receiver. This level mainly concerns the ability to acquire the signals.

(2) Geometric relationship between the receiver location and the triad is satisfactory. This relationship is known as Geometric Dilution of Precision (GDOP). The expression and derivation of this measure can be found in Reference 4.

To evaluate the first condition, signal strengths at the receiver location from all ground stations are computed. This requires the computation of the propagation loss of the LORAN-C signal gound wave from its transmitting source to the receiver location. The exact calculation is complex because it depends on a variety of factors such as ground conductivities, terrain variation, and atmospheric condition along the propagation path (Reference 5). To make the propagation model tractable, it has been assumed that the signal attenuation depends only on the ground conductivities. The ground conductivities of the CONUS are approximated by dividing the CONUS into cells of average conductivity values. For propagation over a path of constant conductivity, the signal attenuation curve as a function of distance is employed (Reference 6). Since the propagation may be over mixed conductivity paths, the Millington method is used (Reference 5).

The noise calculation procedure used in the coverage model follows that of the CCIR (Reference 7). The noise source considered is the atmospheric radio noise. A detailed discussion on the CCIR procedure can be found in Reference (2). The application of the CCIR procedure yields the 95-percentile

* The multi-rho mode of navigation is not addressed in this paper.

value of the noise power for each 4-hour time block of the day and for each season. The noise power in the time blocks of the summer season is on the average higher than those of the other seasons.

For civil aviation, system coverage is required for all seasons. Therefore, the noise power in the SNR calculation is conservatively based on the average of the noise powers (95%) of the six time blocks in the summer season.

4. RELIABILITY ANALYSIS

The reliability of the LORAN-C system to provide coverage is dependent upon the user's location within the CONUS. Therefore, the overall reliability assessment of the LORAN-C system will require the reliability analysis at individual locations within the CONUS. This approach is the same as the NAVSTAR GPS reliability analysis (Reference 3).

4.1 Reliabilty Model

This section discusses the technique developed for evaluating the system reliability of LORAN-C at a given location. The main objective is to calculate the probability of a system outage during a specific time period. This technique deviates from the previous methods (References 1 and 3) in that signal strength limit, geometry, and receiver capability, such as master independent/dependent modes and minimum SNR, are taken into account. Similar to Reference 3, a Markov Chain model is utilized, but the formulation of the model is different due to the above considerations.

Figure 2 illustrates the Markov Chain model used for analyzing LORAN-C system reliability. One of the inputs to this model is the combinations of triads that satisfy the coverage requirement. Without loss of generality, let N be the number of usable triads and M be the number of stations involved. In general, N is smaller than the combination of M items taken 3 at a time, due to geometry and SNR restrictions. Each circle in this figure denotes a state in the Markov Chain. For this model, a state is defined as one of the possible sets of usable triads. The time-to-fail distribution of the stations is assumed to be identical, independent, and exponential. The time-to-restore is also assumed to be exponentially distributed.

Figure 2 describes basically the sequential deterioration of system coverage from the initial state (left-hand side of figure) to the outage state (extreme right-hand side). Initially, all N triads and M stations are assumed to be available. After a small interval of time, one of the M station fails and this results in a smaller set of triads. However, at a particular state, the repair of the affected station by the maintenance crew reverts the system to the previous coverage state. As time goes on, the failure of the stations leads to the coverage by only one triad. When one of the stations in this remaining triad fails, a system outage results.

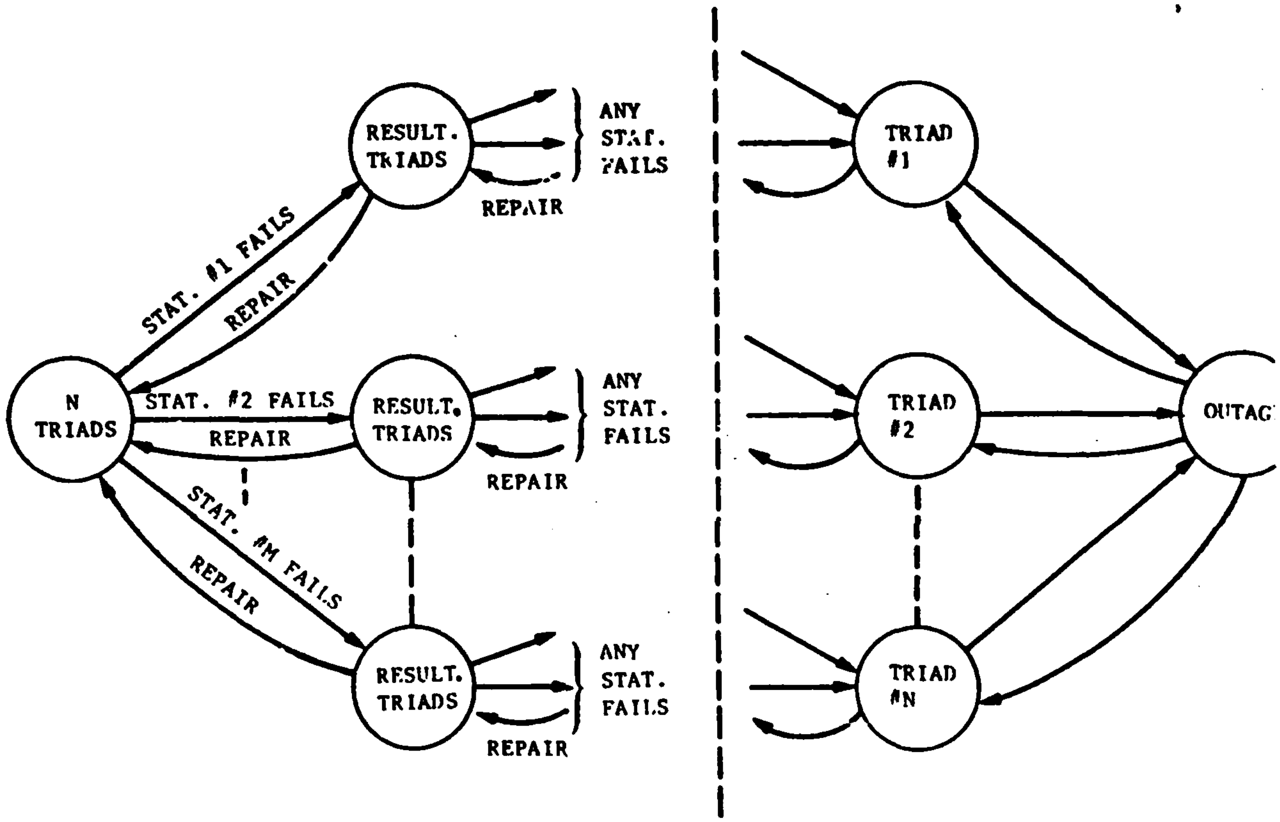


FIGURE 2
MARKOV MODEL

Consider the case in which a given location is provided coverage by a chain of 4 stations, A, B, C, and D, where A is the master station. Figure 3 shows the Markov model for the master dependent case. The top half of Figure 3 depicts the failure paths. It can be noted the failure of the master station leads to an outage whereas the failures of two secondaries are required for system outage. The bottom half of Figure 3 shows the complete model with restoration paths included. In addition, the middle three states (ACD, ABD, ABC) in the top half of this figure have been combined to form one state (1 triad working), thus reducing computation effort.

The case illustrated is an example of nonredundant coverage because an outage of a critical station, the master in this case, causes system outage. Figure 4 shows a case of redundant coverage, in which 5 stations and 5 triads are involved. It can be observed from this example that the number of states can be quite large as the number of stations and triads increases.

Analytical solution of the Markov Chain reliability model for cases containing more than three or four states is cumbersome. Therefore, a numerical method (Reference 8) is used to derive unreliability, which is defined as (1 - reliability).

4.2 Bounds in Reliability Performance

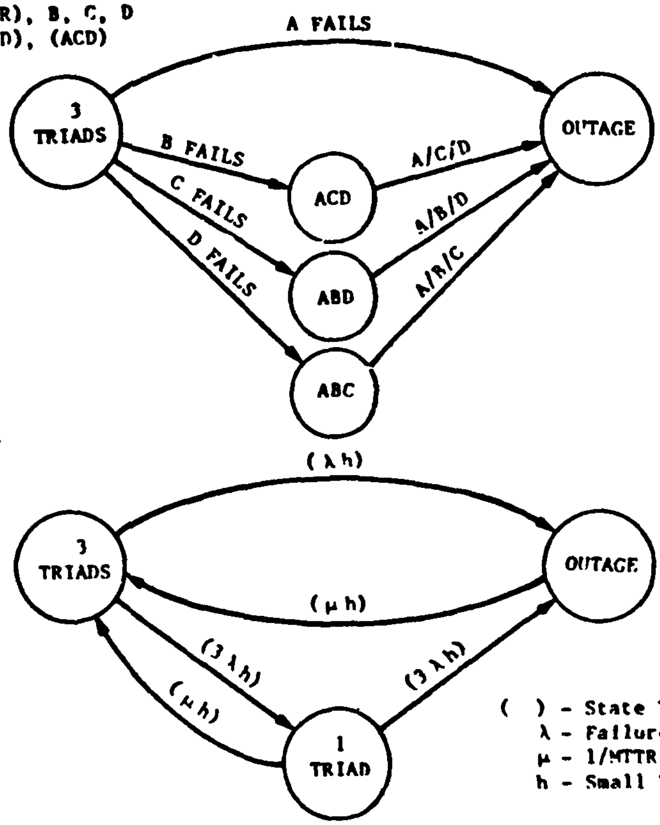
The description of coverage at a given location in terms of the number of usable triads can be misleading for conveying reliability performance. The reason is that some stations are more critical than others with respect to their contribution to an outage. As shown previously, for the master dependent mode, the master station is more critical if its chain is the only one providing coverage. However, the failure of a secondary station in this chain does not necessarily lead to system outage if the chain contains more than two secondary stations.

The term, level of redundancy, is used here to quantify the relative reliability of coverage. It assigns a numerical value to each coverage type. It is defined as:

Level of redundancy = (Smallest number of failed stations leading to system outage) - 1

Therefore, the coverage by one chain in the master dependent mode is assigned the redundancy level of zero, or no redundancy regardless of the number of secondaries. Redundancy levels of 1 and 2 are also called single and double redundancy, respectively.

STATIONS - A (MASTER), B, C, D
TRIADS - (ABC), (ABD), (ACD)



( ) - State Transitional P
λ - Failure Rate of Stat
μ - 1/MTTR, Repair Rate
h - Small Time Interval

FIGURE 3
MARKOV MODEL FOR MASTER DEPENDENT MODE—
NO REDUNDANCY CASE

STATIONS: A, B, C, D, E
TRIADS: (ACD), (ABD), (ADE), (ABC), (BDE)

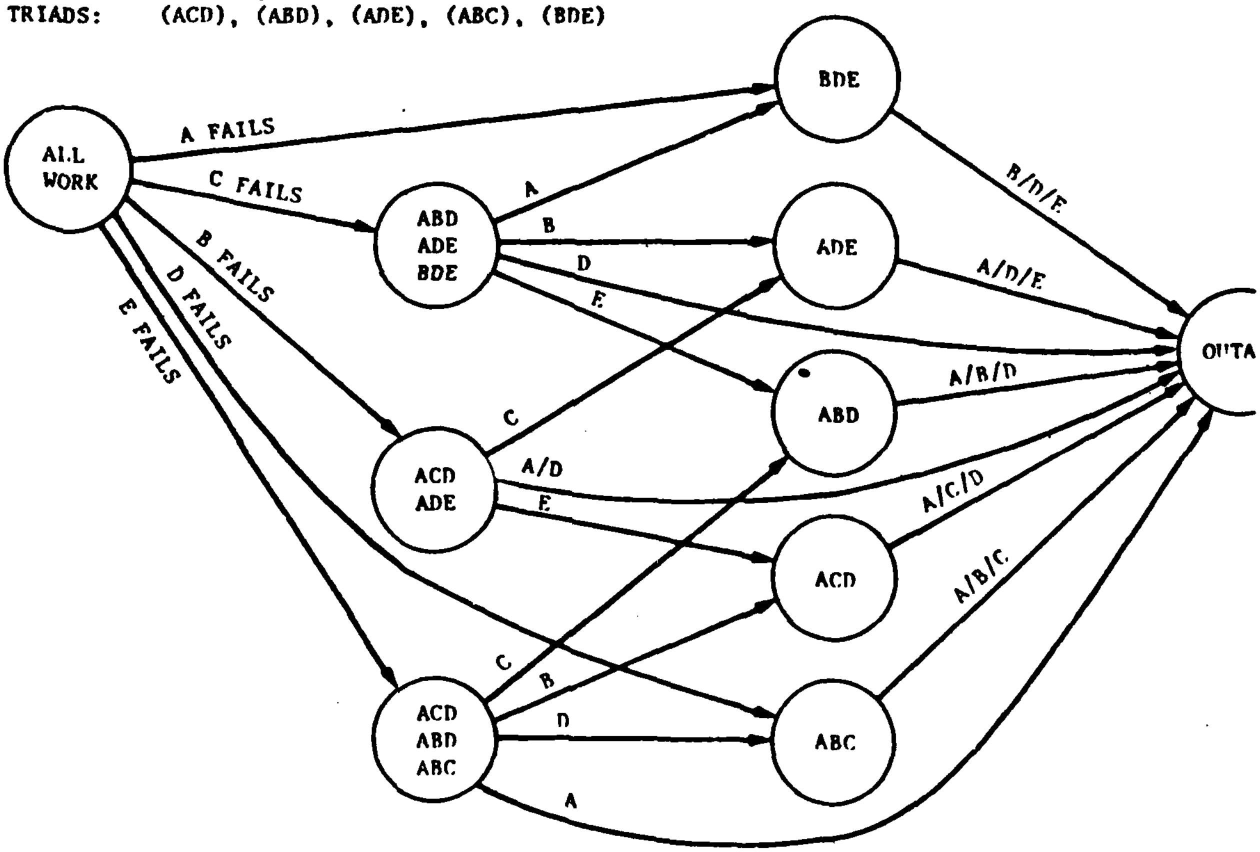


FIGURE 4
MARKOV MODEL FOR EXAMPLE OF SINGLE REDUNDANCY CASE

The identification of redundancy level for a given coverage requires a failure mode analysis of the usable triads, i.e., all possible combinations of stations leading to system outage. Since the Markov Chain model of Figure 2 describes the outage process, it can be used directly to derive the redundancy level. After the Markov model is formulated for a particular coverage situation, visual inspection can identify the smallest number of paths (station failures) leading to outage. For the example in Figure 4, the minimum number of station failures is two and, therefore, the redundancy level is 1, or single redundancy.

Since each location can be characterized by a level of redundancy and many areas share the same value, another approach is to find the reliability bounds corresponding to the redundancy levels. Most likely only redundancy levels of two and less need to be considered because higher levels of redundancy would produce satisfactory reliability performance.

Consider the zero redundancy case. The worst reliability performance for this case is when only three stations satisfy the coverage requirement, i.e., when one of the stations fails, a system outage results. The top half of Figure 5 shows the block diagram of this scenario as a series connection of three stations, as well as the corresponding Markov Chain model. The upper bound in reliability occurs when two of the stations each have multiple back-up stations. If the number of back-up stations is large, the portion of the system as represented by the dotted lines in Figure 5 can be considered as approaching 100 percent reliability. Therefore, only one station is used to represent the best case. This satisfies the constraint of the zero redundancy since, by definition, the failure of one critical station results in a system outage. It should be noted that this is not a physical realization of coverage, but is used as a mathematical bound.

The reliability bounds of the single redundancy case is shown in Figure 6. The worst scenario is composed of two independent triads such as two separate LORAN-C chains. This is a minimal configuration for single redundancy because the failure of one station from each triad leads to an outage of that triad and that each of the six stations does not have backups. When the outage state is reached, two failures have occurred. Since it is assumed that only one station is restored at a time, the factor of two in the restoration path is used to account for the restoration of either one of the failed stations. By the same argument as in the zero redundancy case, the best scenario corresponds to the parallel combination of two stations.

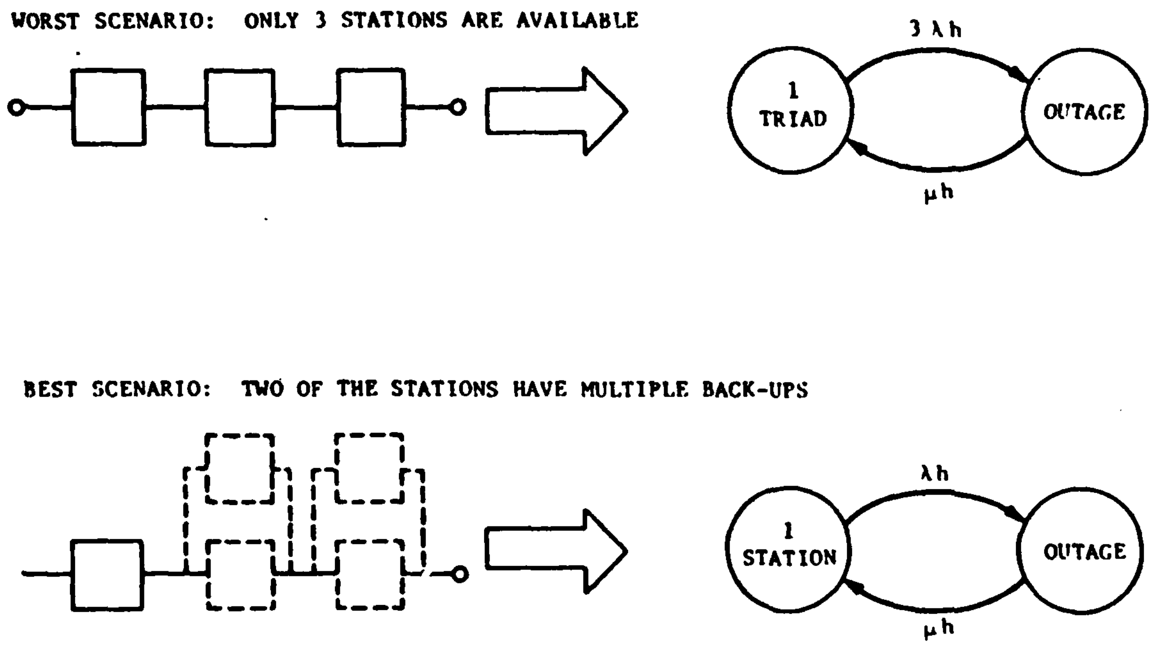


FIGURE 5
BOUNDS IN RELIABILITY PERFORMANCE—NO REDUNDANCY

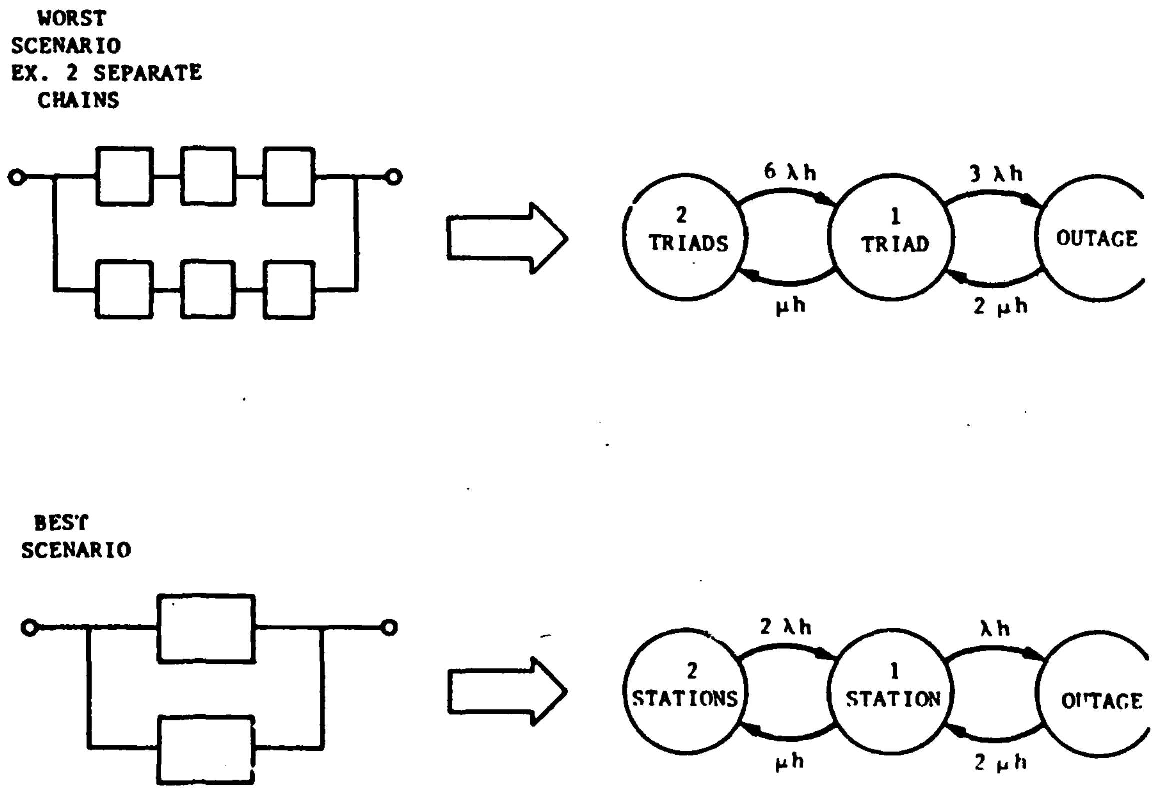


FIGURE 6
BOUNDS IN RELIABILITY PERFORMANCE—SINGLE REDUNDANCY

Proceeding similarly, the reliability bounds as represented by Markov Chain models for the double redundancy case can be found and they are shown in Figure 7. This procedure can be similarly extended to higher levels of redundancy. It can be noted from Figure 7 that only four states are required to represent the Markov model. Therefore, the computation is easily manageable. Another property of these derived bounds is that they are not a function of master independent or dependent modes, thereby providing further savings in computation.

The reliability bounds can be used in the following fashion to simplify the overall LORAN-C system reliability evaluation. If the upper bound of the reliability performance (i.e., reliability of best scenario) corresponding to a redundancy level does not satisfy the reliability performance criterion, then every geographical location with this level of redundancy is unsatisfactory. For example, if the reliability of the best scenario for zero redundancy is judged as unsatisfactory, then it can be concluded, without further calculation, that all areas in CONUS with zero redundancy are unsatisfactory in reliability performance.

On the other hand, if the reliability of the worst scenario for a particular level of redundancy provides satisfactory reliability performance, then all locations with this level of redundant coverage can be considered as satisfactory in reliability performance. Furthermore, the same conclusion also applies to higher levels of redundancy.

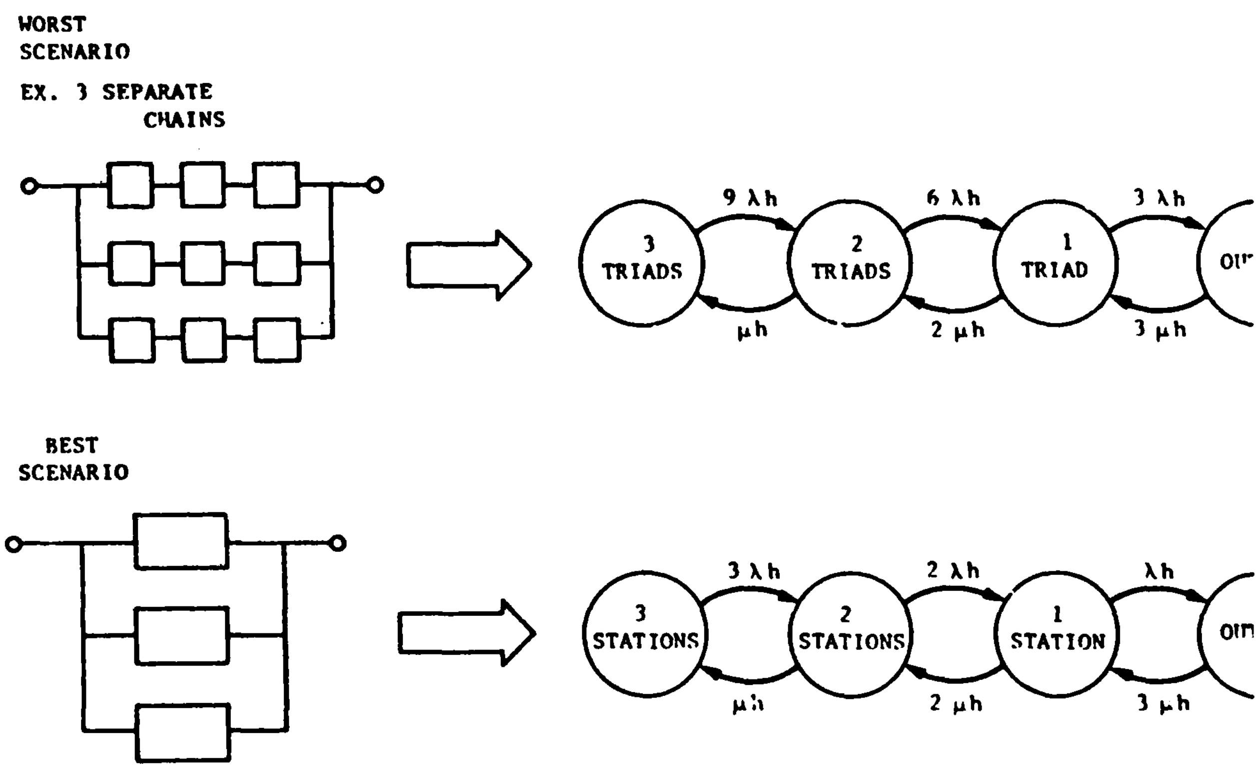


FIGURE 7
BOUNDS IN RELIABILITY PERFORMANCE—DOUBLE REDUNDANCY

5. APPLICATION

This section illustrates the reliability analysis precedure with a numerical example, based on a previously proposed station configuration for full-CONUS coverage, a simplified model of the low-cost receiver, and a preliminary analysis of the reliability data from stations with solid-state transmitters.

Presently, approximately two-thirds of the CONUS are provided with LORAN-C coverage. Several station configurations have been proposed to cover the mid-continent, which is currently without LORAN-C coverage. One past proposal was to install five additional mid-continent stations to fill the current coverage gap. The locations of the five proposed and the current CONUS stations are shown in Figure 8. The radiated power of the five additional stations is assumed to be the same as the maximum radiated power of the existing solid-state transmitting stations (800 KW).

The receiver model used in this analysis is assumed to be low-cost, operating only in the hyperbolic mode with master dependent or master independent capabilities. The minimum acquisition SNR is assumed to be 1/3 or -10 dB. The equivalent receiver noise bandwidth is assumed to be 20 KHz. The noise powers in the CONUS are the same as those of Reference 2. The accuracy limit of LORAN-C coverage for this low-cost type of receiver is taken as 1500 feet (2 dRMS) with standard deviation of TD (time difference) error 0.1 μsec. This corresponds to a maximum GDOP of:

$$
\begin{aligned}
\text{GDOP} &= \text{dRMS/standard dev. of TD} \\
&= 750 \text{ ft}/0.1\,\mu\text{sec.} \\
&= 7{,}500 \text{ ft}/\mu\text{ sec.}
\end{aligned}
$$

The MTBF and MTTR of the stations used in this example are 20 days and 9 minutes*, respectively. It must be emphasized that these values are preliminary estimates and used for illustrative purposes only.

---

* Transient or momentary station outages that last less than a minute are not included.

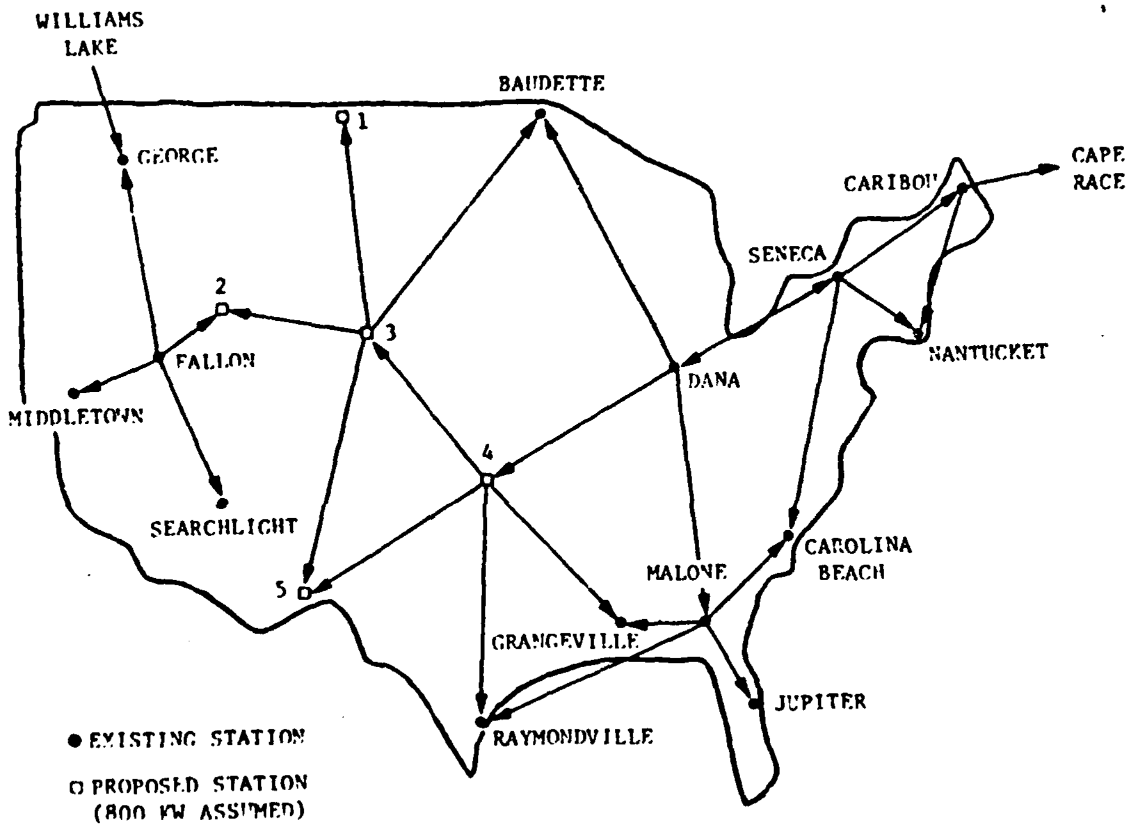


FIGURE 8
PROPOSED FIVE MID-CONTINENT AND EXISTING STATIONS

5.1 Effect of a Single Station Outage on Coverage Area

The coverage diagram of the proposed full-CONUS coverage station configuration is shown in Figure 9. The plotting increment is two degrees in latitude and longitude. Blanks within the CONUS boundary denote satisfactory coverage. The symbols 'S, 'G', 'E' and '*' are used to identify different causes of coverage deficiency.

'S' denotes inadequate signal strength only. 'G' signifies inadequate GDOP only. 'E' indicates either a signal or GDOP deficiency, i.e., there exist at least 2 triads at this location where one triad satisfies SNR threshold but not the GDOP threshold whereas the other triad has the opposite deficiency. '*' denotes deficiencies in both signal and GDOP. It can be seen from this figure that based on the assumed powers of the proposed stations, there are still a few small areas without coverage. The difference in coverage areas for the master dependent and master independent modes is insignificant. As indicated in Figure 9, this is due to signal strength limitation, rather than geometry.

Figure 10 shows the effect of an outage of the Seneca LORAN-C station on the CONUS system coverage. The Seneca station is a dual-rated station which serves as a master to the Northeast Chain and also as a secondary to the Great Lakes Chain. Since this station contains equipment common and necessary for the transmissions of the two rates, such as antenna and power system, the outage at Seneca can impact the operations of the two chains. The shaded areas of Figure 10 show the areas of no coverage as a result of the Seneca station outage. For the master dependent mode, the area affected can be substantial, about 500 NMI in the north direction. As expected, the master independent mode is superior in redundant coverage as compared with the master dependent mode. However, the area affected can be close to 300 NMI in one direction. Similar conclusions can be drawn concerning the effect of outage of the dual-rated Malone station, Figure 11. This station is the master for the Southeast Chain and secondary for the Great Lakes Chain.

Figure 12 presents the consequence of outage of the Fallon station, master of West Coast Chain. Again, the aircraft whose receiver operates only on the master dependent mode will not be provided with navigation capability in a large portion of the western CONUS. However, users with master independent mode receiver would not be affected.

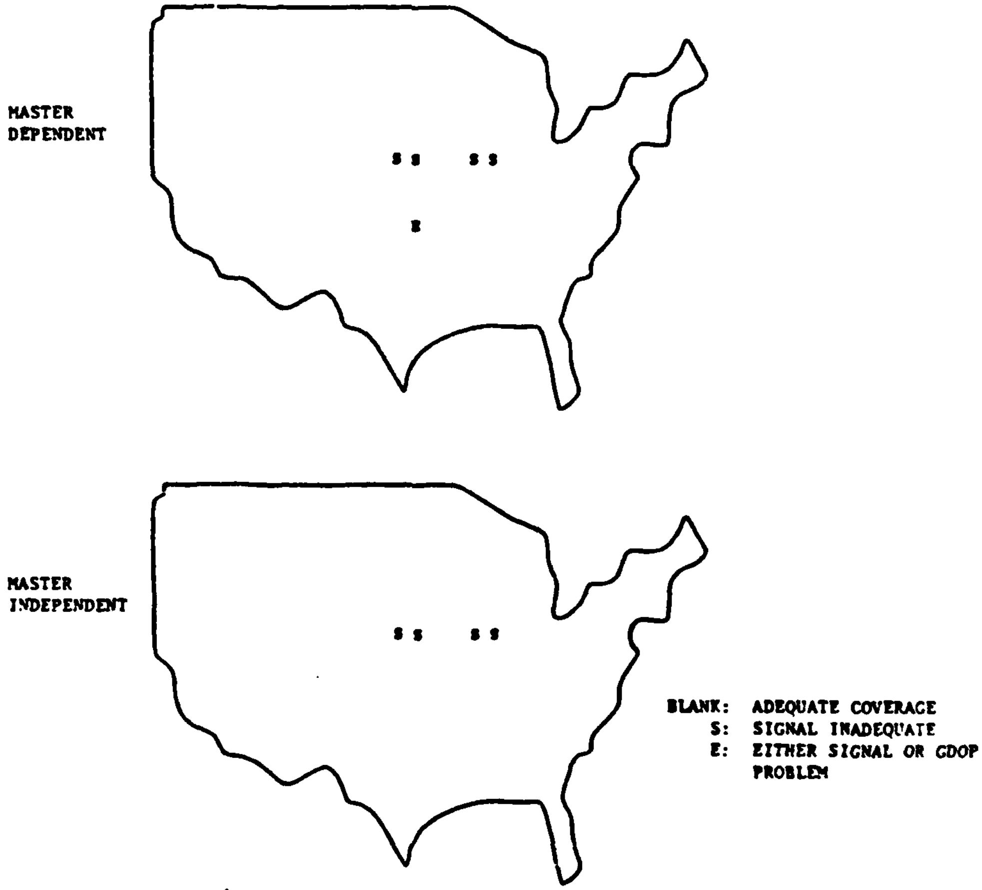


FIGURE 9
COVERAGE OF PROPOSED AND EXISTING STATION CONFIGURATION

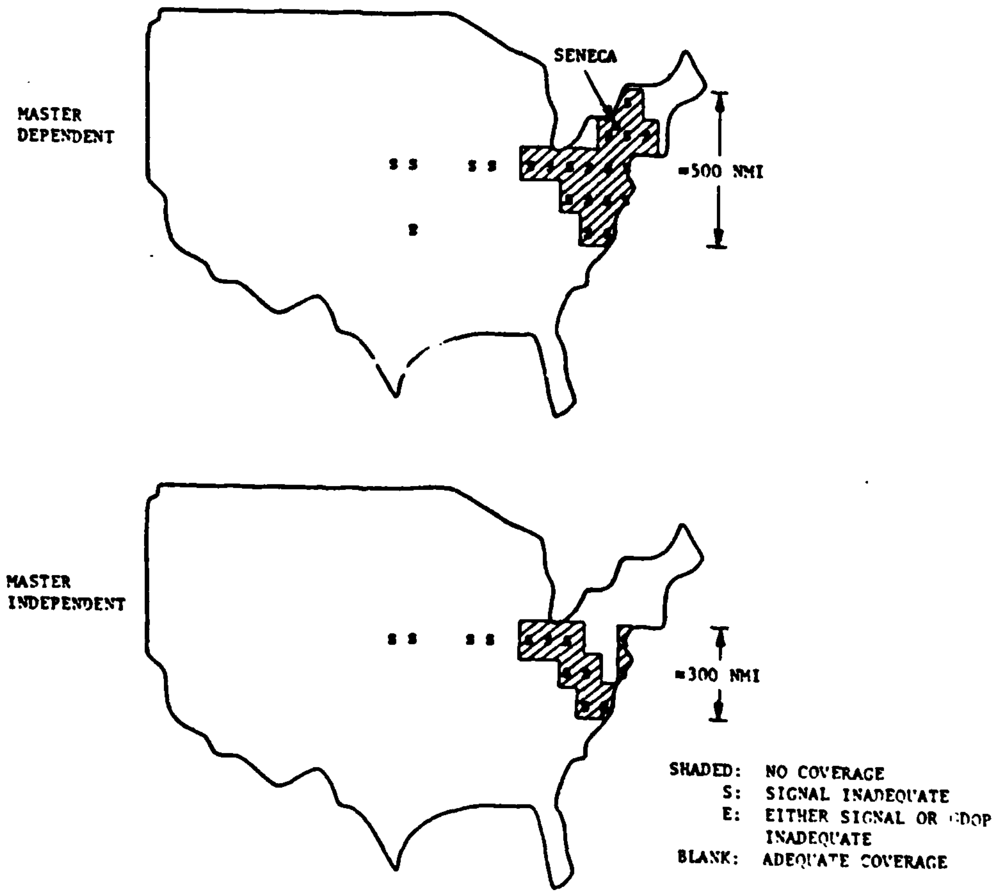


FIGURE 10
EFFECT OF SENECA STATION OUTAGE

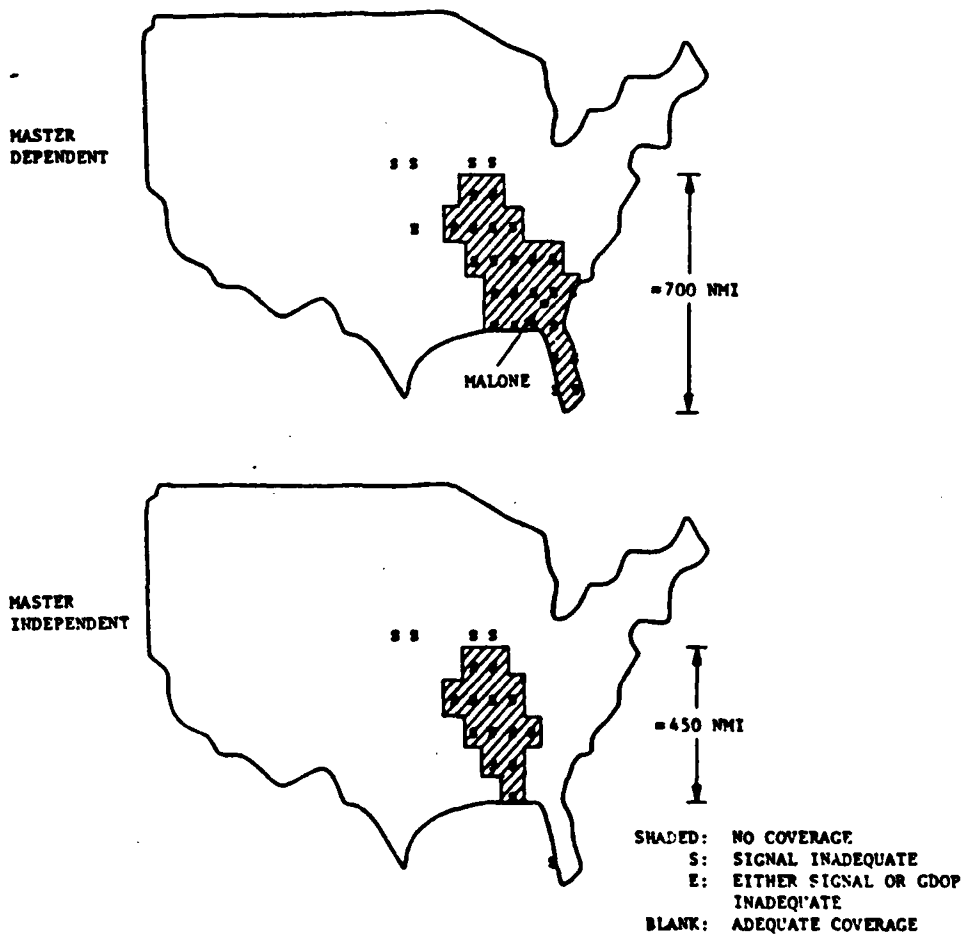


FIGURE 11
EFFECT OF MALONE STATION OUTAGE

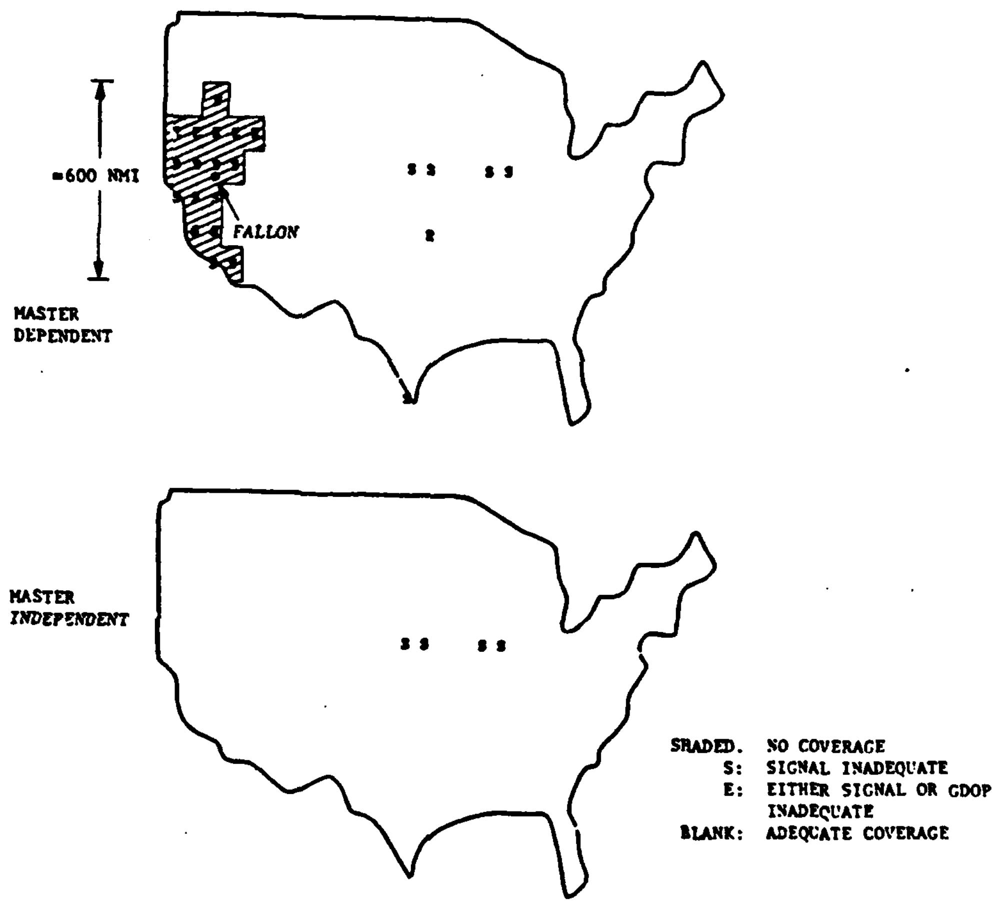


FIGURE 12
EFFECT OF FALLON STATION OUTAGE

In summary, the addition of five mid-continent stations of the assumed radiated power to the existing network of LORAN-C ground stations would provide nearly full coverage to the CONUS when all ground stations are operational. However, when one of the CONUS stations fails, a large area of several hundred nautical miles may be devoid of coverage and users in these areas would be without navigation service unless additional redundancy is provided.

5.2 Areas of Redundant Coverage

For convenience, redundancy in coverage is defined as the existence of at least one usable triad (satisfying coverage criterion) regardless of which station fails. This means that the airborne user is protected against an outage due to the failure of a single ground station.

Figure 13 shows the areas of redundant and nonredundant coverage within the CONUS for the master dependent and master independent modes with the proposed five additional mid-continent ground stations. The shaded area in this Figure identifies the areas of nonredundant coverage. As expected, the master independent mode provides significantly more redundant coverage areas than the master dependent mode. Approximately 50 percent of the CONUS contains redundant coverage for the master dependent mode, whereas the master independent mode provides 75 percent of the CONUS with redundant coverage.

5.3 Illustration of the Probabilistic Analysis

The probability of system outage within a time interval, or unreliability, is illustrated in Figure 14. In this example, the time interval of interest is for the en route flight segment and hence the time scale is on the order of hours. Similar results in unreliability performance (i.e., as time increases, unreliability also increases) as those shown in Figure 14 have also been calculated for shorter (on the order of minutes) and longer (on the order of days) time intervals. The shaded portion of this figure indicates the unreliability performance regions for the zero redundant and the single redundant coverage. The upper and lower limits* in unreliability for

* The upper and lower limits in unreliabilty corresponds to the lower and upper limits in reliability, respectively.

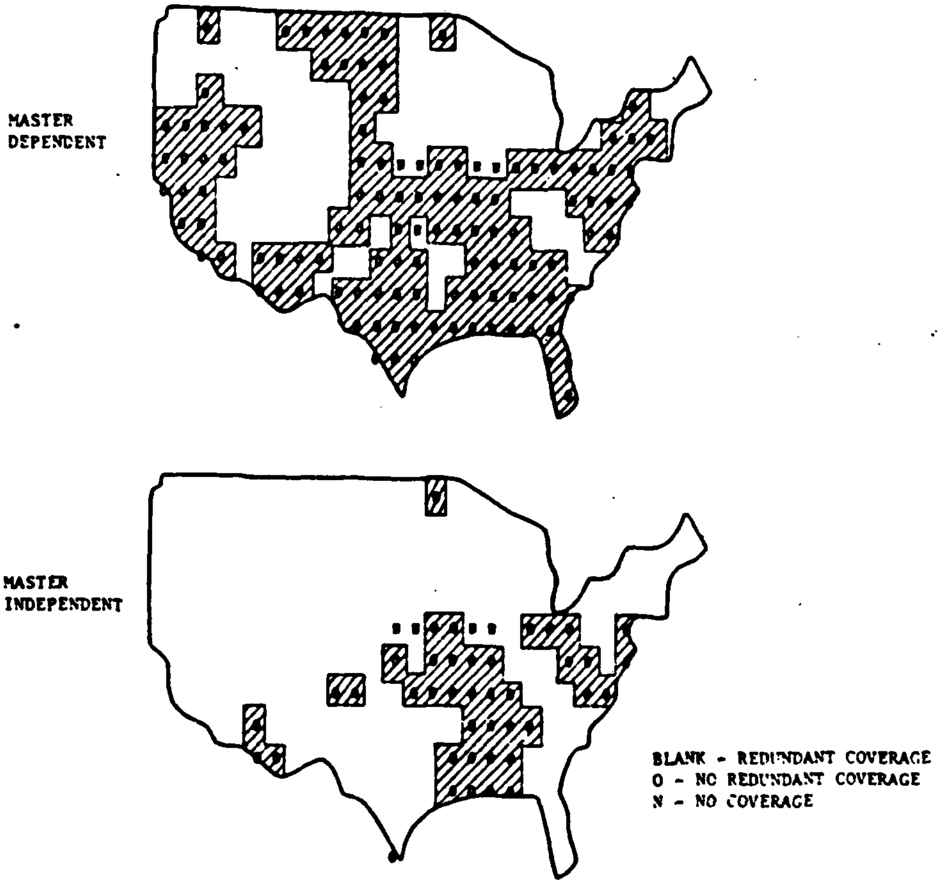


FIGURE 13
AREAS OF REDUNDANT COVERAGE

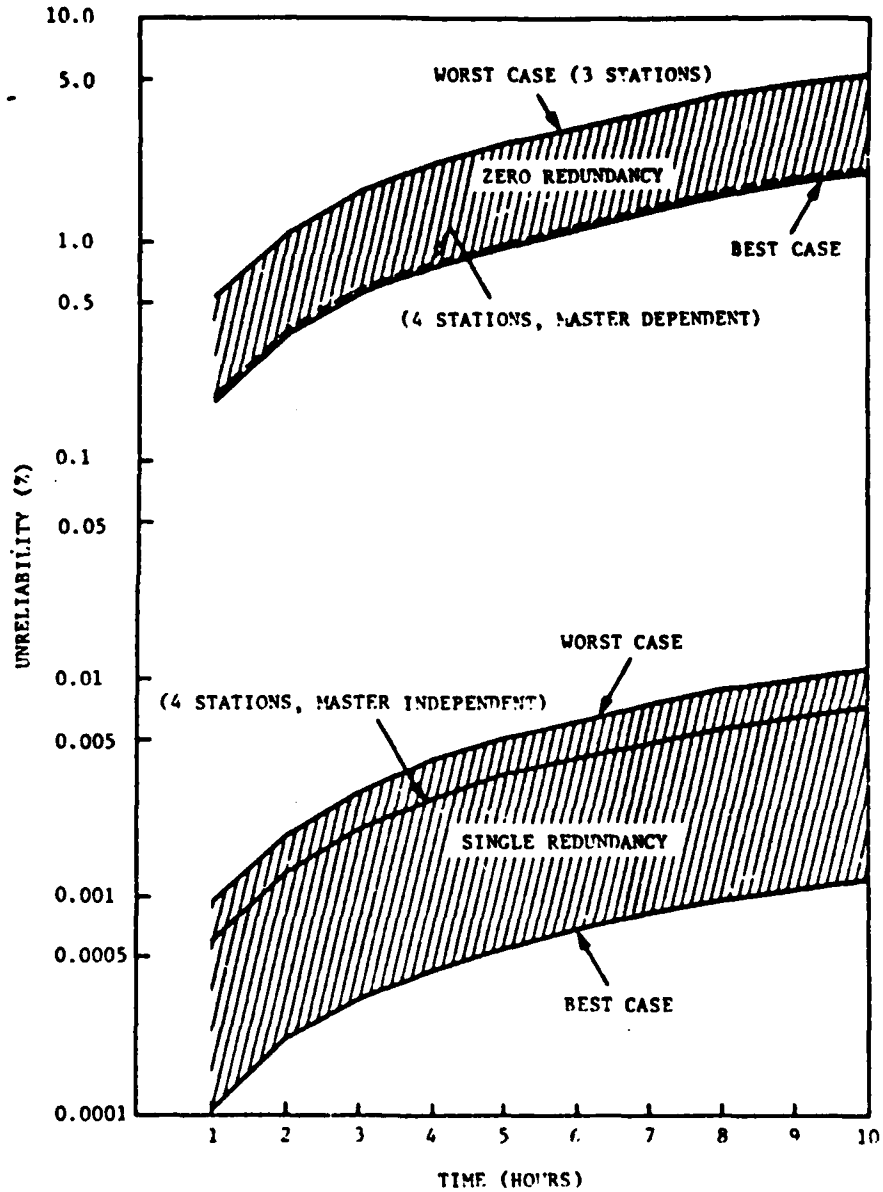


FIGURE 14
ILLUSTRATIVE UNRELIABILITY FOR ZERO AND SINGLE REDUNDANT COVERAGE

these two types of redundancy levels have been calculated using the Markov Chain models shown in Figures 5 and 6. It can be observed that unreliability in areas of single redundancy is significantly lower than that of the zero redundancy. For a flight duration of five hours, the average unreliability (mid-point between the worst and the best scenarios) in area of zero redundant coverage is approximately one thousand times larger than that in area of single redundant coverage.

Figure 14 also displays the unreliability for the master dependent and master independent mode when the coverage is provided by a chain of four stations. This figure shows that the master independent mode out performs the master dependent mode in reliability by a factor of approximately 250. It can also be seen from this figure that the unreliability of a four station chain in the master dependent mode is almost the same as the best scenario for zero redundancy.

The application of the unreliability bounds such as those shown in Figure 14 to facilitate the reliability analysis for the entire CONUS has been discussed in Section 4.2. An alternative but equivalent procedure is provided as follows. This is based on the assumption that a threshold for unreliability (time-dependent) has been pre-determined via an independent method such as the result of an investigation of the reliability of the VOR system or consensus voting among experts. The developed unreliability threshold line can then be drawn directly on the unreliability curve such as Figure 14 to determine the adequacy of reliability for various redundant coverage levels.

Consider the example of the redundant coverage provided by the proposed station configuration and the receiver capable of master independent operation. The redundant coverage map is shown in Figure 13. If the unreliability threshold line is above the unreliability bounds of zero redundancy, then it can be concluded immediately all redundancy levels (zero and higher) are satisfactory in reliability performance throughout the entire CONUS.

Consider the next case in which the unreliability threshold line lies between, but not intersecting, the unreliability region of zero redundancy and that of single redundancy, then the shaded areas in CONUS of Figure 13 can be viewed as unsatisfactory in reliability performance. However, the blank areas of Figure 13 with redundancy levels of one and higher would be considered as satisfactory in reliability performance. These conclusions are drawn simply by visual observation of the unreliability bounds, without resorting to computation.

The unreliability threshold line may also lie inside the unreliability region of a particular redundant coverage type. The developed unreliability bounds cannot be used directly to determine the adequacy of the reliability for this coverage level. Instead, the generalized Markov Chain model shown in Figure 2 needs to be applied. However, since the unreliability regions of higher redundancy levels are below the threshold line, geographic areas with higher redundancy levels can be concluded as satisfactory in reliability performance.

6. SUMMARY AND DISCUSSIONS

This paper has described an analytical technique for the assessment of the LORAN-C system reliability in the CONUS. This technique can be utilized to investigate the sensitivity of LORAN-C system reliability due to various proposed station configuration scenarios for full-CONUS coverage, different airborne receiver models, and different ground station reliability performance parameters. This technique has been illustrated by a numerical example.

Currently, the FAA is sponsoring an effort to develop a laboratory model of a low-cost General Aviation (GA) receiver. The planned operational capabilities of this receiver will be incorporated in the future analysis of LORAN-C system reliability. A data reduction and analysis effort is underway to estimate the MTBF and MTTR of the solid-state stations from the historical data supplied by the USCG. The MTBFs of the individual equipment in a station such as antenna, transmitter, and power system will also be extracted.

The ultimate objective of the LORAN-C system reliability assessment is to determine the ground station configuration that would meet the civil aviation reliability requirement in the post-1995 time period. The determination of such a configuration would most likely be an iterative process that also involves the low-cost GA receiver model. A particular station configuration scenario for CONUS coverage and a specific set of station MTBF and MTTR are initially used in the analysis. If system reliability based on these two assumptions is found to be unsatisfactory, two alternatives can be used to improve reliability performance. One alternative is to change the station configuration and this may increase the number of ground stations. This corresponds to the improvement of system reliability through ground station redundancies. The other alternative is to increase the reliability of the station by adding equipment redundancies (above the present equipment configuration) to the station, subject to the constraint that some equipment such as transmitting antenna should not be duplicated at a station site due to interference considerations. These two alternatives will be analyzed by the analytical technique presented in this paper.

APPENDIX A

REFERENCES

1. Bruchner, J.M.H, and Auerbach, B.A., "LF/VLF Navaid Signal Reliability in Airborne Application," Navigation: Journal of the Institute of Navigation, Vol. 23, No. 3, Fall 1976.

2. Joglekar, A., Gupta, J, and Ylvisaker I. "Evaluation of LORAN-C for Domestic Air Navigation" MITRE Corp. Technical Report MTR-7180, October 1976

3. Braff, R., Shively, C., and Bradley, J. "Navigation System Integrity and Reliability for Civil Aviation," Position Location and Navigation Symposium Proceedings, December 1980.

4. O'Day, Sattinger, I, Scott, R., and Sullivan "Study and Analysis of Selected Long Distance Navigation Techniques," Navigation and Guidance Lab., Institute of Science and Technology, University of Michigan, Federal Aviation Agency Final Report, Contract ARDS-436, Vol. I, Dec. 1962 and Vol II, March 1963.

5. Samadar, S.N. "The Theory of LORAN-C Ground Wave Propagation - A Review" Navigation: Journal of the Institute of Navigation, Vol. 26, No. 3, Fall, 1979.

6. Van Etten, J. P., "Medium Accuracy, Low-Cost Navigation: LORAN-C Versus the Alternative", Presented at the 30th Technical Meeting of the Avionics Panel, Advisory Group for Aerospace Research and Development, Sandefjord, Norway, September 1975.

7. C.C.I.R. Report 322, Documents of the Xth Plenary Assembly, Geneva, 1963, published by International Telecommunications Union.

8. Braff, R., Computer program to calculate a Markov Chain Reliability Model, unpublished work, MITRE Corporation.