MAORY/MORFEO: the RAM analysis approach for the preliminary design

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ABSTRACT

MORFEO is the Multi-conjugate adaptive Optics Relay For ELT Observations, formerly known as MAORY (Multi-conjugate Adaptive Optics RelaY), designed for the ELT first light instrument MICADO. With the goal of being compliant to Reliability, Availability and Maintainability (RAM) requirements, we present the approach for the RAM analysis carried out for MORFEO at system level. RAM analysis allows to monitor the possible failures that could occur at lower levels and to highlight criticalities, hence leading to recommendations for design changes, thus preventing failure propagation at higher levels, and providing a maintenance strategy to keep the system in operation.

The RAM process requires not only a series of interactions with all subsystem engineers, but also with AO specialists that identify all possible degraded modes that are a key aspect of failure assessment, but must be driven by requirements on science. The RAM approach we will outline is the base for having a more reliable design and for defining a suitable maintenance plan, with the final goal of enhancing the system availability, thus avoiding critical down time of the instrument during its entire lifetime.

Keywords: MAORY, MORFEO, ELT, RAM, Reliability, Availability, Maintainability, Maintenance

1. INTRODUCTION

MORFEO is the multi-conjugated Adaptive Optics (AO) module for the ESO's ELT, it will improve the compensation for the atmospheric turbulence and is designed to work with the first-light instrument MICADO; moreover and it is foreseen to have a second port for a second-generation instrument.

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Reliability, Availability and Maintainability (RAM) activities start at the beginning of the design phase, in fact, the RAM analysis will help the subsystems to choose components with a suitable failure rate in order to guarantee the required reliability at system level for the MORFEO instrument. This analysis allows to: monitor the overall possible failures that could occur at system, sub system and lower levels; highlight criticalities, lead to recommendations for design changes; preventing failure propagation at higher levels. The RAM assessment will be frozen at FDR

Starting from FMECA analysis from the lower levels at the Line Replaceable Units (LRU), critical items are identified already in the preliminary phase. In this way, mitigations can be pondered and introduced within the design: RAM analysis in fact is a design driver.

In this proceeding we summarize the design of the MORFEO instrument in Section 2. Section 3 is dedicated to the ELT RAM Requirements to which MORFEO has to comply with as well as the RAM strategy. Section 4 aims at reporting the RAM model focusing on those subsystems that impact in the final RAM assessment. And finally Section 5 highlights particular cases of MORFEO subsystems.

2. THE MORFEO INSTRUMENT

2.1 MORFEO Consortium and status

MORFEO is being managed, designed and developed by an International Consortium of partners comprehensive of

- INAF – the Italian National Institute for Astrophysics, Italy, which is the lead Institute of this Consortium
- IPAG - Institute for Planetary sciences and Astrophysics, Grenoble, France
- NUIG - National University of Ireland Galway, Ireland

MORFEO is approaching the closure of the Preliminary Design Review milestone, and it is expected to be in commissioning by 2029.

Figure 1 shows a rendering view of MORFEO (rightmost instrument) and the other instruments on the Nasmyth platform at ELT. Several instruments share the physical space, this condivision must be taken into account for accessibility issues related to maintenance procedures since the beginning of the design. RAM analysis, in fact, is a driver in this case in particular for the Maintenance strategy.

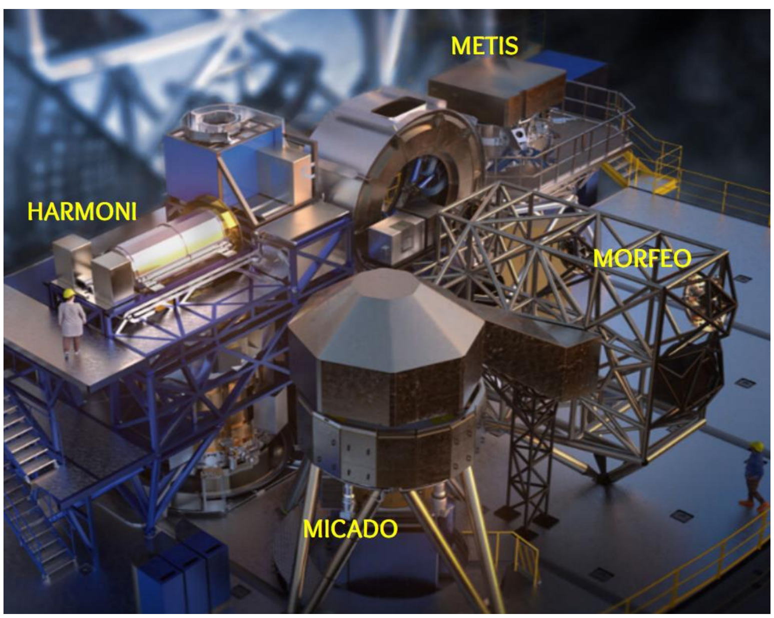

Figure 1. MORFEO rendering within the Nasmyth platform and together with other first generation instrumnets

2.2 Design description

The main function for MORFEO is to relay the light beam from the ELT focal plane to the client instrument while compensating the effects of the atmospheric turbulence and other disturbances affecting the wavefront from the scientific sources of interest.

Light from the ELT enters MORFEO and passes through a post-focal relay system composed by seven mirrors (M6 to M12), several of which having complex motorized functions and where at least one, M9, is a Deformable Mirror (DM) as baseline, but with the goal of having also M10 as DM too. After M10, a dichroic allows a beam to enter the module for artificial Laser Guide Star Wave-Front sensing (LGS-WFS), where the high-order effect of turbulence is measured and monitored, while the remaining light is directed towards the scientific channels. Light reflected by M12 enters the Natural Guide Star (NGS) module for the measure and monitoring of the low-order effects of turbulence. The Real Time Computer (RTC) module combines the information from LGS-WFS and NGS-WFS (and M4 from ELT) and closes the loop controlling the shape of the DMs. A passive thermal control system regulates the MORFEO environmental conditions, and is composed by sensors, active air recirculation system and a glycole cooling system.

MORFEO has two operation modes:

- MCAO mode wavefront sensing is performed by up to six LGS and three NGS: the NGS are used for both Low-Order and Reference (LOR) sensing; wavefront compensation is performed by means of the telescope's M4/M5 mirrors and by the post-focal DMs inside MORFEO. The choices to implement the MCAO technique and to use LGS for wavefront sensing have been taken to improve the performance uniformity over the field of view and the sky coverage.
- SCAO mode wavefront sensing is performed by a single NGS as close as possible to the direction of the scientific target in the sky; wavefront compensation is performed in this mode by means of the telescope's M4/M5 mirrors only. The SCAO mode is a joint development between the MORFEO and the MICADO consortia.

MORFEO will be installed on the ELT Nasmyth platform. It feeds two focal stations: the gravity invariant port underneath the MORFEO bench for MICADO and the lateral port for another second generation instrument. In Figure 2 is shown a skectch of MORFEO with its subsystems and components. A general overview of MORFEO is given in [1], and the optical design status update is given in [2].

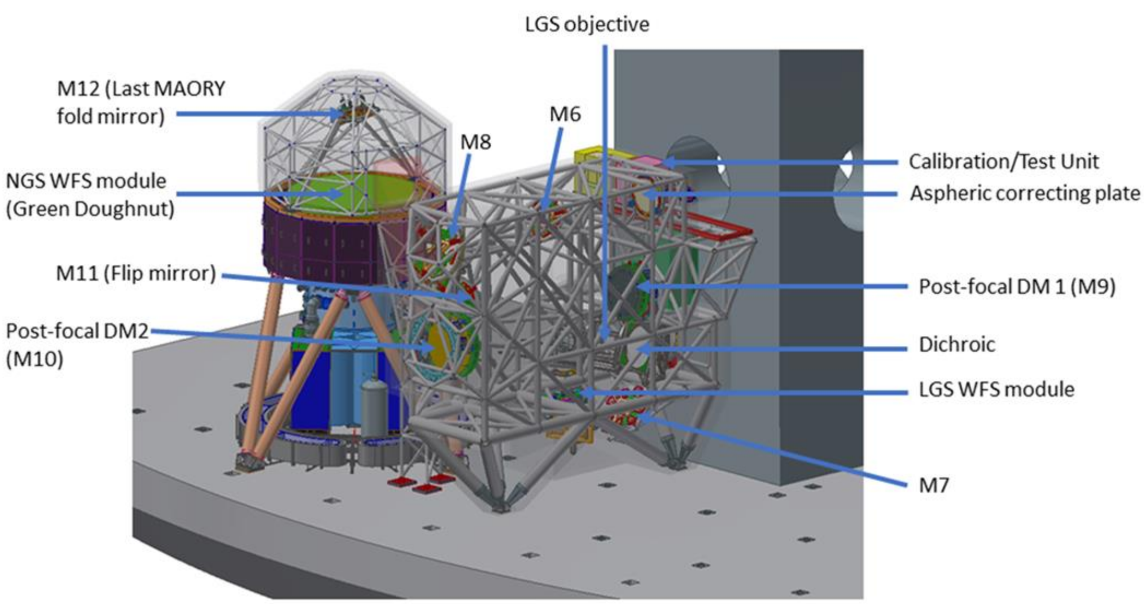

Figure 2. MORFEO sub-systems and main components

3. ELT RAM REQUIREMENTS

RAM analysis based on top level requirements is usually a compromise with other requirements such as safety, mass, cost, schedule, etc. Its outputs are essentially recommendations for reaching this compromise: an awareness of the risks, a choice of procurement, the identification of potential weaknesses, and so on. In the design phase, the reliability analysis shall be implemented to ensure the availability of the tool throughout its life cycle.

MORFEO reliability strategy, taking into account the ESO requirements bases its analysis on the following guidelines:

Modularity

By basing the maintenance of the instrument on Line Replaceable Units (LRU) concept, allows to consider MORFEO made up of several products and dedicated modules.

This approach in particular allows:

- to control failure propagation inside boundaries of the module. Calculation on failures and their detection, when propagated, is obtained in a reliable way using a modular approach in the design.
- through the LRU identification, to assess more easily maintainability and availability analysis
- to carry on parallel design, allowing different WPs to work independently.

Standardization

Standardization is strongly encouraged by ESO, through a thorough definition of ELT standards. Advantages for RAM are:

- A high maturity and use of standards permit to have reliable failure rate estimations and reliable components and materials.
- Verification of components is a product of standards using standardized pass/fail criteria.

Derating

Derating means avoiding, whenever possible, to operate components to the limits of the capabilities, assuring simpler maintenance programs by means or preventive/predictive maintenance. Less corrective maintenance, less spares, less visual inspections are typical advantages for not stressing the components. The drawback can be major costs in procurement, and a trade-off in this sense has to be coordinated with MORFEO Project Office.

3.1 ELT RAM Requirements

Lifetime

MAORY, as all the instruments from ELT, is required to have an operational lifetime of 10 years and to be available for an average number of nights per year. Different modules in MORFEO will have different duty cycles, i.e. will be operative during each observing night for a different amount of time. A clear example is the Calibration Unit, which will operate for a short time before scientific operations (actual time still to be defined). These different duty cycles for each configuration item have to be taken into account for a proper bottom-up verification of the RAM budgets. This means that either the components procured are selected with an MTBF that covers the expected minimum lifetime of 10 years or more, or a maintenance strategy has to be defined to avoid failures by means of maintenance.

Reliability

The reliability of a system is measured through its Mean Time Between Failure (MTBF) value, computed as the appropriate combination of MTBFs for each of the system components, on the basis of the functional relations between the items (serial, parallel, with redundancies). Failures could impact the overall system with different severities (from worst case identified as loss of science, to minor failures that allow degraded modes). ESO requirements provide a budget for the MORFEO MTBF for each of these classes of severities:

- Severity 3: if failure causes loss of science or corrective maintenance cannot be deferred
- Severity 2: if a failure causes a performance degradation of science observation
- Severity 1: any failure not belonging to the previous two categories

Availability

As stated by its requirement the maximum Unavailability of MORFEO shall not exceed 0.84%. This parameter is strictly correlated to the MTBF (Mean Time Between Failures) and MDT (Mean Down Time) of the System by the following relation:

$$A\ [\%] = \frac{MTBF\ [hrs]}{MTBF\ [hrs] + MDT\ [hrs]} \quad (1)$$

With this definition it is possible to estimate the MDT budget of MORFEO.

Maintenance

ESO provides requirements, guidelines and budgets (on manpower) for the maintenance of MORFEO. Maintenance cannot be performed during nighttime, and any failure occurring during observations have a strong possibility to impact the availability of the instrument (according to the type of failure)**.**

There are three types of maintenance are defined:

- Corrective maintenance is performed to restore/maintain system hardware integrity (in-situ repairs, replacement of LRUs).
- Preventive maintenance shall be carried out during non-observational hours at daytime with a budget on the total number of hours and manpower.
- Predictive maintenance foresees the monitoring of sensitive data that can report in advance deterioration in the performances of components. In this way conditional preventive maintenance can be carried out to avoid system failures.

Moreover ESO grants the possibility for an Overhaul Maintenance every 3 years. This possibility has a strong positive impact on the chance to comply with the budget, by planning predictive/preventive maintenance accordingly.

3.2 RAM Strategy

As already stated, RAM analysis is important from the beginning of the design phase, and it is a design driver, allowing System Engineering (SE) and sub-system teams to achieve a more reliable final product by introducing recommendation from the RAM assessment.

The design of the System must be compliant to the top level requirements for RAM:

- Lifetime of the instrument, considering the instrument duty cycle (fraction of operative time versus lifetime)
- Availability, defined as the percentage of time in which the instrument shall be able to operate during the lifetime of the instrument.
- Reliability, defined as the probability that the instrument will perform according to specifications during lifetime without failures.
- Maintainability is the ability of the instrument to be retained or restored in case of failure.

Following ESO requirements definition, Eq.1 in Section 3.1, the System MDT is constrained, because of System Unavailability and MTBF values (for the different Severity types) are defined as requirements. In this way, we have an upper level of MDT to be flown down to sub-systems level. An iterative process allows to assign MDT to the subsystems, based on the bottom up analysis from the single configuration items MTBF and maintenance complexity. This in turn allows to plan a maintenance strategy that keeps the system operative within the MDT budget.

As we will see, all the planned maintainability activities, estimated in terms of redundancies, spare parts, maintenance manpower and time, allow to assess if a subsystem can me maintained and fulfills its requirements.

Depending on the Availability and Reliability (RA) requirements, the maintainability strategy is sketched to comply with RA requirements. The system is either maintained and/or restored to operation based on the type of failure. Corrective Maintenance strategy reflects the necessity of being compliant to the requirements of MTTR and MCMT. Preventive and/or predictive Maintenance strategy reflects the necessity of being compliant to the requirements of daytime maintenance period window, Yearly Maintenance staff time, Overhaul Maintenance.

Maintenance activities can be organized as follows:

Corrective Maintenance, as an undeferrable activity, allows to restore the System after a failure. Its strategy includes the planning of resources, i.e. persons and time, including the planning of those AIV activities (e.g. alignment, verification) needed after the LRU replacement.

Preventive and Predictive Maintenance allows to maintain the System to prevent the occurrence of failures. The strategy aims to maintain or increase the overall MTBF. As in the previous case, the strategy includes the planning of resources, i.e. persons and time.

A final RAM assessment is the base of the Integrated Logistic Support documentation organizing all the activities needed to ensure the delivering of the spare parts in the due time.

4. MORFEO RAM MODEL

ESO requirements are quite stringent, aiming to have a reliable and highly available instrument to maximize the science return from the ELT facility. These requirements, as explained in the previous sections, are translated into budgets and guidelines, that rule every aspect of the MORFEO RAM analysis.

ESO requirements and budgets, as outlined in the previous section, drive our RAM model in which is of great importance, since early design phase, that:

- Each LRU is properly identified and (as easily as possible) accessible, to minimize the MDT related to its failure
- Failures are appropriately identified managed and quickly reported
- Redundancies are included in the design whenever possible according to costs budget
- Spare needs are gathered and optimized according to their MTBF, duty cycle, lifetime

To proceed with the RAM model, the processes described in the following sections have to be implemented iteratively.

MORFEO Functional analysis

From the functional point of view in the RAM Analysis, MAORY is composed of 9 sub-systems, each one delivering one or more products (see Figure 3):

- DM(s)
- Opto-mechanics
- Instrument Control hardware (HW)
- LGS WFS
- Main Structure
- LOR WFS
- RTC
- Thermal Control
- Calibration Unit (CU)

At this stage a first identification of LRUs can be assessed within each subsystem. This information is then implemented into the Bill of Material (BoM) that is based on the Product Breakdown Structure (PBS).

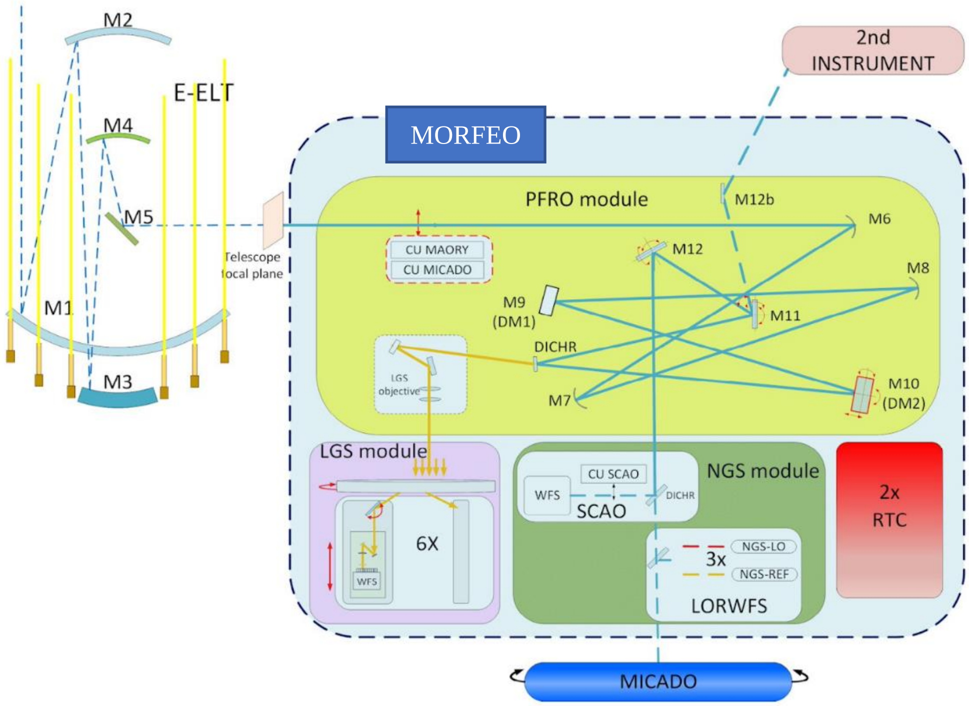

Figure 3. MORFEO functional overview.

4.1 FMECA

At this stage with have all the tools (Bill of Material (BoM)/LRU, functional analysis) to identify all the failures in a bottom up approach at lower level that can propagate and affect the system. This process is based on the Failure Mode Effect and Criticality Analysis (FMECA). The final result will be to solve or mitigate the effect of potential failures, giving insights on the design, HW configuration and maintainability of the system.

The final output highlights that only two subsystems have failure modes with high criticality: DM(s) and LOR WFS. In the case of the DMs, the critical failures are all referred to the loss of communication in the safety system. This criticality is high due to the combination of probability and impact. In the case of the LOR WFS Module, the analysis highlighted critical failures in the detector acquisition. Also in this case the high score is due to the combination of probability and impact.

4.2 Reliability Model

The reliability model is based on the RBD, defined at each level, down to the identified LRU. The RBDs describe the configuration relationship among the components, allowing to assess the equipment failure rates, operating functionalities, and maintenance strategies. The Reliability model is not a rigid description of the system but allows to assess RAM performances at any level driving the optimization of the system.

MORFEO has been structured in way that the following different configurations of items can be present:

- Serial

- Parallel
- n out m
- n out n+1 with active redundancy with cold spare units

The last two configurations are proposed as mitigation when the required budget of MTBF cannot be reached with a serial configuration.

Different reliability budgets are flown down taking into account the three severity level types, thus meaning we will have three Reliability models. In the sections below, devoted to some subsystem, we describe cases by highlighting different reliability model subsystems for different configuration and failure severities.

4.3 MTBF Budget and Verification model

Following the V-model diagram, the MTBF budgets in requirements (see Sect. 3.1) have been flown down to subsystems.

Criteria for the budget assignment are

- the complexity of the design of the products
- the maturity of the technology adopted
- the duty cycle applied to the products.

The subsystem budget is fine-tuned by iterations between the RAM engineers and WP managers during the overall design phase. The bottom-up verification of the compliancy to budget is obtained combining the MTBF at LRU level in the reliability model described in the previous section.

The principles for the collection of MTBFs are the following:

- in case of CoTS, MTBF are retrieved from datasheet or by standards (e. g. MIL-HDBK-217 or NSWC-98/LE1)
- in case of custom design, values must be estimated using standards and/or similarity

Considering that some components must be available all the time, their duty cycle is 100%. An example is the control electronics. In case of components subject to a 100% duty cycle, the failures are classified as:

- Severity 3, if the failure occurs during operations (80 days over 365 days by ESO requirements, i.e. 22% of the total time)
- Severity 1 if the failure happens in the remaining time

4.4 Maintenance verification strategy and spares parts

The list of MTBF at LRU level allows to properly quantify the number of failures expected for each component, and thus to define:

- the minimal list of spares needed to guarantee the availability of the instrument
- the resources needed to perform corrective maintenance

The FMECA analysis drives the quantification of the predictive/preventive maintenance needs. In fact, the mitigation of the impact of a failure gives clear insight on the maintenance procedures needed to enhance the MTBFs.

5. MORFEO RAM HIGHLIGHTS

Only those configuration items that can fail in a random way (active elements) enter in defining the RAM model. Maintenance strategy and Reliability configurations for these components are chosen to minimize MDT.

Most of the subsystems and its components work in serial configuration and if one fails all the system fails. The strategy is that in some cases is possible to implement parallel configuration, redundancies, introduce preventive/predictive maintenance with the aim to increase MDT and the reliability of the system.

In the following, we will present some cases among the MORFEO subsystems.

5.1 Deformable mirrors – Preventive/predictive Maintenance approach

The DM(s) in MORFEO light path [3], is one of the most challenging optical components of the instrument, in fact it will be among the biggest DMs ever made. An adaptive mirror allows its surface to be deformed in order to correct for atmospheric turbulence. The baseline is having DM(s) composed of about ~1000 voice coil and permanent magnet (VCM) actuators that change the shape of the mirror up to 1000 times per second. Among the active elements of a DM, the VCM are most critical items from a failure probability point of view.

Functionally, VCMs are LRUs, these have quite a long MTBF. However, due to the high number of actuators (~1000) a failure is expected every ~1.7 years for DM1 and ~1.5 for DM2. Since performances for the DMs are not affected up to 12 failed actuators (estimated value), an RBD configuration of 1014 out 1026 VCM is defined for DM1. A monitor based predictive maintenance with the threshold of 12 VCM can be implemented to assure the availability of the DM, and the typical maintenance program can be implemented during Overhaul maintenance, e.g. in combination with the recoating of the mirrors. Using this strategy, the availability and reliability of the instrument are not affected by the single VCMs failures, so at system level no Severity 3 failures are foreseen for DM.

The other components of DMs have a very large MTBF and no replacement is foreseen in the maintenance plan. In any case, the design allows an easy access to each item. Due to relatively new technology of the DMs, its reliability is generally considered challenging. However, the approach followed within the FMECA analysis since early design phase allowed to design a product whose MTBF is comparable to other MORFEO subsystems.

5.2 LGS and NGS – Degraded modes

MORFEO will use three natural stars (NGS) and six artificial laser stars (LGS), two separated subsystems are devoted to these tasks (LOR WFS and LGS WFS). LOR WFS ensures the sensing of the NGSs using 3 probes patrolling the region around the scientific field of view [4]. LGS WFS ensure the sensing of the LGSs with 6 arms reimaging their light.

Degraded modes are identified for both subsystems:

- LOR WFS: sensing with less than three probes is possible, leading to acceptable scientific data albeit technically out of specification (severity 2). If only one probe is available, LOR tomographic capabilities are lost, then MORFEO provides fast tip-tilt and reference correction only in the direction of the available NGS (severity 2).
- LGS WFS: if up to three arms are missing MORFEO may still operate in MCAO mode, however out of specification (severity 2). Otherwise MORFEO is not working (severity 3).

5.3 Real Time Computer

Two functions are covered by the RTC product [5]:

- the Soft Real Time Cluster (SRTC).
- the Hard Real Time Core (HRTC)

SRTC is composed by a 6-server system in serial configuration, at this stage designed to be identical subassemblies.

The HRTC subassembly can be designed into two ways:

- first configuration:

- 6 servers working in a 3 out 6 configuration. From the functional point of view, each server is devoted to a given Laser Guide Star. The same considerations on the failure severities made for the LGS subsystem apply (Section 5.2).
- 1 server performing all the other operations needed for HRTC

- second configuration
  - 1 server performing all the operations needed for HRTC

For RTC, the LRU is a single server. The failed item is easily accessed in its RTC rack, but the MDT is driven by the logistic. We can avoid corrective maintenance by introducing redundancy with a cold spare that activates in case of failure of one of the servers. This option helps to increase its reliability and again, avoid MDT.

6. CONCLUSION

With the goal of being compliant to Reliability, Availability and Maintainability (RAM) requirements, we presented the approach for the RAM analysis carried out for MAORY system level. This analysis allows to monitor the overall possible failures that could occur at system, sub system and lower levels, and to highlight criticalities, hence leading to recommendations for design changes, thus preventing failure propagation at higher levels.

Starting from FMECA analysis and Reliability Block Diagrams of the system and its lower levels, eventually down to Line Replaceable Units (LRU), critical items are identified already in the preliminary phase. In this way, mitigations can be pondered and introduced within the design: RAM analysis in fact is a design driver. The maintenance strategy is also sketched already in this early phase so that possible configurations can be evaluated.

The RAM process requires internal interaction with all subsystem engineers, also with AO specialists that identify all possible degraded modes: therefore an overall and more detailed analysis can be carried on. The RAM approach outlined is the base for having a more reliable design and for defining a maintenance plan, with the final goal of enhancing the system availability, thus avoiding critical down time of the instrument during its entire lifetime.

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