Military Technical College
Kobry Elkobbah,
Cairo, Egypt
April 3-5,2018

9th International Conference
on Mathematics and
Engineering Physics (ICMEP-9)

Overall Effectiveness Analysis ofL.E.O. Satellite Payload Subsystem

Ayman A. EL-Badawy*, Abou Bakr M. Elhady**,and Rehab E. El Badway ***

Rehab_bdaway@yahoo.com

ABSTRACT

The payload of the low earth orbit (LEO) satellite consists of all the components that provide communications services, that is, which receive process, amplify and retransmit information. The payload can be divided into two distinct parts: Panchromatic and multi-spectral camera (PMC), Payload data handling subsystem (PDH). The PMC camera is intended for reception of digital image of assigned areas of the Earth surface of the Earth by registration of reflected and own earth radiation. The other components in the payload make up the PDH. This includes all the components that process and amplify the uplink signal obtained from the receiving PMC before delivering the downlink signal to the transmitting PMC. This study presents an iterative simple technique to calculate the payload operational effectivenessfunction over time (using Monte Carlo simulation), and improve reliability with low redundancy.The most critical system component and their contribution values play a strong role in the identification of the weak path which leads to system failure.And propose the candidate component(s) to be duplicated as backup technique.

The work result shows how the proposed technique is high effective. Whereas the reliability and operational effectiveness 96.47% and 94.2%, instead of 90.48% and 86.2% consequently.

Keywords

Reliability Analysis, Fault Tree, System Effectiveness,satellite payload Subsystem,

Introduction

Generally, satellite' circular orbits are categorized as Geosynchronous Earth Orbits (GEO), Medium Earth Orbits (MEO) and Low Earth Orbits (LEO). The main difference among them is in the attitude above the Earth surface [1-3]. The satellites traversing in orbits of attitudes up to around 1400 km (limited by Van Allen belt [4]) are considered as LEO satellites. LEO satellites are moving at around 7.5 km/s velocity relative to a fixed point on the Earth (ground station) [5]. The characteristics of LEOs are: the shortest distance from the Earth compared with other orbits and consequently less time delay. These characteristics make themvery attractive even for scientific applications or communications networking [5-6].

* Professor, Dept. Mechatronics German University , Cairo, Egypt and Dept. of Mechanical Engineering, AL-Azhar University, Cairo, Egypt.
** Adjunct Prof. NexSat Project Manager, NARSS, Cairo, Egypt.
*** Ph.D. Candidate, Dept. of Mechanical Engineering, AL-Azhar University, Cairo, Egypt

A growing interest in the use of distributed systems or constellations of small satellites has been generated following the rise in popularity of small satellites,especially in the past decade. This growth in the use of small satellites has been primarily driven by the miniaturization of electronics and sensors [7] and the availability of commercial-off-the shelf components with increasing capability, significantly reducing the cost of hardware development. The access-to orbit and economy of these spacecraft is also improved through availability of secondary payload launch opportunities [8- 9], especially for small satellites which conform to standardized form factors such as CubeSat [10].
The satellite consists of a payload and a platform. The payload includes all the equipment needed to receive the uplink signal and to transmit the downlink, after amplification and frequency shift. The platform consists of subsystems that permit the payload to operate, including mechanical structure, electric power supply, temperature control, attitude and orbit control, propulsion equipment, tracking, telemetry and command equipment [11].

To ensure service with a specified availability, a satellite communication payload exploits the redundancy of the most critical units. Because repair of failed components is not feasible, many functions are duplicated and complex switching matrices provide redundancy. As a result, all recent satellites have an increased design lifetime and increased reliability but are more complex in payload design [11].

Reliability studies are always conducted to provide information for stakeholders as a basis for decisions. Relevant data needed as input, and the technique(s) to be used, are often dependent on the decision problem at hand [12]. It is, therefore, good practice, before a reliability study is conducted, to specify clearly the decision problem at hand.
The Monte Carlo simulation [13] is used in this paper as one of the fault tree analysis tasks. The fault tree analysis in this paper involves both qualitative and quantitative techniques [14-16]. The qualitative technique provides information on the system operational effectiveness function over time (using Monte Carlo simulation).
Reliability should be calculated for all sub-systems on a communication satellite. In this paper, only satellite Payload subsystems(Panchromatic and multi-spectral camera (PMC), Payload data handling subsystem (PDH)) are analyzed using fault tree analysis. Also Payload subsystem reliabilities and operational effectiveness are calculated and presented.

Proposed Satellite Payload Configuration

The proposed payload composed of two subsystems; Panchromatic and multi-spectral camera (PMC)Subsystem and Payload data handling subsystem (PDH)as shown in Fig. 1.

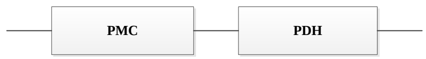


Fig.1. Block diagram of the proposed satellite payload

The PMC camera is intended for reception of digital image of assigned areas of the Earth surface of the Earth byregistration of reflected and own earth radiation.PMC measures radiance of subjects using the received digital images.
it provides information acquisition concerning spatial distribution and magnitude of theradiance of a visible (observable) area of the Earth surface and formation of anoptical image in required bands of electromagnetic waves;registration of the focused radiation energy and its spatial distributiontransformation to the time sequence of electric signals; and finally multiplicities the generated electric signals and their transformation to adigital binary code; processing and transformation of the received digital code and its transfer to thepayload data handling subsystem (PDH) of the satellite.

The payload data handling subsystem is intended for gathering andcompression of images from PMC camera, storage of these images data in the mass memoryunit, formation of the output frames of the information of optical system with addition of annotation information from platform command data handling subsystem and their transfer to the X-bandequipment of the communication subsystem.

Payload Reliability Block Diagrams

The reliability block diagram is drawn so that each element or function employed in the item can be identified. Each block of the reliability block diagram represents one element of function contained in the item. The blocks in the diagram follow a logical order, which relate to the sequence of events during the prescribed operation of the item [17].

The present work considers that satellite payload is composed of two separate subsystems, so the payload reliability block diagram is shown and described as:

For PMC subsystem the main component and type of connections shown in fig.2. From the subsystem specifications thereliability block diagram was generated for the line (contains analog, CCD arrays, signal processor, and power supply unit) as the “2/3”, which means that one line failure is acceptable but two lines failures lead to a subsystem (multi spectral) failure.

Figure.3; shows PDH components connected asa series connection and The DCC has “2/5”,connection which means that one DCC element failure is acceptable but two element failures lead to a DCC failure.

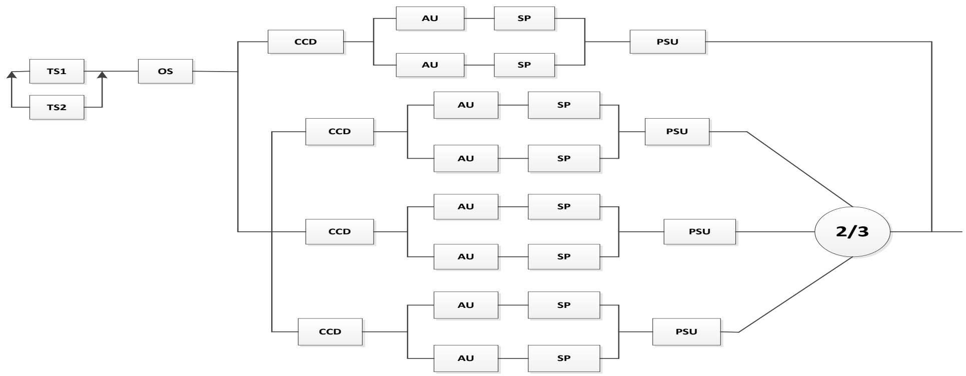


Fig.2. Panchromatic and Multi-spectral Camera (PMC) Block diagram

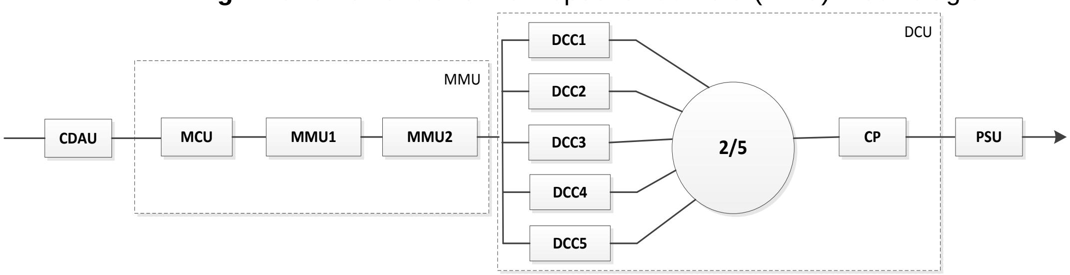


Fig.3. Payload Data Handling Subsystem (PDH) Block Diagram

Reliability Modeling

A conventional Probability Modeling Method is used to determine the mathematical model payload. The reliability equations could also be expressed asshown in the following sections:

The reliability R_I (t) of any component at any time t is given by [18-19]:

$$R_i(t) = e^{-\lambda t} \tag{1}$$

The reliability $R_s(t)$ of a series system of components has the following relationship [18]

$$R_s(t) = R_1(t) \times R_2(t) \ldots \ldots R_n(t) \tag{2}$$

Where:
$R_i(t)$: Reliability of any component i
n: number of component

The reliability $R_p(t)$ of parallel system of components can be calculated as [19]:

$$R_p(t) = 1 - \prod_{i=1}^{n}\left(1 - R_i(t)\right) \tag{3}$$

A special case of the parallel system is the *k* out of *n* system. Then, the reliability $R_s(t)$ is represented by [19]:

$$R_s(t) = \sum_{i=k}^{n} \binom{n}{i} \times [R(t)]^{i} \times [1 - R(t)]^{n-i} \quad (4)$$

Reliability Calculations

In reliability theory, mechanical components are assumed to have Poisson distribution; while the reliability of electrical components has exponential distribution throughout these study components are assumed to have constant failure rates. Reliability data of the satellite payload equipment are presented in Table 1 This table contains the subsystem composition, its architecture and abbreviations for subsystems and components. Also the reliability mathematical model is used to identify weak links, and indicates where reliability improvement activities should be introduced. The payload reliability is calculated using reliability values listed in Table.1, and is using mathematical equations (1-4). For the proposed payload block diagram presented in the previous Fig. (1-3), Reliability of each subsystem is calculated and presented in Table 2.

Table1. Payload equipment reliability parameters

No.	Component Name	Abb.	R(t)
Panchromatic and Multi-spectral Camera		PMC	
1	Thermostatting system	TS	0.991
2	Optical System	OS	0.998
3	Signal processing unit	SPU	
4	CCD array	CCD	0.989
5	Analog Unit	AU	0.995
6	signal processor	SP	0.995
7	power supply unit	PSU	0.999
Payload Data HandlingSubsystem		PDH	
1	Control & data acquisition unit	CDAU	0.945
2	Signal processing	SPSU	0.996
3	Memory control unit	MCU	0.998
4	Mass memory unit	MMU	0.994
5	Data Compression Unit	DCU	0.997
6	Data Compression Channel	DCC	0.995
7	Control Processor	CP	0.992
8	Power Supply Unit	PSU	0.988

The Satellite payload system under study shall provide operation within one year of satellite active lifetime.

Table 2. Payload subsystem reliability parameters

Subsystem	R(t)
PMC	99.29%
PDH	91.13%
payload	90.48%

Payload Fault Tree Analysis

For the initial stages of FTA, each of the payload subsystems (PMC & PDH) was investigated separately. First, a top event was defined for a particular subsystem. The primary task in the FTA was to determine the relationships between components in a given subsystem and find how combinations of component faults could lead to the top event. In many cases, it took only one component fault to result in a top event – such events were classified as single points of failure, because if such an event occurred it would lead to potential failure of the entire system. An instance of such a failure would be if the power connection (PSU) failed, which would lead to the satellite payload failure.

The current fault trees are being "quantified" to an extent. Qualitative probabilities have been assumed to each event, using this information it is possible to determine the probability of any particular fault tree branch to occur. While this is not a rigorous approach, it should help to intuitively describe which event sequences have the highest chance of happening.

Fault tree is constructed for an implemented and operational system, detailed design and operational information is shown in Fig (4, 5, and 6). In this case, the goal in carrying out a FTA is often to improve the system with a low cost. The fault tree may also be constructed to monitor system reliability performance as shown in Fig (7, 8).

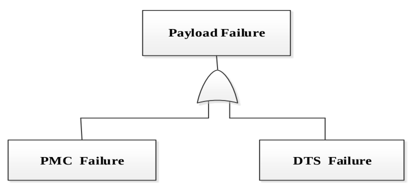
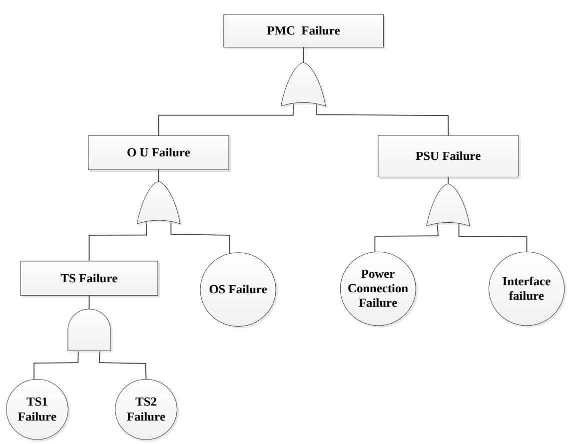


Fig.4. Payload Fault Tree



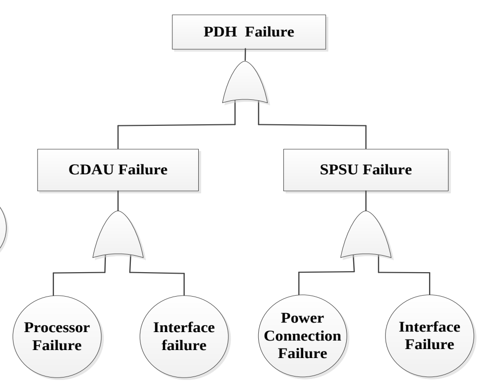


Fig.5.PMC Fault Tree**Fig.6.**PDH Fault Tree

When a performance fault tree constructed for an implemented PMC subsystem, this means that any failure occurs in Signal processing unit and its parameters (analog unit, CCD array and signal processor) due to reduce the PMC performance.

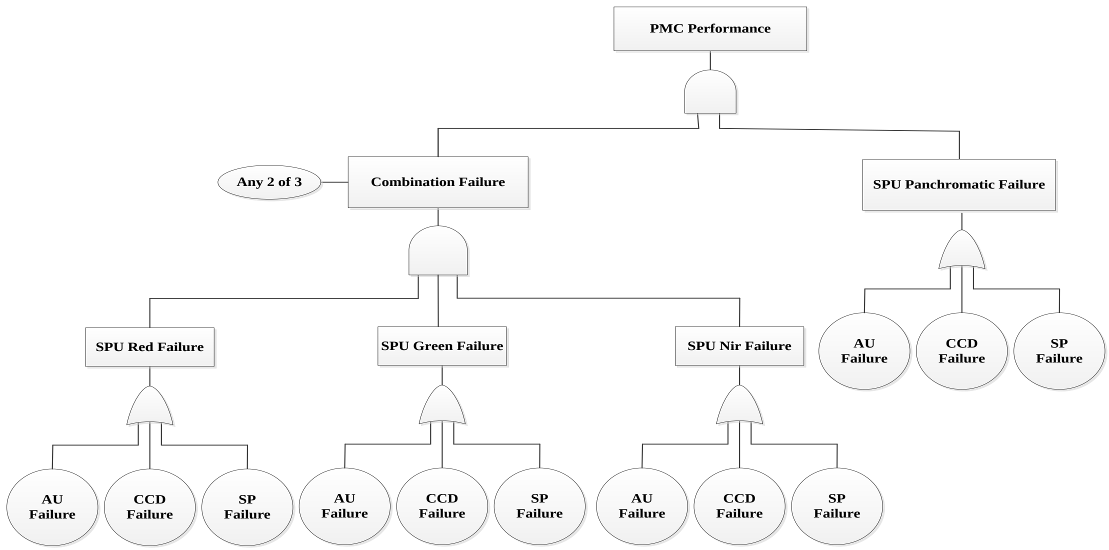


Fig.7. Panchromatic and Multi-spectral Camera (PMC) Performance Tree

For PDH performance fault tree shown in Fig.8,any failure occurs in storage process and its components (mass memory unit and memory control unit) or in compression process and its components, this failure reduces PDH performance.

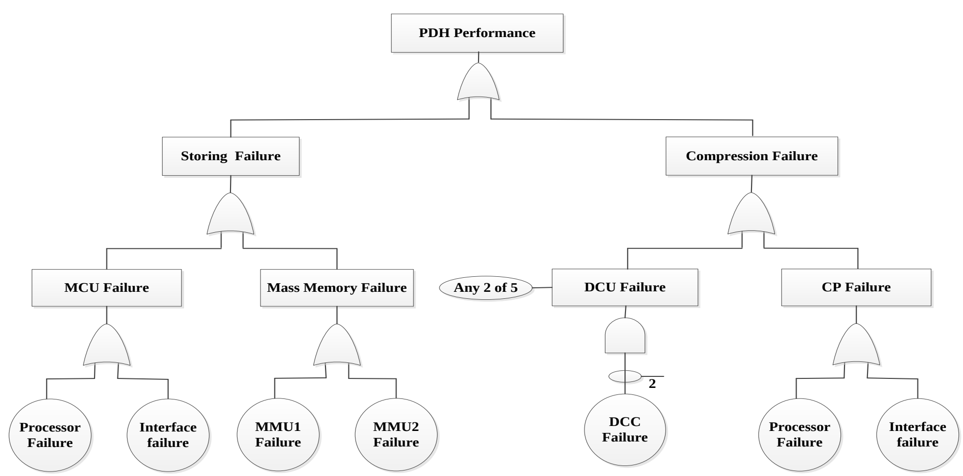


Fig.8. Payload Data Handling (PDH) Performance Tree

Payload Operational Effectiveness

System operational effectiveness is a measure of the degree to which an item or system can be expected to achieve a set of specific mission requirements.The fault tree analysis in this paper involves both qualitative and quantitative techniques [14-16]. The qualitative technique provides information on the system operational effectiveness function over time (using Monte Carlo simulation). The quantitative technique provides information on the critical system components, the nature of the basic events (block failures) and the number of basic events in the combined sets. This in turn gives important information about the top event occurrence, the occurrence probability of the top event (system failure probability) and also the dominant most critical system componentthat contribute to the top event probability. The quantitative importance of each basic event contributing to the top event is also shown.

The most critical system components in this case are sorted by probability. Low probability critical system componentsare truncated from this analysis. Our program involves the following steps:

1. For 100,000 times (trials), the program completedthe following: Generating random failure times forevery block in the system using an exponentialdistribution function, which is based on the blockpredicted failure rate, and calculating the systemoperational effectiveness over the satellite life time(Monte Carlo simulation).
2. Calculating the system average operationaleffectiveness (for 100,000 trials) over the satellitelifetime.
3. Computing the failures that lead to the top event andidentifying thecritical system component.
4. Calculating at certain times the occurrenceprobability of each critical system component which uses thesystem blocks reliability values.
5. Calculating the top event occurrence probability andthen the system reliability at certain times.
6. Calculating the contribution percentage of eachcritical system componentfailure and generatingthe program results report.

This conventional method calculated the system reliability in the worst case where the CDAU is connected in series with the SPSU. For this series connection of the CDAU and SPSU the consequences of a CDAU failure will appear when using the weighted reliability technique by giving the CDAU a weighting coefficient that is less than 1 to reflect the consequence of its failure to the system failure. The only drawback of this technique is accurately determining the CDAU weighting coefficient. Using Monte Carlo simulation with the various CDAU weighting coefficients will help determine the correct value of the CDAU weighting coefficient, estimate the system operational effectiveness over the satellite lifetime and the non-failure probability of the system (system reliability). System failure occurs when the system operational effectiveness is less than a certain threshold value.
Weighting coefficients for some system elements wereused to reflect the actual performance of the system. The weighting coefficients used are shown in Table 6. After many iterations of the fault tree analysis program with different CDAU weighting coefficient values, it is found that, the system operational effectiveness and the system reliability is saturated at a CDAU weighting coefficient less than or equal 0.5. Thus a weighting coefficient equal to 0.5 was used for the CDAU.

In the case of CDAU failure the system operational effectiveness over one year of satellite lifetime is equal to zero (complete failure) as shown in Fig.9 and the rank of the most critical system component and their contribution values are shown in Table3

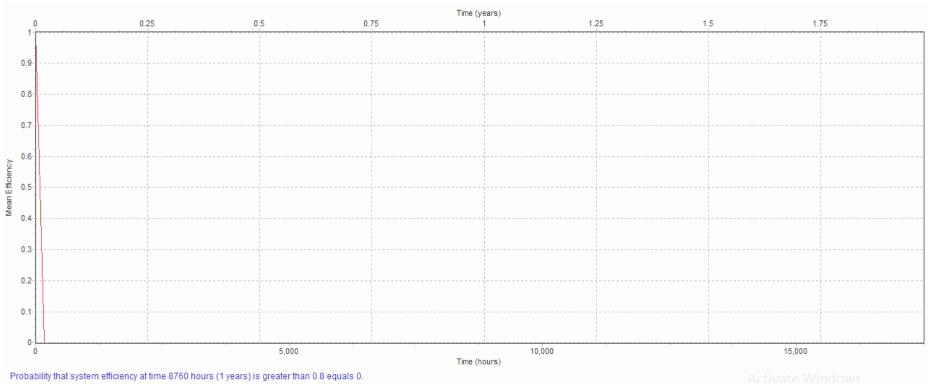


Fig.9. System operational effectiveness over one year of satellite lifetime is equal to zero (complete failure)

Table.3. Rank of the payload most critical system component And their contribution values

Component	Contribution %
DCAU	93.01 %

The system operational effectiveness over one year of satellite lifetime without any failure equal to 86.2% as shown in Fig. 10,and the rank of the most critical system component and their contribution values are shown in Table.4.

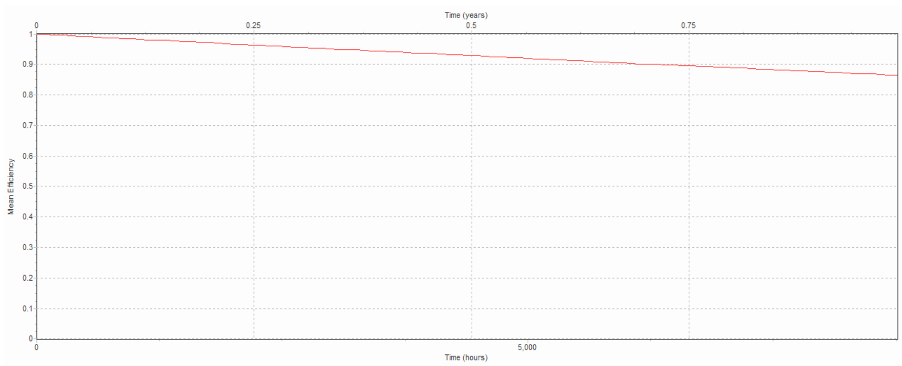


Fig.10. System operational effectiveness over one year of satellite lifetime is equal to 86.2% (Without failure)

Table.4. Rank of the payload most critical system component And their contribution values

Component	Contribution %
DCAU	45.64 %
PSUS	9.49 %

Backup technique is used to increasing reliability of the system by including a backup or identical component, to the system that will take over if the original component fails. This backup technique is known as redundancy. Redundancy is not a solution to all reliability problems since redundant systems usually increase weight, cost, and complexity, but redundancy is a good solution for backing up inherently unreliable components that are essential to the success of the system [20]. Parallel redundant "Cold standby" technique is used on CDAU component to increase reliability. The reliability block diagram of the "cold standby" CDAU is shown in Fig. 11.

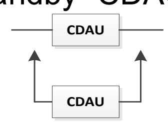


Fig.11. Parallel "Cold standby" CDAU Component

The fault tree analysis program which generates the system operational effectiveness over one year of satellite lifetime are re-executed again to study and analyze the effect of the new CDAU configuration on the payload operational effectiveness. The results are shown in Fig. 12.andthe operational effectiveness increased to be 91.8 % as shown in Fig.12

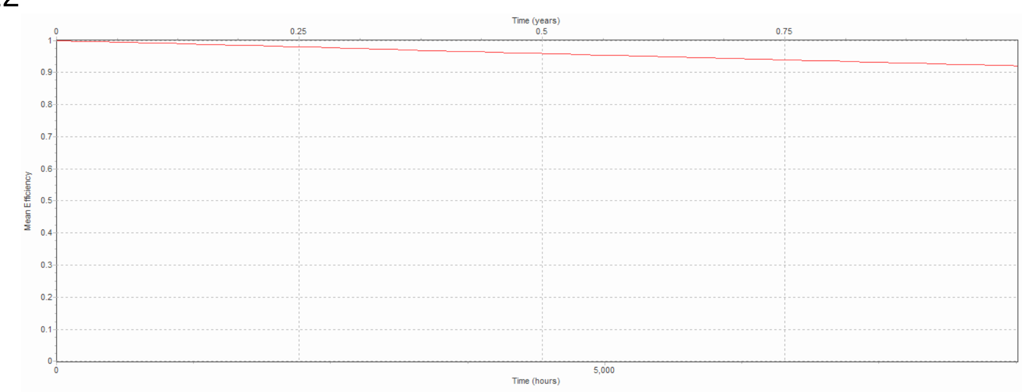


Fig.12. System operational effectiveness over one year of satellite lifetime is equal to 91.8% ("Cold standby" CDAU Component)

For continues improvement a redundant technique Implemented again during this operation with cold (standby) MCU and CP. The fault tree analysis programs are re-executed again many times, to study and analyze the effect of the new components contribution on the payload operational effectiveness.Notice that the payload operational effectiveness increased to be 94.2 % as shown in Fig. 13.

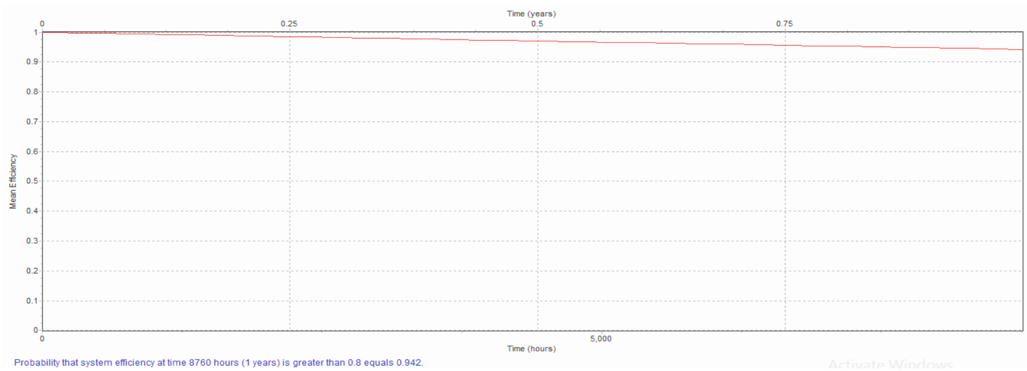


Fig.13. System operational effectiveness over one year of satellite lifetime is equal to 94.2% (“Cold standby” MCU & CP Component)

The reliability mathematical equations (1-4) used again on PDH subsystem.Using the new PDH design block diagram presented inFig.14, and reliability parameters presented in Table 1.The final reliability results presented in Table 5,

These results indicate that backup technique improve PDH reliability to be 97.43 % instead of 91.13% and payload reliability changed from 90.48% to be 96.74%. And the operational effectiveness increased from 86.2%to be 94.2%.

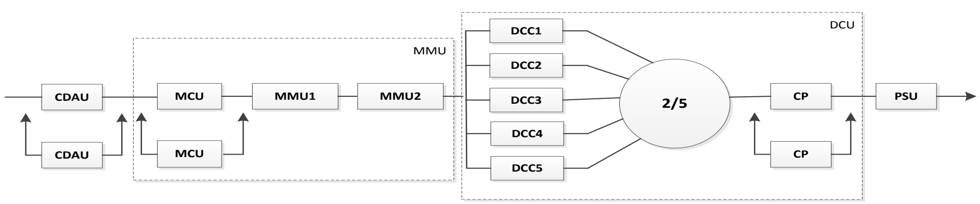


Fig.14. Simplified Payload Data Handling Subsystem block diagram, including back-upequipment.

Table 5. Payload subsystem reliability parameters

Subsystem	R(t)
PMC	99.29%
PDH	97.43%
payload	96.74%

Conclusions

Applicable LEO satellite payload configurations areintroduced in this paper. In this study a reliability specification are introduced and applied in this paper. Conventional andadvanced reliability modeling alsoapplied for estimation and analysis of payload reliability. The satellite payload operational effectiveness was basedon the advanced Monte Carlo Simulation technique. Therank of the most critical blocks is estimated by the help of a developed software program.The results show that the CDAU is the most critical blocksince it contributes by 45.64 % and the payloadoperational effectiveness is 86.2%.A cold redundant was used during operation with a coldredundant (standby)

CDAU. The results show that the rankof the CDAU was reduced to a neglected value < 1%instead of 45.64 %,and the payload operational effectiveness improved to be 91.8%.Implementing the cold redundant on CP & MCU was the next step forcontinuous system improvements. This results that the reliability andoperational effectiveness were 96.47% and 94.2%instead of 90.48% and 86.2% consequently.

References

[1] M. Richharia, “Satellite communication systems”, McGraw Hill, New York, (1999).

[2] D. Roddy, “Satellite communications”, McGraw Hill, New York, (2006).

[3] G. Maral and M. Bousquet, “Satellite communication systems”, John Willey & Sons, Ltd, Chichester, England, (2002).

[4] www.answers.com/topic/van-allen-radiation -belt

[5] R. E. Zee, et al, “The MOST Microsatellite: A low cost enabling technology for future space science and technology missions”, Canadian Aeronautics and Space Journal, 48(1), Canada, pg. 1-11, (2002).

[6] J.E. Oberright, “Satellite artificial”, World Book Online Reference Center, World Book, Inc, (2004).

[7] H.J. Kramer, A.P. Cracknell, An overview of small satellites in remote sensing, Int. J. Remote Sens.29(15),4285–4337,(2008).

[8] D. DePasquale, A. Charania, H. Kanayama, S. Matsuda, Analysis of the earth-to-orbit launch market for nano and microsatellites, in: AIAA SPACE 2010 Conference and Exposition, American Institute of Aer nautics and Astronautics (AIAA), Anaheim, CA, (2010).

[9] G. Webb, A. da Silva Curiel, The changing launcher solutions of the small satellite sector, in: The 62nd International Astronautical Congress, International Astronautical Federation (IAF), Cape Town, SA, (2011).

[10] K. Woellert, P. Ehrenfreund, A.J. Ricco, H.R. Hertzfeld, Cubesats: cost-effective science and technology platforms for emerging and developing nations, Adv. Space Res. 47 (4),663 684, (2011).

[11] G. Maral and M. Bousquet, “Satellite Communications Systems”, New York: John Wiley, (1998).

[12] Rausand, M., and Høyland, A., System Reliability Theory: Models, Statistical Methods, and Applications, 2nd ed., Wiley-Interscience, Hoboken,NJ, pp. 7–52, (2004).

[13] AchintyaHaldar and SankaranMahadevan, “Reliability Assessment Using Stachastic Finite Element Analysis”, ISBN 0-471-36961-6, John Wiley & sons, (2000).

[14] MIL-HDBK-338B, “MILITARY HANDBOOK ELECTRONIC RELIABILITY DESIGN HANDBOOK”, 1 October (1998).

[15] European Cooperation For Space Standardization, “fault tree analysis”, CEI/IEC 1025: 1990, 7 September (2001).

[16] Dr. Michael Stamatelatos, Dr. William Vesely, Dr. Joanne Dugan, Mr. Joseph Fragola, Mr. Joseph Minarick III and, Mr. Jan Railsback, “Fault Tree Handbook with Aerospace Applications”, NASA Office of Safety and Mission Assurance, NASA Headquarters, Washington, DC 20546, Version 1.1, August, (2002).

[17] Andrews, J. D., Moss, T. R.,“ Reliability and Risk Assessment”. American Society of Mechanical Engineers Press, New York, NY, (2002).

[18] Terje Aven, 1992. Reliability and risk analysis, Elsevier Applied Science.

[19] Kenneth S. Stephens “Reliability Data Analysis with Excel and Minitab”,American Society for Quality, Quality press, Milwaukee,pag 254:259, (2011).

[20] Guangbin Yang, “Life Cycle Reliability Engineering”, John Wiley & Sons, Inc.,(2007).