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Reliability Modeling of NASA McMurdo Antenna System with Engaging Graduate Students in Research

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Abstract

The increasing complexity of system reliability such as the antenna system at McMurdo Ground Station calls for a more proactive reliability and maintainability approach. This research deals with the use and the importance of reliability and availability study in a complex system, integrated with the training of graduate students. With the help of BlockSim software, the reliability and availability model of NASA McMurdo antenna system is developed and analyzed. The reliability model and service availability of the McMurdo antenna system is critical and important due to the very limited accessibility of the McMurdo facilities at a remote and weather-harsh location. Through the developed model, a risk level is assigned to the components associated with the system. These component's contributions to the system availability are also analyzed and mission critical components are identified.

1. Introduction

Morgan State University (MSU) has successfully collaborated with NASA Goddard Space Flight Center (GSFC) for many grants and research projects. This project is one of them. In this antenna reliability system project, several graduate students from MSU, under the guidance of Dr. Guangming Chen, worked with a group of NASA reliability engineers at GSFC, on the reliability modeling for NASA McMurdo antenna system, supported in part by Maryland Space Grant Consortium [1-4]. These research topics are real NASA projects and are exemplary collaborations to guide student's research jointly by faculty and NASA engineers and students can benefit greatly from this collaboration.

In engineering systems, repair is a common operation since cost associated with repair or replacing component parts is much less than that required replacing the entire system. Since repairs and preventive maintenance are necessary activities, the maintenance of repairable system becomes a topic of utmost concern. When the maintenance of a repairable system is studied, the function of availability is often used as the figure of merit. As a result has been a research attention in a lot of mission-critical systems, as used in aerospace, military, and power generation industries [5]. Studying the availability of a system will among so many benefits be useful as a decision tool for predictive maintenance planning, spare parts allocation, and maintenance related logistic planning.

The availability of a system is the proportion of time it's in a functioning condition during its lifetime [6]. Another definition is the ability of a product to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval assuming that the required external resources are provided [7]. Availability is of critical concern in system performance measurement over its life or a given time period. The level of availability achieved in operation depends on a number of logistical factors but the two most important are the reliability and maintainability of the system. Before the reliability and maintainability of a system can be improved, a good understanding of the system availability is vital, as it forms a baseline upon which incremental improvement can be set and achieved. Over the many years of NASA supported-missions, systems have become more complex and support costs have increased significantly. It is also a NASA requirement that reliability and maintainability activities chosen for every deployed system are such that will ensure the system operates successfully for the required mission life cycle [8]. These reasons make it very important that the availability of systems be studied in order for gains in the reliability and maintainability to be achieved.

There is a lot of emphasis on the reliability or availability in all of NASA's missions and systems. The availability is used in repairable items to denote the proportion of uptime over the total operational time. The availability study of McMurdo Ground Station antenna system is intended to be an asset management tool that will be used in evaluating the system risk level and help in logistic planning. Preventive and predictive maintenance planning, spare allocation, fund allocation, estimating a life cycle cost, and identification of mission critical units or "road blocks" to the required service level are all examples of benefits of this study. Through this project, a measure of risk is assigned to each subsystem, and component based on their respective contribution to the overall system unavailability or unreliability.

This study is a part of major deliverables in the station upgrades required before the it begins to support the Meteorological Operations Satellite (MetOp) and the European Meteorological Satellite (EUMESAT) planned to begin between year 2011 and 2014 [9]. The objectives of this project include:

- Developing a value added analysis to be used for the reliability centered maintenance of McMurdo Ground Station antenna system;
- Computing system availability metrics such as scheduled system availability, point availability, expected number of system failure, expected number of component failure and failure criticality index.

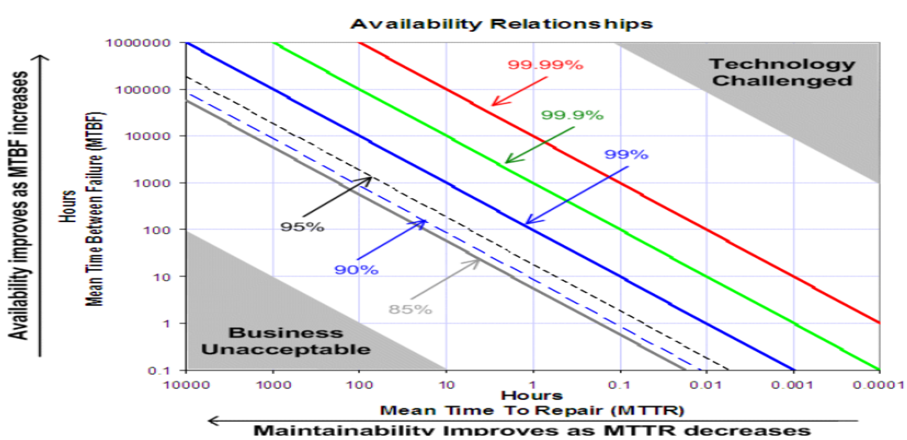

Figure 1: Relationship between availability, MTBF, and MTTR

These metrics all contribute to understanding risk and making decisions to mitigate it through logistics and maintenance planning. Jihong Zeng studied the mean time between failure (MTBF) to the reliability and the mean time to repair (MTTR) to the maintainability of a maintained system and how they relate to the availability measurement of the same. Figure 1 shows the illustration of the relationship [10]. In the case study, Zheng used block diagram modeling approach to compute the system availability of a web service having networking, web application server, and database server as subsystems using BlockSim from Reliasoft©. Figure 2 shows the BlockSim availability outputs for the web service system.

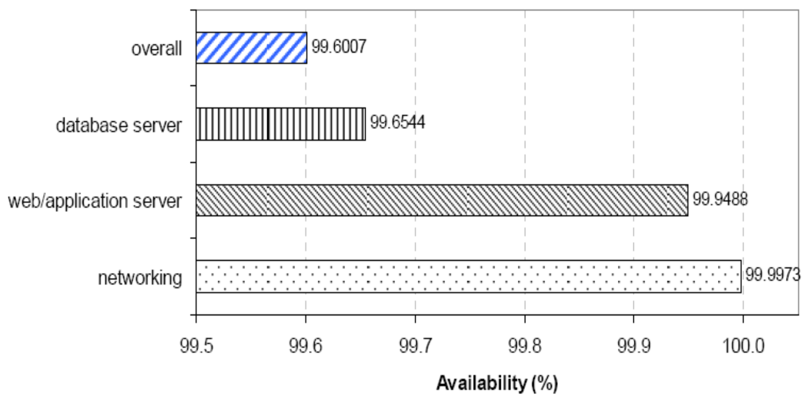

Figure 2: BlockSim overall system availability output for the web service system

The reliability, availability, and maintainability are mostly modeled on a two-state failure model; uptime and downtime. Bae, Cho, and Hwang [11] proposed a flexible three-state availability model, arguing that it's problematic to determine a level of operational performance as a decision point to operate or be down. They proposed that the first state is the state when the system operates within design specifications, second state is when the system operates at some level below design specifications, but continues to operate, and the third state is when the system fails completely and cannot be operated. The figure 3 below illustrates the two-state and three-state availability models.

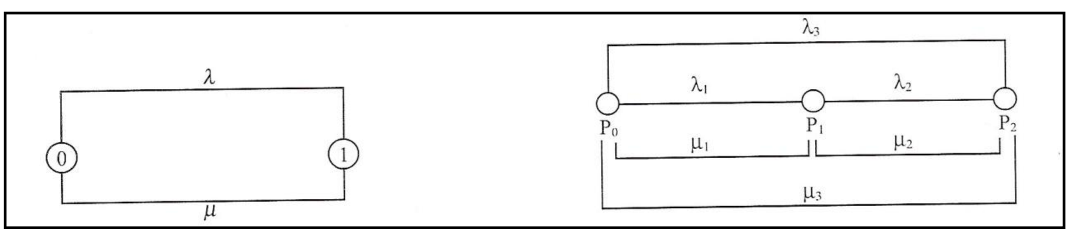

Figure 3: Two-state and three-state availability model

The McMurdo Sound, Antarctica is a site for one of NASA's key asset to collect satellite radar mapping for the entire Antarctic continent and download data for polar orbiting missions [12]. National Science Foundation (NSF) manages the facility. MG1 is the designation for the 10-meter S-Band and X-Band antenna installed in 1995. As part of the Integrated Program Office (IPO) preparedness to serve EUMETSAT and MetOp, several upgrades are planned for the station to include new systems to be installed. The project team as part of quality control is required to compute the availability of the system with the proposed upgrades. At the time

Morgan State University began this study, the NASA-project team had just begun the Preliminary Design Review and Critical Design Review (PDR/CDR) of MG1 upgrade. The PDR/CDR by itself is purposed to disclose the complete system design in full detail, and ascertain that technical problems and design anomalies have been resolved without compromising system performance, reliability and safety.

2. McMurdo Ground Station (MGS)

The MGS is one of the several NASA's ground stations that comprise the NASA Near Earth Network (NEN), formerly known as Ground Network (GN). MGS is a NASA-operated facility located on the southern tip of Ross Island on the shore of McMurdo Sound in Antarctica. It is operated by United States through the United States Antarctic Program (USAP), a branch of National Science Foundation (NSF). MG1 consists of the antenna site on a hilltop 2 km north of McMurdo Station, a control room in central McMurdo Station, and a boresight antenna verification system on Observation Hill [12]. The antenna site includes a 10 meter auto-tracking antenna system housed in a radome (Figure 4), and a controlling building which contains the receiving equipments connected to the antenna via fiber optics lines. MG1 provides a beneficial tracking location for polar orbiting satellites due to its high latitude. The primary functions of the station are the tracking and data acquisition of the Synthetic Aperture Radar (SAR) satellite system, tracking and data acquisition of polar orbiting S-Band missions, and launch vehicle/payload tracking during launch and early orbit period of high inclination missions. The station also includes the NASA Tracking and Data Relay System (TDRS) communications system. NSF and NASA are operating this station on a 24-hour, 7days/week availability basis receiving data telemetry from satellites. The MG1 is currently marked for upgrades which include support of the European Meteorological Satellite (EUMETSAT) operation and the Meteorological Operations Satellite (MetOp). The upgrades are to be achieved by the replacing some vital component parts of the existing 10 meters antenna system for support capabilities of the MetOp x-band downlink signal.

Figure 4: 10-meter antenna at McMurdo Station before the radome installation.

3. Instantaneous or Point Availability *A(t)*

If one considers both reliability and maintainability (the probability that the system is successfully restored) then an additional metric is needed for the probability that the system or component is operational at a given time, or has been restored after a failure. This metric is availability. Availability is a performance criterion for repairable systems that accounts for both reliability and maintainability properties of the system or component [13]. It can be defined as “a percentage measure of the degree to which a system, or equipment is in operable and committable state at the point in time when it is needed”. The definition includes operable and committable factors that contribute to the system, the process being performed, and the surrounding facilities and operation. Availability can be measured in various ways. Instantaneous or point availability is the probability that a system (or component) will be operational (up and running) at any random time, t. This is very similar to the reliability function in that it gives a probability that a system will function at the given time t. The system functioned properly from 0 to t with probability R(t), or it functioned properly since the last repair at time u (0< u < t), with probability [14]:

$$\int_0^t R(t-u)m(u)du \qquad (1)$$

Where *m(u)* is the renewal density function of the system. The point availability is the summation of these two probabilities:

$$R(t)+\int_0^t R(t-u)m(u)du \qquad (2)$$

The mean availability is the proportion of time during a mission or time period that the system is available for use. It represents the mean value of the instantaneous availability function over a period [0, *T*] and is given by:

$$\overline{A(t)} = \frac{1}{t}\int_0^t A(u)\,du \qquad (3)$$

The steady state availability of the system is the limit of large operating times, that is the instantaneous availability function as time approaches infinity or:

$$A(\infty) = \lim_{t\to\infty} A(t) \qquad (4)$$

The instantaneous availability function will start approaching the steady state availability value after a time period of approximately four times the average time-to-failure. The steady state availability can be considered as the stabilizing point where the system’s availability is a constant value. It however cannot be used as the sole metric for a system. The inherent availability is the steady state availability when considering only the corrective downtime of the system. It is defined as the expected level of availability for the performance of corrective maintenance only. A_i is determined purely by the design of the equipment. It assumes that spare parts are 100 percent available with no delays. It excludes logistic time, waiting or administrative downtime, and preventive maintenance downtime. It includes corrective maintenance downtime. For a single component, it’s written as:

$$A_i = \frac{MTTF}{MTTF+MTTR} \qquad (5)$$

4. Importance of MG1 Availability

An important outcome of MG1 availability study is that it gives the project team an assessment of the quality of design and moves the review process forward to the next critical milestone. It also allows the project team to identify potential weakness in the design that may hamper reliability and availability of the system. It's also important to note that the study will also allow the asset managers to identify area of costly over-design. Figure 5 illustrates important terminologies in availability: MTBF (Mean Time between failures), MODT (Mean operative downtime), MLDT (Mean logistic downtime), MTTR (Mean time to repair), MPDT (Mean preventive maintenance downtime), MIT (Mean idle time), MOT (Mean operational time), MWT (Mean waiting time), MTTM (Mean time to maintain), MTTF (Mean time to failure), MDT (Mean downtime), MUT (Mean uptime).

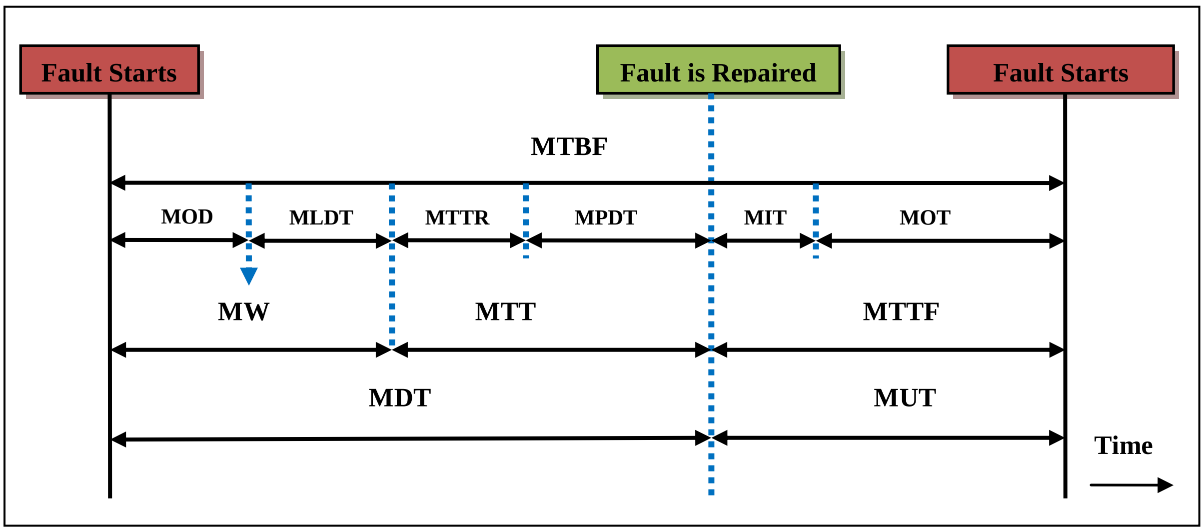

Figure 5: Availability Terms

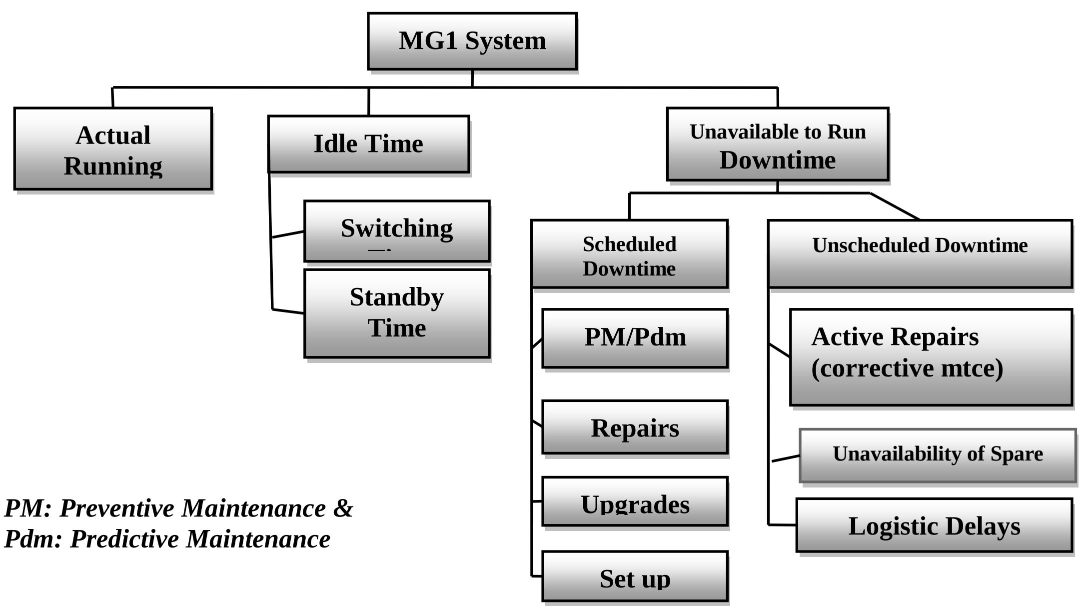

Figure 6. MG1 Time designations.

Within the MG1 system and operations, there are a number of events that may constitute "time". The figure below illustrates the different time designation. When the elements of downtime from a design engineer's perspective are examined, it's quite common to address only the active maintenance segment. This is because of being able to directly relate system characteristics like fault diagnosis to downtime. From the perspective of systems engineering though, it's important to deal with the entire downtime spectrum.

5. System Architecture

The system boundaries of the McMurdo antenna system were determined in collaboration with NASA Near Earth Network team to set limits for the study and identify all elements of the installation that were not to be included in the model. This effort involved identifying the Line Replacement Units (LRU) pertinent to the availability and reliability of the station. The system components were organized into a system Reliability Block Diagram (RBD). Failure relationships within each subsystem and between all the subsystems were evaluated. The possible relationships are; series, parallel, m-out-of-n relationships (Figure 7). These are inputs for BlockSim availability modeling.

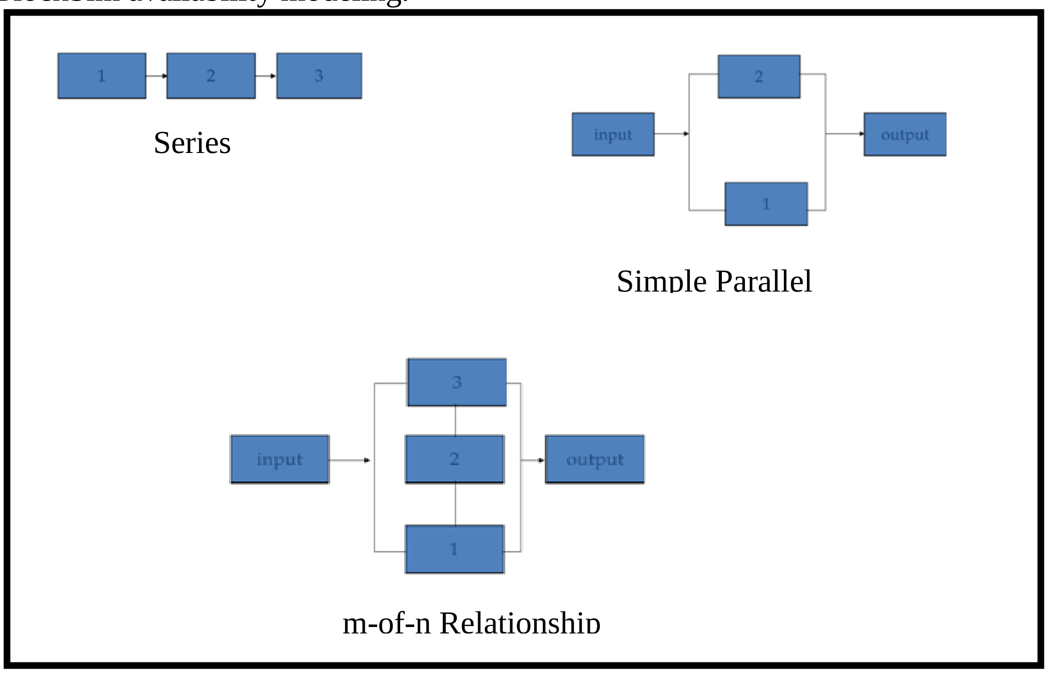

Figure 7. Reliability diagrams for Blocksim.

The components are listed out, grouped according to their functions; Figure 8 shows a simplified component functional grouping showing major subsystems of MG1. This is further simplified until all Line Replacement Units (LRU) are all identified. From the components functional representation, a set of reliability block diagrams (RBD) are developed. The reliability RBDs are rectangular blocks representing each LRU. The RBDs are developed based on the failure relationships of the system components. This was jointly done with equipment operators and design contractors. Figure 8 illustrates the steps in the development of MG1 architecture.

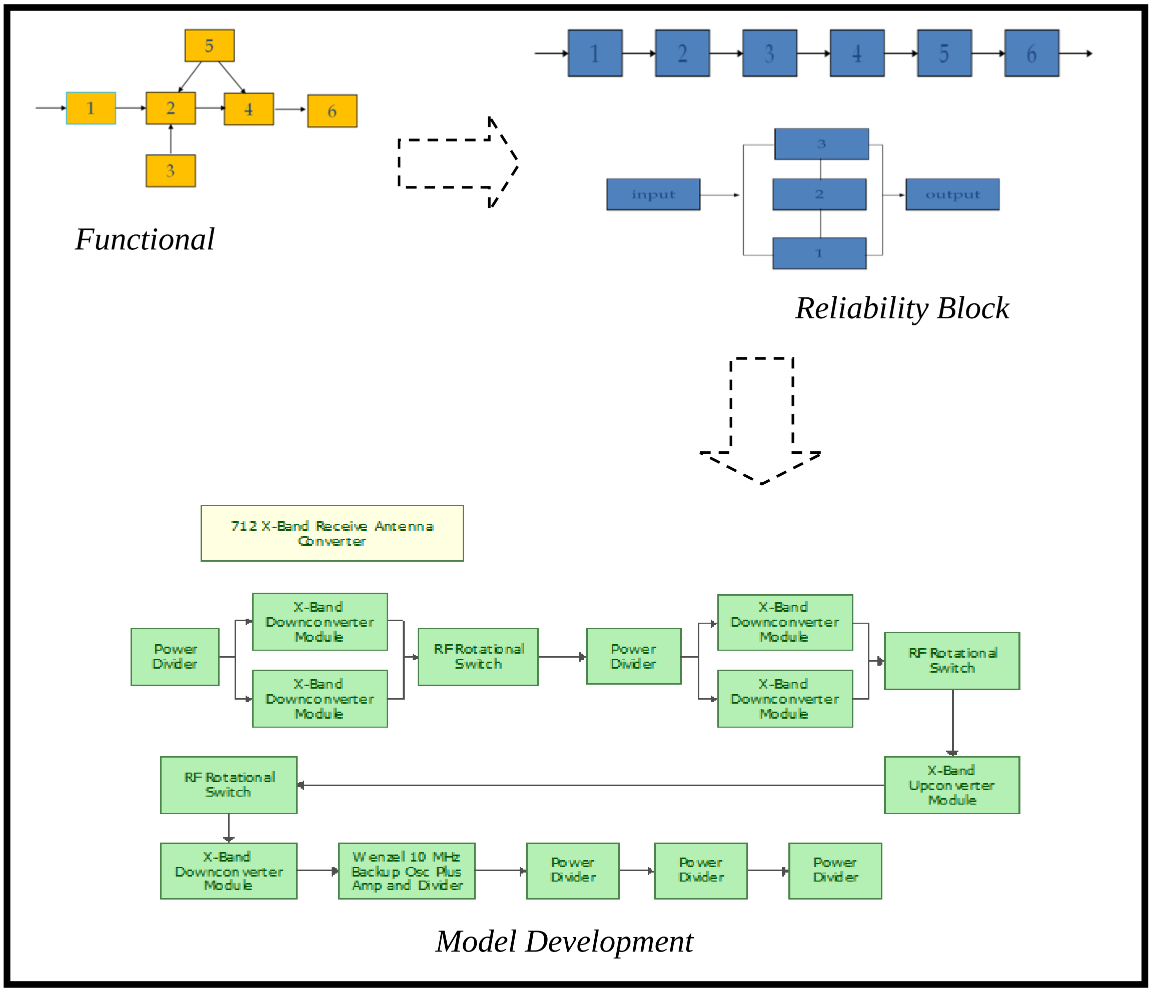

Figure 8. Procedure to develop reliability model for Blocksim.

Figure 9 illustrates the product breakdown structure which is the basis for the reliability model development for Blocksim input. All the requirements needed for the project were organized and systematically sourced. The requirements included a component and manufacturer/vendor listing, the input data (MTBFs and MTTRs) needed for BlockSim modeling and also collected. Contacts were established with the MG1 operators, manufacturers and vendors of the system components to access the design MTBFs, the historic MTBFs and the MTTRs. The MTBF and MTTR values used in the study are the best estimates of experienced operators, or manufacturers of the system components.

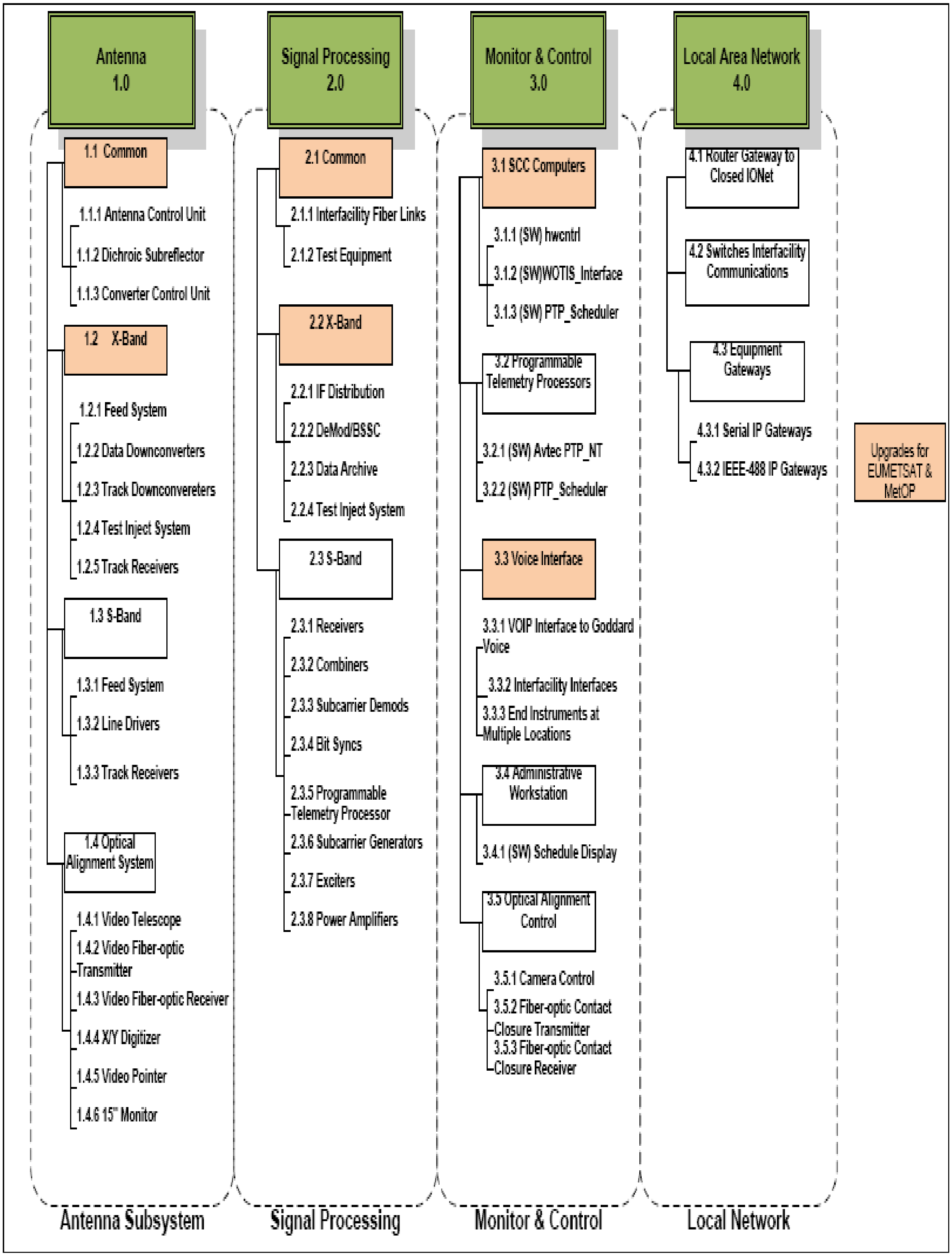

Figure 9: Component Grouping According to functions

6. Model Building and Analysis

Reliability block diagrams (RBD) are used to model failure and service delivery components and their interrelationships between the components of each of the sub-system and the system. A RBD is a representation of system components and how they are reliability-wise related which may differ from how the components are physically connected. The modeling is done using rectangular blocks connected by direction lines, each representing a repairable component in the system. The system availability has been calculated by modeling the system as an interconnection of series, parallel or m-out-of n relationships. In Figure 10 shown below, "aaa" and "ccc" illustrates a series relationship where the failure of either "aaa" or "bbb" will result in no output from subsystem A. The relationship between the two strings of"aaa-bbb" depicts a parallel relationship where only one of the two strings is needed to give an output to subsystem B at a time. Subsystem B has components "jjj", "hhh", "fff", and"ggg" simple "m out of n" relationship. Here, one of the four components in the subsystem is required to function for an output. The notation m denotes the number of components needed for an output and n denotes the total number of components.

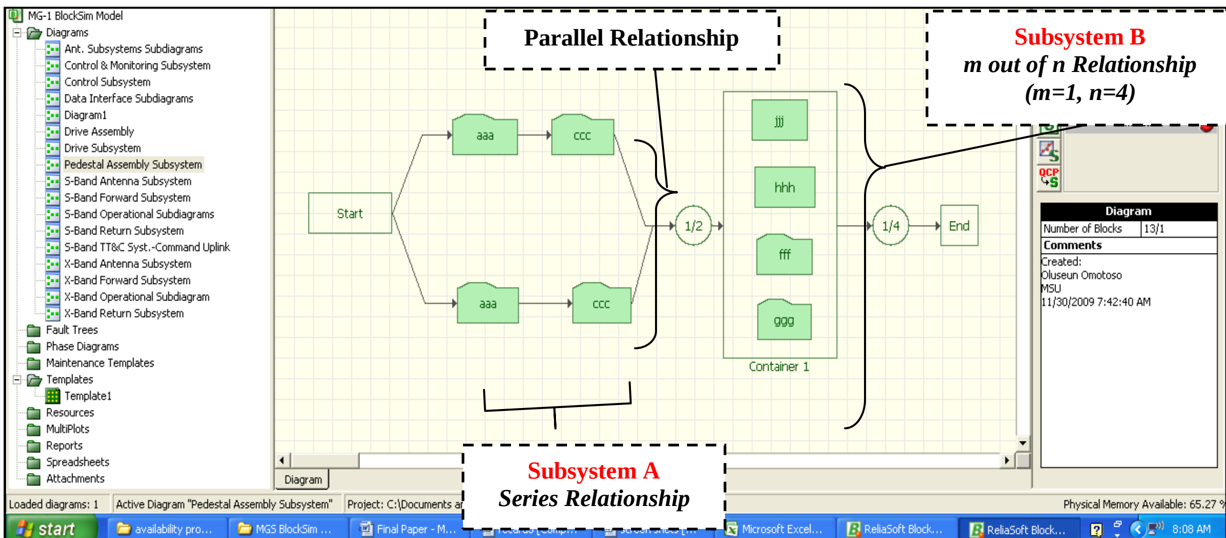

Figure 10: Types of Relationships

The MTBFs for all components in the system were gathered from the equipment vendors and the best judgments of the experienced operators. Relevant data include dates and times of failure incidents, dates and times of restoration, preventive maintenance schedule and log, records of logistic delays in restoration. Other related information such as NASA policy pertaining to preventive and corrective maintenance was also assessed. The MTBFs are assumed to have exponential distribution, which is widely employed in reliability engineering, and it describes components and system with single parameter, the failure rate. The probability of a component of the system being in the "up" state is the availability component; the probability of that component being in the "down" state is one minus the availability component. Assuming that the operational state of every component in the system is independent of the other, the system availability is the product of all the component state probabilities:

$$A_{system} = A_1 \cap A_2 \cap ....A_n \quad or \quad A_{system} = \prod_{i=1}^{n} A_i \qquad (6)$$

Where,

A_{system} = The system availability (combination of components availability)

A_i = The availability of i^{th} component in a system having a total of n components.

So for a subsystem that contains n repairable components, there are 2^n combinations of components operational states.

BlockSim provides a comprehensive platform for system reliability, maintainability and availability analysis. It provides flexible capabilities to model a system with the use of reliability block diagram. Simulation provides the methods for studying a wide variety of models of real-world systems by numeric evaluation using software designed to imitate the system's operations or characteristics, often done over time. However, it's important to realize that because many real systems are affected by uncontrollable and random inputs, many simulation models involve random or stochastic, input components, causing their outputs to be random too. A model is a representation of a system for the purpose of studying it. The model is not only a substitute of the system; it is also a simplification of it. The model used should be sufficiently detailed to permit valid conclusions to be drawn about the real system. The following are the steps performed during the development and building of MG1 availability model.

1). Data Accessing

This involved trips to one NASA facility and another major design contractor, and several virtual meetings organized by the project team. Pertinent data like the MTBF, and the MTTR were retrieved. Some of the data used were the designer's or operators best judgments.

2). Data Analysis

For the failure data, exponential distribution was used since actual failure data is not available.

3). Model Verification and Validation

The verification process involves checking that the model represents the intended real system. NASA system and reliability engineers evaluated the developed model to ensure the adequate simulation of the system.

4) Model Output Reporting

The system overview gives the system simulation reports after running the model 10000 times for 80000 hours. The table shows a system mean availability of 98.46%, resulting from uptime of 78,771.004 hours and a downtime of 1228.9958 hours. It was shown that the MG1 system simulation has a "Number of Failures" metrics of 336.6477. This can be explained as the number of times that the system experienced a failure, or "was down". It should also be noted that only corrective maintenance is assumed at this time and other downing events are not included. This could also be interpreted as the number of spare parts required for corrective maintenance actions for the system. Likewise, the "Number of Failures" for individual components can be used to determine the amount of spare needed for each component.

7. Conclusion and Discussion

In this study, a BlockSim model of MG1 system has been developed. The model consists of all necessary system components that will enable asset managers as well as the upgrade team to further evaluate the station design and report a readiness assessment on the ongoing upgrade. The model developed can also provide a discrete event simulation for reliability, availability, maintainability, life cycle cost summaries and related analyses. It also will, after the upgrade is over be used for MG1 system performance benchmarking which is a very useful quality control tool. The logistic planning and sparing allocation for the 135-components system is expected to be easier done with the use of the model developed as failure critical components within the system are identified and adequate proactive measures can be planned.

The results obtained from this study are preliminary but necessary, and would not by itself be used in taking any decisions as of yet. Further work is required in making the model more representative of the MG1 system. Some of the aspects that may be studied further are; the logistic delay involved in maintenance and accessing the station, the inclusion of switching time between redundant units. Other sources of downtime will have to be investigated and imputed in the model as well; these will include the predictive and preventive maintenance policies.

Acknowledgement

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