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Availability Analysis of the Traveling-Wave Maser Amplifiers in the Deep Space Network

Part I: The 70-Meter Antennas

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TDA Mission Support and DSN Operations

This article describes the results of the reliability and availability analyses of the individual S- and X-band traveling-wave maser (TWM) assemblies and their operational configurations in the 70-meter antennas of NASA's DSN. For the period 1990 through 1991, the TWM availability parameters for the Telemetry Data System are: mean time between failures (MTBF), 930 hr; mean time to restore service (MTTRS), 1.4 hr; and the average availability, 99.85 percent. In previously published articles, the performance analysis of the TWM assemblies was confined to the determination of the parameters specified above. However, as the mean down time (MDT) for the repair of TWMs increases, the levels of the TWM operational availabilities and MTTRS are adversely affected. In this article, a more comprehensive TWM availability analysis is presented to permit evaluation of both MTBF and MDT effects. Performance analysis of the TWM assemblies, based on their station monthly failure reports, indicates that the TWMs required MTBF and MDT levels of 3000 hr and 36 to 48 hr, respectively, have been achieved by the TWMs only at the Canberra Deep Space Station (DSS 43). The Markov Process technique is employed to develop suitable availability measures for the S- and X-band TWM configurations when each is operated in a two-assembly standby mode. The derived stochastic expressions allow for the evaluation of those configurations' simultaneous availability for the Antenna Microwave Subsystem. The application of these expressions to demonstrate the impact of various levels of TWM maintainability (or MDT) on their configurations' operational availabilities is presented for each of the 70-m antenna stations.

I. Introduction

The traveling-wave maser (TWM) assemblies exist as part of the Antenna Microwave Subsystem (UWV) at each Deep Space Station (DSS). They are used on the large antenna structures at the Goldstone, Madrid, and Canberra communication complexes. The technical performance of TWMs as well as their operational availability are critical

factors in the performance of the DSN. The important performance and operational characteristics of these TWMs are presented in Section II.C of this article.

Previous analyses of the performance reliability and availability of the DSN TWMs are described in [1,2]. These were confined to the mean time between failure

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(MTBF) determination for the TWMs network-wide, and their average availability for the DSN Telemetry System for the period 1981 through 1983. The results indicated that the averaged MTBF (1200 hr) was considerably below the desired level and the averaged MTTRS (2-5 hr) was very long as compared with the requirements. Therefore, a number of recommendations were made to improve the TWM assembly availability characteristics.

Achieving high levels of reliability and availability for the TWM assemblies is a very demanding task. It requires continued improvements in the TWM assembly maintenance procedures, as well as in the assembly's engineering development process. In recent years, it has become apparent that the availability of the TWM assemblies has been degrading. Their operational MTBF is currently believed to be in the range of 1000 to 1400 hr (except for the Canberra complex). This situation demonstrates the need to quantitatively assess the operational availability of the TWMs.

This article is the first of two on the availability modeling and analysis of the DSN TWM configurations. The analysis in this article, Part I, was performed on the TWM configurations in the 70-m antenna subnet. Part II will present the results of the analysis performed on the TWM configurations in the 34-m antenna subnets.

Section II of this article provides the functional description and operational characteristics of these TWMs. Section III presents the application of the Fault Tree Analysis (FTA) technique to the failure analysis of a TWM assembly and provides the results of the quantitative availability evaluation of individual TWMs. Section IV applies a Markov Process technique to derive the steady-state availability expressions for the TWM configurations. Section V describes the application of the derived expressions to the availability analysis of the TWM configurations in the 70-m antennas. Section VI provides a discussion of the study findings and related observations. The last section includes a summary and concluding remarks.

II. Description of TWM Configurations In the 70-M Antennas

A. Functional Configuration

The TWM assemblies are the dominant elements of the UWV at each of the 70-m antenna stations (DSS 14, DSS 43, and DSS 63). There are two TWM assemblies providing low-noise amplification at each of the S-band and X-band frequency feeds. Figure 1 represents a functional

block diagram of these TWM configurations as part of a 70-m Antenna Microwave Subsystem.

A single TWM assembly consists basically of a maser (amplifier) and its closed-cycle refrigerator (CCR), referred to simply as the TWM assembly. Figure 2 shows the TWM and CCR equipment connections.

B. Theory of Operation

The TWM assembly provides low-noise amplification for the received S- or X-band frequency. To accomplish this, the maser (amplifier) is cooled to approximately 4.5 K using closed-cycle refrigeration. To initiate a maser cooldown, the helium compressor (Fig. 2) circulates helium gas to and from the helium refrigerator at controlled pressure and flow rates. The helium refrigerator cools the helium until some of the gas reaches a liquid state (4.5 K) at the bottom of the refrigerator (the cold station). The maser is physically attached to the cold station and is cooled to the correct operating temperature of 4.5 K by metallic conduction.¹

C. Functional Requirements

This section contains data related to the performance requirements and operational characteristics (reliability and availability) of the TWM assemblies in the 70-m antenna subnet.

1. Performance Requirements. The TWM assemblies perform the function of low-noise amplification for the received S- and X-band frequencies. The basic performance requirements for the TWMs at each frequency feed are given in Table 1.

The total performance of the entire antenna system (i.e., Antenna Mechanical and Antenna Microwave Subsystems) is impacted by gain and noise temperature contributions of the TWMs, as well as by other critical elements of the system.

2. Operational Characteristics. The TWM assemblies were designed to demonstrate an operational (field) performance that meets the following characteristics:²

- (1) Functional availability of at least 0.998, since the desired availability for the Antenna Microwave Subsystem is at least 0.996.

¹ General Procedures, "S-Band Traveling-Wave Maser Group Block IV," TM03703 (internal document), Jet Propulsion Laboratory, Pasadena, California, September 15, 1979.

² Communication Complex System Functional Requirements (1991-1996), "Antenna Microwave Subsystem," 824-16 (internal document), Jet Propulsion Laboratory, Pasadena, California, November 1, 1991.

- (2) An MTBF level in excess of 3000 hr.
- (3) MTTRS for a single-channel operation (TWM backup is available) of 5 min. with a maximum of 10 min.
- (4) Mean down time (MDT) of a TWM assembly for repair maintenance is a maximum of 48 hr.

A TWM failure (due to its CCR failure) is recognized by the operator when deviations from requirements are detected in the CCR operating parameters (temperature levels, pressure levels, and helium flow rates). Also, major discrepancies in the observed antenna gain to system noise temperature ratio would indicate a possible TWM failure.

III. Individual Performance Analysis of TWM Assemblies

In this section, the individual performance analysis of TWM assemblies is presented using both qualitative and quantitative approaches. The two basic objectives of this analysis are

- (1) To develop an understanding of the TWM failure characteristics pertinent to various failure modes and their effects, which could be a useful tool for TWM-CCR design reviews (Section III.A).
- (2) To identify relevant operational performance measures related to reliability, maintainability, and availability of the TWM assemblies (Section III.B).

A. Qualitative Failure Analysis

1. Failure Cause-Effect Analysis. The failure analysis of a TWM assembly is primarily concerned with identification of its failure effects, referred to as top events, and determining how these can be caused by individual or combined lower level failures or faults. Standard symbols are then used for developing an FTA to describe failure events and their logical connections in relation to predefined top events (effects). The FTA technique and its applications to reliability assessment are discussed in greater detail in [3,4].

To demonstrate the application of the FTA technique to the TWM-CCR failure analysis, data related to failure modes and fault events of TWMs were collected and organized into some general cause-effect relationships. Using only the DSN Discrepancy Reports (DRs) and the stations' monthly failure reports, only top failure effects and contributing failure events were possible to identify. The logical connections between failure events were difficult to determine based on the current station reporting forms.

Therefore, only a simple FTA is shown in Fig. 3 for a TWM assembly, in which the top event is an operational failure. The FTA shows that this failure may be caused by any of the first-level failure modes (four-input OR gate). The analysis then proceeds, as shown, by determining how each of the lower level failure events can be caused by individual basic faults or events.

It is noteworthy that a different FTA will have to be constructed for each top failure event of the TWM assembly that can be caused by various relations between lower failure events. Therefore, individual FTA should be performed for the major failure effects of the TWM, such as cooldown failure, refrigerator low flow, and compressor failure. These analyses are particularly relevant to the development, operation, and maintenance improvements of the TWM assemblies, since critical levels of failure would indicate their contributions to the TWM reliability and availability.

2. Failure-Cause Distribution. Analysis of 1990-1991 TWM station failure reports gave the probability distribution of the major areas (causes) contributing to the 70-m TWM assembly failure. The distribution is summarized in Table 2. Refrigerator contamination and low helium flow proportions constitute about 65 percent of total TWM failures. More than 75 percent of the refrigerator failures were attributed to contamination of the helium gas. A significant proportion of TWM failure was attributed to the helium compressor failure.

B. Quantitative Availability Analysis

In this section, relevant availability factors and measures are quantitatively determined for the individual TWM assemblies in the 70-m antenna subnet. The factors include MTBF, MDT for corrective maintenance, and mean preventive-maintenance time (MPT); the measures include operational availability (A_o) and achieved availability (A_a).

Data related to TWM assembly outages and service restorations (during spacecraft scheduled support periods) were taken from the DR System. However, since TWM assembly failures (basically hardware-fault related) occurring over nonspacecraft support periods are not reported by the DR system, it is thought that the station monthly failure and maintenance reports should also be reviewed for this analysis.

1. Reliability (MTBF) Analysis. Earlier analysis of the TWM failure data based on the DSN DRs was reported in [1,2]. Network-wide estimates of MTBF as reported for three different periods are shown in Table 3. An

operational MTBF level of approximately 2500 to 3000 hr was considered a desirable and achievable reliability target for individual TWM assemblies.

This reliability analysis considers the individual performances of the TWMs at DSS 14, DSS 43, and DSS 63. The MTBF analysis is based on the station monthly failure reports for the period from November 1990 through December 1991. Estimated MTBF levels for the individual TWMs at each station are summarized in Table 3. An MTBF level of 2400 to 3000 hr has been achieved by the TWMs at the Canberra Complex (DSS 43). The TWMs at DSS 14 demonstrated an MTBF level in the range of 1400 to 1600 hr, whereas the MTBF level for the TWMs at DSS 63 is in the range of 1400 to 1900 hr.

2. Availability Analysis. Determination of TWM availability includes (1) a data-availability estimate of TWMs relative to each DSN data system, which is determined for a total scheduled mission-support time over a given period and (2) an overall-availability estimate of TWMs determined for the total period considered (including mission and other activity support times).

a. Data-Availability of TWMs. This availability for any data system is a function of both MTBF (or data-outage rate) and MTTRS. Separate analyses were conducted on the Antenna Microwave Subsystem availability for the Telemetry Data System and the individual 70-m station TWM availability for the Telemetry Data System for the period 1990 through 1991. The outage data for these analyses were obtained from the DR system, and the results are shown in Tables 4 and 5, respectively.

The average TWM availability for telemetry data is 99.8 percent. The average MTBF of a TWM assembly (approximately 930 hr) is good relative to that of other major Telemetry System elements; however, it is considerably lower than the desired MTBF level of 2500 to 3000 hr. The average MTTRS (1.4 hr) is relatively high and far off the service restoration requirements (these include mean and maximum durations of 15 and 30 min, respectively, for all support activities).

b. Overall availability of TWMs. This availability includes the determination of the TWM operational availability (A_o) and achieved availability (A_a) levels. For evaluating these measures, failure and maintenance data were taken from the 70-m stations' TWM monthly performance reports. Then operational and achieved availabilities for the individual TWMs were determined, as shown in Table 6, for the period November 1, 1990, through December 31, 1991, using the relationships provided in [3,4] as follows:

$$A_o = \text{MTBF}/(\text{MTBF}+\text{MDT}) \quad (1)$$

$$A_a = \text{MTBF}/(\text{MTBF}+\text{MDT}+\text{MPT}) \quad (2)$$

where

MTBF = MTTF (mean time to failure only)

MDT = (waiting-time to restore service
+ logistic delay time
+ corrective maintenance time
+ CCR decontamination time
+ assembly cooldown and testing time)

MPT = (preventive-maintenance time
+ decontamination time
+ cooldown and testing time)

The lower MDT levels for DSS-43 TWM assemblies indicate an improvement in both repair and operating procedures. The TWMs at both DSS 14 and DSS 63 demonstrated relatively higher MDT levels.

IV. Operational Availability Modeling of TWM Configurations

In this section, the operational availability performance of the X- and S-band TWM configurations is being considered for modeling. Each configuration is most frequently operated as a two-assembly standby configuration. The availability measure for the case of the two-assembly parallel configuration was derived in [5,6].

The purpose of this modeling effort is to derive the steady-state availability measures for the TWM standby configuration using the Markov Process technique discussed in [6,7]. In the following subsections, the model assumptions, model formulation, and the derived availability measures for the TWM standby configuration are presented.

A. Model Assumptions

The following are the basic assumptions of the Markov model for the TWM configurations under study:

- (1) The model represents an S- or X-band TWM standby configuration consisting of two redundant assemblies and a single maintenance technician.

- (2) The stochastic failure and repair processes for the operating assembly are stationary (constant failure and repair rates).
- (3) The repair activity and its duration (total downtime) of the failed TWM covers the time for corrective maintenance and the total time for decontamination and cooldown processes.
- (4) The backup TWM is warm (power-connected) but in a nonoperating mode (i.e., it receives only a duplicate signal and does not provide output to other processors in the link). Therefore, it is assumed that the standby TWM has a negligibly small failure rate (an approximate zero rate) relative to that of the prime operating TWM.
- (5) In the initial operating state of the TWM configuration, State 1, one of the TWM assemblies is in an operable standby mode.
- (6) During the TWM operation, only one change can take place in the state of the configuration at each instantaneous increment of time.

B. Model Formulation

The state-space diagram associated with the TWM standby configuration under study is shown in Fig. 4. The following symbols are associated with this diagram:

i denotes the i th state of the TWM configuration, for $i = 1, 2, 3$; where $i = 1$ (one assembly is operating, the other assembly is in standby mode); $i = 2$ (one assembly failed and is under repair, the other assembly is linked and operating); $i = 3$ (both TWMs are down, and one of them is under repair).

P_i denotes the steady-state probability that the TWM configuration is in State i , for $i = 1, 2, 3$.

λ denotes the constant failure rate of the operating TWM assembly.

μ denotes the constant repair and maintenance of the failed TWM assembly.

The steady-state availability model for this configuration is developed using the frequency-balance principle of the Markov Process theory as described in [5,7]. The frequency balance equations for the three-state availability model of Fig. 4 can be written as

$$\text{State 1:} \quad \lambda P_1 = \mu P_2 \quad (3)$$

$$\text{State 2:} \quad (\lambda + \mu) P_2 = \lambda P_1 + \mu P_3 \quad (4)$$

$$\text{State 3:} \quad \mu P_3 = \lambda P_2 \quad (5)$$

Using Eqs. (3) and (5) and the unity equation $P_1 + P_2 + P_3 = 1$, the state probability expressions are defined as follows:

$$P_1 = \mu^2 / (\lambda^2 + \lambda\mu + \mu^2) \quad (6)$$

$$P_2 = \lambda\mu / (\lambda^2 + \lambda\mu + \mu^2) \quad (7)$$

$$P_3 = \lambda^2 / (\lambda^2 + \lambda\mu + \mu^2) \quad (8)$$

C. The Availability Measures

In the state-space model shown in Fig. 4, States 1 and 2 represent the operating (up) states and State 3 represents the failed (down) state of the configuration. Thus, using the state probabilities given in Eqs. (6)–(8), the steady-state operational availability measure of the standby configuration, denoted by A_o , is given by

$$A_o = (\mu^2 + \lambda\mu) / (\lambda^2 + \lambda\mu + \mu^2) \quad (9)$$

and the steady-state unavailability measure of the standby configuration, denoted by U_o , is given by

$$U_o = \lambda^2 / (\lambda^2 + \lambda\mu + \mu^2) \quad (10)$$

The availability measure given in Eq. (9) can also be used to develop a simultaneous availability measure of X- and S-band configurations for the UWV operational support at each 70-m antenna station. This is defined as

$$A_o(\text{for antenna microwave}) = A_o(\text{X-band}) \times A_o(\text{S-band}) \quad (11)$$

The application of Eqs. (9) and (11) to evaluate the availability of the X- and S-band TWM configurations at each 70-m antenna station is presented in Section V.

V. Applications and Analysis

For the application of the availability measures given in Eqs. (9) and (11), pooled MTBF and MDT levels were estimated for the X- and S-band TWM configurations using their individual assembly MTBF and MDT levels, which were computed earlier and listed in Table 6. The pooled MTBF estimate for a TWM was computed as the average of MTBF levels of the individual assemblies (in a configuration) reduced by 30 to 35 percent of the total variation

of an assembly MTBF level from that average MTBF. On the other hand, the pooled MDT estimate for a TWM was computed as the average of MDT levels of the individual assemblies (in a configuration) rounded off to the closest integer representing an average number of 12-hr maintenance cycles (shifts) required for a TWM repair completion.

The estimates of pooled MTBF and MDT for the TWM assemblies and their use for availability evaluation of the X- and S-band configurations at each 70-m antenna station are described as follows.

A. Availability of TWMs at DSS 14

The estimates of pooled MTBF and MDT for the prime and backup assemblies of the X-band TWM configuration are

$$\text{MTBF} = 1615 \text{ hr, or } \lambda = 0.000619 \text{ failure/hr}$$

$$\text{MDT} = 84 \text{ hr, or } \mu = 0.011904 \text{ repair/hr}$$

and the estimates for each TWM assembly in the S-band configuration are

$$\text{MTBF} = 1560 \text{ hr, or } \lambda = 0.000641 \text{ failure/hr}$$

$$\text{MDT} = 84 \text{ hr, or } \mu = 0.011904 \text{ repair/hr}$$

The application of the availability measure given in Eq. (9) to the TWM configurations at this station results in

$$A_o(\text{X-band configuration}) = 0.997435$$

$$A_o(\text{S-band configuration}) = 0.997256$$

The application of the availability measure given in Eq. (11) results in the following simultaneous availability of TWM configurations for the UWV subsystem:

$$\begin{aligned} A_o(\text{for antenna microwave}) &= A_o(\text{X-band}) \times A_o(\text{S-band}) \\ &= 0.9947 \end{aligned}$$

The simultaneous availability of TWM configurations, which is 0.9947, is slightly lower than its predicted requirement (i.e., 0.996) for the antenna microwave. The

operational availability of each individual configuration is approximately 0.997, as compared with a desirable level of 0.998. This deviation is primarily attributed to both a low MTBF level (1500 to 1600 hr) and a considerable MDT of 84 hr (3 to 3.5 days), as compared with the corresponding parameter levels for the TWMs at the other stations.

The impact of improved TWM assembly reliability on a configuration's operational availability at various levels of assembly MDT is demonstrated in Fig. 5(a). An examination of the plots in this figure indicates that the operational availability requirement for each TWM configuration, which is 0.998, can be achieved or even exceeded when the reliability (MTBF) and maintainability (MDT) parameters of its assemblies meet any of the following practically feasible combinations:

$$(1) \text{ MTBF} \geq 1500 \text{ hr; MDT} \leq 60 \text{ hr}$$

$$(2) \text{ MTBF} \geq 2000 \text{ hr; MDT} \leq 84 \text{ hr}$$

B. Availability of TWMs at DSS 43

The estimates of pooled MTBF and MDT for each TWM assembly in the X-band configuration are

$$\text{MTBF} = 2350 \text{ hr, or } \lambda = 0.000425 \text{ failure/hr}$$

$$\text{MDT} = 36 \text{ hr, or } \mu = 0.027777 \text{ repair/hr}$$

and the estimates for each TWM assembly in the S-band configuration are

$$\text{MTBF} = 5080 \text{ hr, or } \lambda = 0.000196 \text{ failure/hr}$$

$$\text{MDT} = 36 \text{ hr, or } \mu = 0.027777 \text{ repair/hr}$$

The application of the availability measures given in Eqs. (9) and (11) to the TWM configurations at this station results in the following individual and simultaneous availabilities:

$$A_o(\text{X-band configuration}) = 0.999768$$

$$A_o(\text{S-band configuration}) = 0.999950$$

$$A_o(\text{for antenna microwave}) = 0.9997$$

The operational availability of both TWM configurations at this station, which is 0.9997, is greater than the

predicted requirement of 0.996 for the period 1990 through 1991. The availability of individual configurations is relatively high and in the range of 0.9997 to 0.9999 for this period. This is primarily attributed to both a reasonable MTBF level (2300 to 2500 hrs) and an acceptable MDT of 36 hours (or 1.5 to 2 days).

The impact of improved TWM assembly reliability on a configuration's operational availability at various levels of assembly MDT is described in Fig. 5(b). The plots demonstrate that the operational availability for each TWM configuration will always meet or exceed the requirement at the current MTBF level (greater than 2000 hr) for as long as the MDT level remains at or below 60 hr.

C. Availability of TWMs at DSS 63

The estimates of pooled MTBF and MDT for each TWM assembly in the X-band configuration are

$$\text{MTBF} = 1820 \text{ hr, or } \lambda = 0.000549 \text{ failure/hr}$$

$$\text{MDT} = 60 \text{ hr, or } \mu = 0.016666 \text{ repair/hr}$$

and the estimates for each TWM assembly in the S-band configuration are

$$\text{MTBF} = 2525 \text{ hr, or } \lambda = 0.000396 \text{ failure/hr}$$

$$\text{MDT} = 36 \text{ hr, or } \mu = 0.027777 \text{ repair/hr}$$

The application of the availability measures given in Eqs. (9) and (11) to the TWM configurations at this station results in the following individual and simultaneous availabilities:

$$A_o \text{ (X-band configuration)} = 0.998948$$

$$A_o \text{ (S-band configuration)} = 0.999799$$

$$A_o \text{ (for antenna microwave)} = 0.9987$$

The operational availability of both TWM configurations at this station, which is 0.9987, is slightly higher than the predicted requirement of 0.996 for the period 1990 through 1991. The availability of the X-band TWM configuration exceeds the required level of 0.998. For the S-band TWM configuration, the availability is relatively high for this period as a result of both a reasonable MTBF level (2525

hours) and an acceptable MDT level of 36 hours (less than 2 days).

The impact of increased TWM assembly reliability on a configuration's operational availability at possible levels of assembly MDT is described in Fig. 5(c). The plots demonstrate that the operational availability for each TWM configuration will always exceed a level of 0.998 at the current MTBF level (greater than 2000 hrs) for as long as the MDT level remains at or below 48 hours.

VI. Discussion of the Findings and Observations

In this section, the results of the operational reliability and availability analysis of the TWM configurations are discussed. The appropriate items related to the improvement of the TWM assembly availability characteristics are also presented.

A. Discussion of the Findings

- (1) Failure analysis of TWM assemblies shows that the helium refrigerator contamination is the dominant cause of TWM failure (55 to 65 percent of total failures). An earlier investigation of this problem implied the feasibility of detecting the development of contamination 1 or 2 days in advance of a TWM failure.
- (2) The proportions of compressor and refrigerator drive-unit failures (12 and 15 percent, respectively) are considered significant, as compared with the failure percentages for other TWM elements. If their failure frequencies were reduced, the TWM MTBF would be considerably improved.
- (3) The DR data show that the average MTTRS for the TWMs (1.4 hr) relative to the DSN Telemetry Data System is about two to three times as long as the MTTRS of other telemetry elements. Improving the MTTRS of the TWM assemblies to a desirable level of 0.7 hr would essentially require improved TWM backup availability. This is accomplished when repair durations, and consequently MDT levels of the TWMs, are reduced.
- (4) Analysis of the 1990-1991 TWM station failure data shows a significant variation in the MTBF level at different complexes. The higher MTBF levels for the TWMs at DSS 43 appear to have resulted from improved repair procedures as well as an increased level of preventive-maintenance activity prior to early 1990. On the other hand, TWMs at DSS 14 and DSS 63 have demonstrated lower MTBF

levels, which are believed to have resulted from less efficient repair and preventive maintenance processes at these stations.

- (5) Analysis of the 1990–1991 TWM station repair data shows a variation in the level of MDT for repair at different complexes. For the TWM assemblies at DSS 43, the MDT level is relatively good (36 hr) and lower than MDT levels demonstrated at the other stations (84 hr at DSS 14 and 48–60 hrs at DSS 63). That is perhaps indicative of improved repair practices as well as better trained maintenance personnel at the Canberra complex.
- (6) TWM operational availabilities at the individual stations (computed by using the proposed measures), are in close agreement with their average availabilities for the Telemetry Data System (generated from the DR system). These availabilities at the individual stations are compared in Table 7.

The variations in corresponding TWM availabilities at different stations are primarily attributed to the effect of incorporating the MDT parameter into the proposed TWM availability measures. The use of TWM MDT is more appropriate than the MTTRS parameter for their operational availability evaluations since the former is more representative of TWM actual unavailable (repair) times.

B. Observations

The following observations, which are primarily drawn from the previous work reported in [2], are based on the findings of the TWM failure-cause analysis.

- (1) Solution of the helium gas contamination problem would reap the greatest dividends. The composition and sources of contamination have to be better understood. Some of the items related to this area include
 - (a) Implementation of the previously proposed computer-based monitoring and data-collection and analysis system for the TWM CCRs would improve the identification of possible CCR faults before they cause TWM failure.
 - (b) Improved field techniques for measuring gaseous impurities and other contaminants in helium would be very valuable.
 - (c) Improved gas flow meters and gauges of the helium refrigerators and compressors would allow for the detection of helium low flow and improve the quality of recorded performance data.

- (2) An understanding of the contribution of the compressor oil to contamination at increased temperatures is needed, as is a mechanism to replace in-service compressor filters and adsorbers without affecting maser operation.
- (3) A detailed failure mode analysis, preferably using the FTA technique, for the helium compressors and refrigerators to reduce their current significant contributions to TWM failure is yet to be done and would be part of another phase.

The following observations are based primarily on the findings of the reliability and availability analyses of the TWMs:

- (1) The preventive-maintenance schedules and procedures for the TWM equipment at both DSS 14 and DSS 63 need to be reviewed to achieve higher MTBF levels for their TWM assemblies.
- (2) The TWM corrective-maintenance procedures and support equipment at DSS 14 and DSS 63 need to be evaluated for possible improvements in order to achieve reduced repair durations and improved TWM backup availabilities. This is essential to reduce the average MTTRS for the TWMs network-wide.
- (3) Improving and sustaining training for the maser operation and maintenance personnel would help to achieve a TWM availability performance consistent with the specified requirements.

VII. Summary

This article has reported the results of the reliability and availability analyses of the TWM assemblies at the 70-m antennas and has presented a stochastic availability evaluation model of their operational configurations. The dominant cause of TWM failures is contamination of the helium gas in the CCRs. This is consistent with the findings of a previous study; however, another important finding is that proportions of TWM failures attributed to compressor and refrigerator drive-unit failures have almost doubled in recent years. The current MTBF level of the TWMs for spacecraft support (approximately 930 hr) can practically be improved. The average MTTRS can be reduced to 0.7 or 0.8 hr if TWM backup-assembly availability is improved.

The MTBF and MDT levels of the TWMs at the Canberra Complex DSS 43 indicate that it is possible to achieve the desired levels of these parameters (MTBF of

2500-3000 hr; MDT of 36-48 hr) for the present TWMs at both DSS 14 and DSS 63 when operation and maintenance procedures are consistently improved and practiced. Individual availabilities of TWMs at DSS 14 are considerably lower than corresponding levels for the TWMs at DSS 43 and DSS 63. That is indicative of the adverse impact of the relatively higher MDT (84 hr) for the TWMs at DSS 14.

The derived stochastic expressions provide adequate measures of the S- and X-band TWM standby configura-

tion availabilities and allow for the evaluation of simultaneous operational availability of these configurations for their Antenna Microwave Subsystem. The application of these availability expressions to the 70-m antenna TWM configurations indicates a relatively lower operational availability level achieved at DSS 14. That is primarily attributed to the higher MDT of the failed TWM at this station. The proposed measures can be considered as useful tools to examine possible MTBF and MDT trade-offs that would result in an improved TWM configurations' operational availabilities at the 70-m antennas.

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Table 1. Basic performance requirements of the 70-m antenna TWM assemblies.

Performance parameter	S-band (Block III, IV, V)	X-band (Block IIA)
Frequency, MHz	2270-2300	8400-8500
Gain contribution, dB		
Peak	45	45
Minimum	44	44
Gain stability, dB		
Stationary-10 sec	0.03-0.05	0.03
Stationary-12 hr	0.5	0.5
Moving	0.5-2.0	0.5
Noise temperature contributions, K	8-10 Block III <5.0 Blocks IV,V	<4.0

Table 2. Failure-cause distribution of the 70-m antenna TWM assemblies.

Area of failure	Number of TWM failures			Number of failures (subnet)	Total failures, percent
	DSS 14	DSS 43	DSS 63		
Helium refrigerator	24	16	25	65	69.8
Contamination	(19)	(12)	(20)	(51)	(54.8)
Other (drive unit, etc.)	(5)	(4)	(5)	(14)	(15.0)
Helium compressor	4	2	5	11	11.8
Low flow	4	2	3	9	9.7
Power supply/distribution	2	1	2	5	5.4
Miscellaneous (pump, klystron, maser, etc.)	0	2	1	3	3.3
Total	34	23	36	93	100

Table 3. MTBF history of the DSN TWM assemblies.

Time period	Approximate MTBF, hr	Remarks
DSN DR's data for		
Late 1960s	1000-1300	All complexes/stations
Late 1970s (1979-1981)	3000	All complexes/stations
Early 1980s (1982-1983)	1000-1200	All complexes/stations
Station reports' data for		
Early 1990s (1990-1991)	1400-1600 (S-band)	Goldstone Complex; only DSS14
	1600 (X-band)	
	5000 (S-band)	Canberra Complex; only DSS 43
	2400-4000 (X-band)	
	1900-2500 (S-band)	Madrid Complex; only DSS 63
	1400-1800 (X-band)	

Table 4. Telemetry data system availability based on its major subsystem contributions.

Subsystem	Number of outages	Total outage, hr	MTBF, hr	MTTRS, hr	Telemetry availability, percent ^a
Antenna Mechanical	229	200	171	0.9	99.50
Antenna Microwave (TWM included)	69	96	567	1.4	99.76
Radio Frequency Interference	00	160	244	0.9	99.61
Receiver	195	74	220	0.4	99.82
Telemetry	472	271	92	0.6	99.35
Facility	34	35	3760	0.6	99.94

^aData availability = $MTBF / (MTBF + MTTRS)$

Table 5. Telemetry data availability analysis based on the contributions of the 70-m station TWMs.

Station TWMs	Schedule support time, hr	Number of outages	Total outage, hr	MTBF, hr	MTTRS, hr	Telemetry availability, percent ^a
DSS 14	8356	15	14.6	557	0.97	99.83
DSS 43	9165	1	8.3	9165	8.3	99.91
DSS 63	9533	13	17.4	734	1.3	99.82
Total/average	27054	29	40.3	933	1.4	99.85

^aData availability = $MTBF / (MTBF + MTTRS)$

Table 6. Availability characteristics of TWM assemblies in the 70-m antenna subnet.

DSS complex	TWM type	Availability factor			Availability measure	
		MTBF ^a	MDT ^b	MPT ^c	A _o	A _a
DSS 14, Goldstone, California	S1	1361	92.6	48	0.93629	0.90636
	S2	1963	72.0	48	0.96462	0.94239
	X1	1628	68.0	48	0.95990	0.93348
	X2	1601	95.0	48	0.94399	0.91800
DSS 43, Canberra, Australia	S1	5070	42.0	N/A ^d	0.99178	0.99178
	S2	5091	21.0	N/A	0.99589	0.99589
	X1	5079	33.0	N/A	0.99354	0.99354
	X2	1232	46.75	N/A	0.96344	0.96344
DSS 63, Madrid, Spain	S1	1987	38.4	32	0.98104	0.96578
	S2	5056	20.0	36	0.99605	0.98905
	X1	1070	54.0	30	0.95196	0.92721
	X2	3568	64.0	36	0.98238	0.97274

^a The MTBF levels shown are calculated as the total operating hours of each TWM divided by the number of TWM failure (outage) events for the period considered.

^b The MDT shown is calculated as the total outage times and repair times divided by the number of reported failures for each TWM assembly.

^c The MPT shown is calculated as the total preventive-maintenance time divided by the number of preventive activities performed for a period.

^d Indicates that preventive-maintenance activities were not scheduled for the period considered.

Table 7. A comparison of TWM availabilities at the 70-m stations.

DSS-TWMs	Operational availability (proposed measures), percent	Average availability (DSN DR system), percent
DSS 14	99.73-99.75	99.83
DSS 43	99.97-99.99	99.91
DSS 63	99.89-99.97	99.82

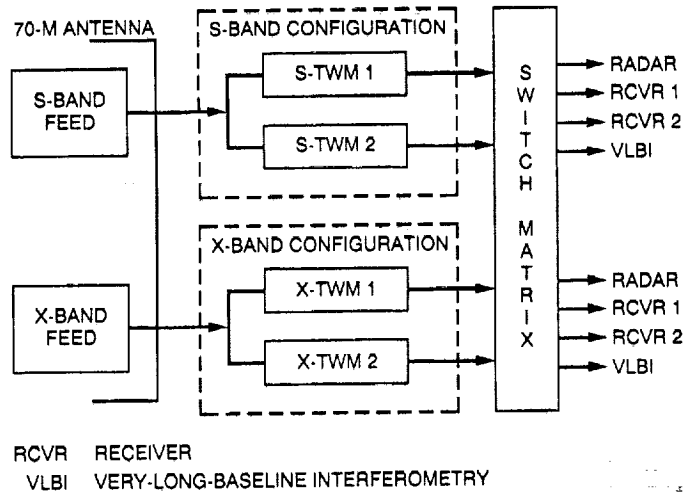


Fig. 1. Functional block diagram for the traveling wave maser (TWM) amplifiers in the 70-m antenna microwave subsystem.

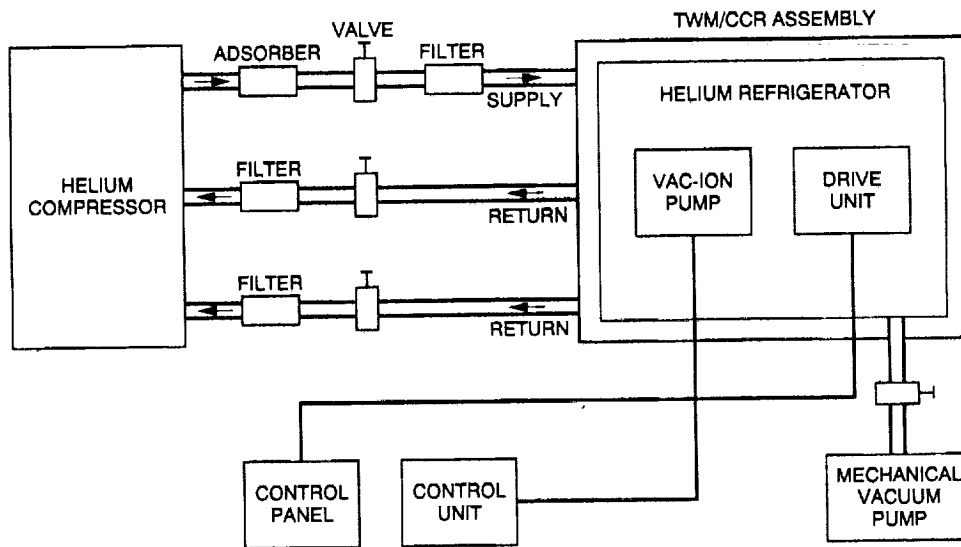


Fig. 2. Simplified TWM/CCR Group Equipment Connections diagram.

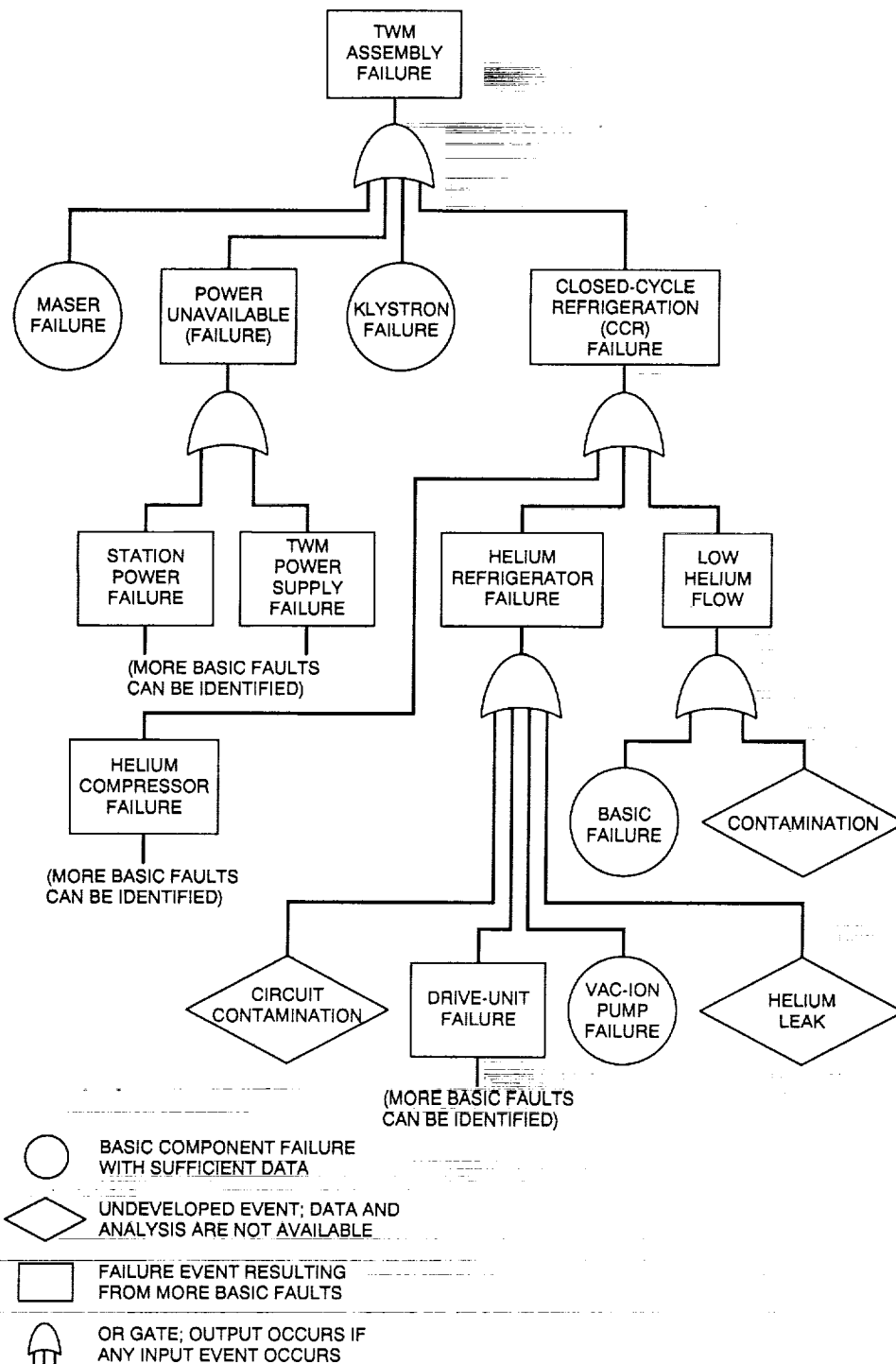
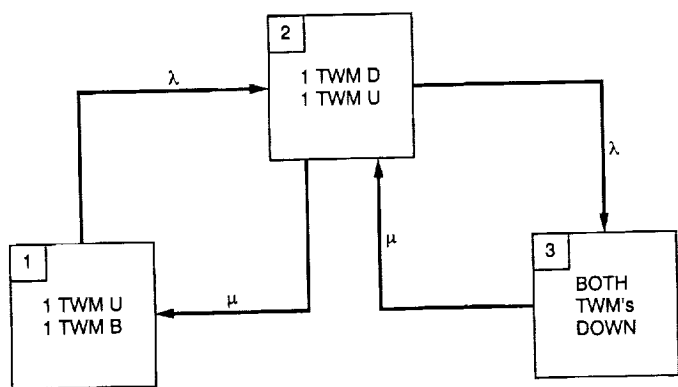


Fig. 3. Fault tree for a TWM assembly (top failure events are shown; basic component failures are not specified).



U UP, OPERATING
D DOWN
B UP, BACKUP

Fig. 4. State-space performance model for a two-assembly standby TWM configuration.

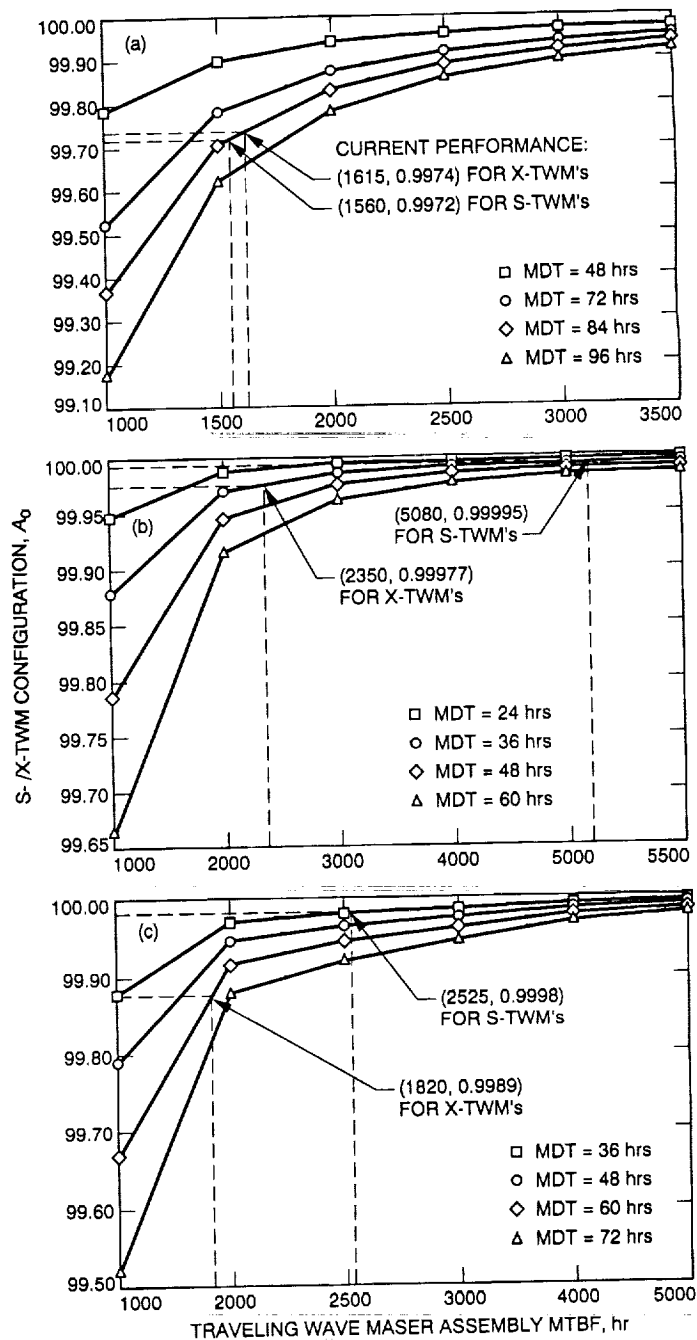


Fig. 5. Operational availability of S- and X-band TWM configuration versus TWM assembly MTBF at various levels of TWM Assembly MDT: (a) Goldstone, DSS 14; (b) Canberra, DSS 43; and (c) Madrid, DSS 63.