Master's thesis

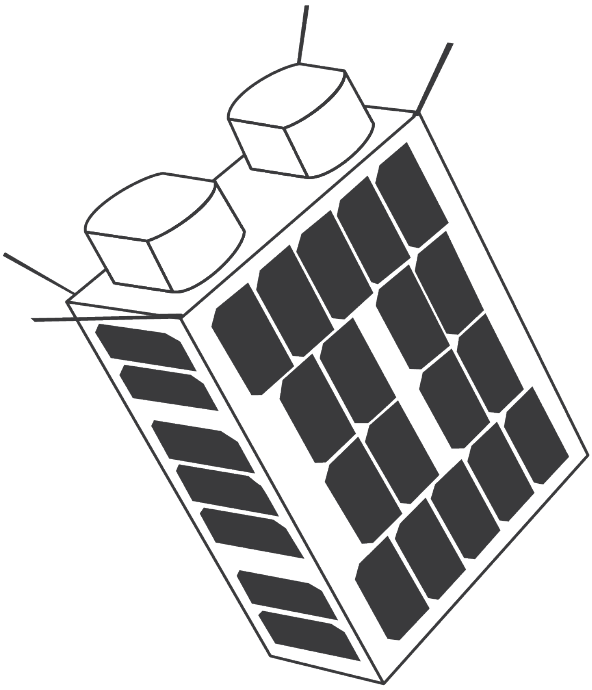
NTNU
Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Engineering Cybernetics

Fredrik Hoel Bevreng

From Words to Numbers

A Fuzzy Fault Tree Approach to Satellite Reliability

Master's thesis in Cybernetics and Robotics
Supervisor: Tor Arne Johansen. Co-Supervisor: Evelyn Honoré-Livermore
July 2020



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Summary

CubeSat projects are on the rise and the need for reliability tools and data is a key component in avoiding infant mortality and reach mission success criteria. Fault tree analysis (FTA) are one such widely used method in order to analyze hazards and calculating a system's overall reliability. Yet, conventional FTA faces shortcomings when a lack of statistical data prevents a quantitative analysis being performed. In such cases, one can rely on expert knowledge in order to help model the hazards. However, people find it difficult and inconvenient to offer probability estimations based on exact numbers and are more confident using linguistic terms when estimating. The terms provide more leeway and includes uncertainty but conventional FTA representation cannot handle this linguistic procedure. In this paper, a fuzzy logic approach is proposed in order to overcome these obstacles and allow expert facilitation to be used in order to turn their knowledge into failure probability numbers using linguistic variables as a gateway.

Failure modes identified from the Failure Modes, Effects, and Criticality Analysis (FMECA) were ranked in a hierarchical order of prioritization with respect to severity for the HYPSO missions goals. Fault trees were constructed for these failure modes and basic events identified. An anonymous questionnaire was devised to gather the team members linguistic evaluations and their confidence rating for the respective basic events. In order to transform these linguistic estimates into analytical data to be used for quantitative evaluations of the components, subsystems and for the overall subcategories of the satellite, a Similiarity Agreement's Method aggregating the risks of the team experts' estimations is utilized. While this fuzzy-based method has been applied to other industry applications, its potential usefulness applied to the SmallSat sector is to the author's knowledge undiscovered territory and originally explored in this paper.

Finally, a fuzzy fault tree model is implemented in this thesis in order to quantitatively test the cause-effect relationship of these satellite specific hazards and failure modes. The results of this analysis are the likelihood of possibility for a specific event and the significance of possible contributing events explicitly shown by importance measures. The findings presented here can help risk analysts prepare their mitigation measures to effectively manage the risks in a satellite system.

Sammendrag

CubeSat-prosjekter øker i andel, og behovet for pålitelighetsverktøy og data er nøkkelkomponenter for å unngå tidlig tap og oppnå suksesskriteriene for oppdraget. Feiltreeanalyse (FTA) er en mye brukt metode for å analysere farer og beregne systemets generelle pålitelighet. Likevel har konvensjonell feiltreanalyse ulemper når mangler på statistisk data forhindrer at en kvantitativ analyse kan bli gjennomført. I slike tilfeller kan man benytte fagkunnskap for å hjelpe med å modellere farene. Imidlertid synes folk det er vanskelig og upraktisk å tilby sannsynlighetsestimater basert på eksakte tall og er mer komfortable med å bruke språklige begreper når de estimerer sannsynligheten for at en hendelse inntreffer. De ordlige uttrykkene gir mer spillerom og inkluderer usikkerhet, men konvensjonell FTA-representasjon kan ikke håndtere denne språklige prosedyren. I denne artikkelen foreslås en fuzzy logisk tilnærming for å overvinne disse hindringene og tillate eksperttilrettelegging å bli brukt for å gjøre kunnskapen deres om til sannsynlighetstall ved å bruke språklige variabler som et verktøy.

Feilmodus identifisert fra Failure Modes, Effects and Criticality Analyse (FMECA) har blitt rangert i en hierarkisk prioriteringsrekkefølge med hensyn til alvorlighetsgraden for HYPSO-oppdragsmålene. Det ble konstruert feiltrær for disse feilmodusene og grunnleggende hendelser ble identifisert. Et anonymt spørreskjema ble utviklet for å samle teammedlemmenes språklige evalueringer og deres tillitsvurdering for de respektive kjernehendelsene. For å transformere disse språklige estimatene til analytiske data som skal brukes for kvantitative evalueringer av komponentene, delsystemene og for de overordnede underkategoriene til satellitten, benyttes en Similiarity Agreement's Method aggregering av risikoen for teamekspertenes estimater. Selv om denne fuzzy-baserte metoden er brukt på andre bransjeapplikasjoner, er dens potensielle nytteverdi aldri brukt tidligere i SmallSat-sektoren etter det forfatteren er kjent med og er derfor opprinnelig utforsket i denne oppgaven.

Til slutt i denne oppgaven implementeres en fuzzy feiltremodell for å kvantitativt teste årsak-virkningsforholdet til disse satellittspesifikke farene og feilmodusene. Resultatene fra denne analysen er sannsynligheten for at en spesifikk hendelse inntreffer og betydningen av de mulige påvirkningene er eksplisitt vist ved viktighetsrangeringer. Funnene som er presentert her kan hjelpe risikoanalytikere med å forberede sine risikotiltak for å effektivt håndtere risikoene i et satellittsystem.

Preface

After graduating from Oslo Metropolitan University in the spring of 2018, I wanted to pursue more knowledge in the fields that I harbored an interest in. Computers, electronics, space technology, cybernetics, it was all available to be studied at NTNU. Of course, one cannot foresee the future, but during the first months I had no idea that it was possible to write a master's thesis on space technology. Not only that, but the space community at NTNU or in Trondheim has become very well developed over the last decade.

After being accepted into HYPSO's team to write the pre-thesis in the autumn of 2019 on Worst Case Circuit Analysis, I felt that I(the Eagle) had landed into what is probably one of the best project teams at NTNU. A project structure that is flat, and made it easy to ask anyone for help was a relief. Social activities and warm inclusion were the driving force of effectiveness behind the HYPSO team. And additionally, I was given the chance to combine my interests into writing this master's thesis for HYPSO through their fantastic groundwork.

The 2 years of my life spent studying in Trondheim culminates into this thesis. The following paper will aim to bring focus to the hazards that interact with a satellite system. Examining what these are, how they are commonly addressed in the industry, and how we can analyze these issues. While doing so, some neat tricks from the world of control theory like fuzzy logic will be used. At the end of this thesis, I hope that whoever reads through all of this has learnt something. If that something didn't turn out to be about reliability or satellites, at the very least may it be about seeing the light at the end of the tunnel. This master's thesis didn't come freely, nor does the degree to which it fulfills its requirements. I suppose that is what makes it worthwhile.

A big thank you to my co-supervisor Evelyn for supporting me, reviewing, follow-ups and being patient with my shortcomings and flipped circadian rythm. Another big thank you to my supervisor Tor Arne whose faith in my work led me to properly finish it.

Finally, a big thanks to the HYPSO team. You will be missed.

The following sections are imported from the pre-thesis:

- Introduction: 1.1, 1.2, 1.3, 1.4

COVID-19 Outbreak

During the spring months of 2020, the outbreak of the virus known as Covid-19 that turned into a global pandemic had a significant and sudden impact on our daily lives. Not only here in Norway, but the entire world to some degree. Norway shut down on the 12th of March, and NTNU's campuses with it. We who were present at the campus that day were instructed to go home and borrow any required equipment to take home with us if needed. Due to this unfortunate event, the rest of the semester was spent working from the student flat. Any work requiring the participation, discussion and interaction with other team members was done remotely over the internet. The timing of this outbreak came in the beginning stages of working at this paper, and so the vast majority of the work laid out in this thesis was mostly done and written in isolation and solitude. Hence, the distracting and detached environment from which this thesis was made had an impact into the workflow and framework of the paper, but also the mental fortitude of the author. Only thanks to the HYPSO team's cooperation and willingness to aid support and assistance when needed made this thesis possible. Thank you all.

"*Without great solitude, no serious work is possible*"

— Picasso

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Abbreviations

AR	=	Aggregated results
ADCS	=	Attitude Determination And Control System
AMOS	=	Autonomous Marine Operations and Systems
AAD	=	Average agreement degree
BE	=	Basic Event
CoA	=	Center of area
COTS	=	Commercial off-the-Shelf
CoE	=	Center of Excellence
CRM	=	Continuous Risk Management
CubeSat	=	Type of small satellite
DOA	=	Dead on arrival
ECSS	=	European Cooperation for Space Standardization
EPS	=	Electrical Power System
ESA	=	European Space Agency
F-V IM	=	Fussell-Vesely importance measure
FMEA	=	Failure Modes and Effects Analysis
FMECA	=	Failure Modes, Effects and Criticality Analysis
FP	=	Failure probability
FPS	=	Fuzzy probability score
FTA	=	Fault Tree Analysis
FFTA	=	Fuzzy Fault Tree Analysis
HSI	=	Hyperspectral Imaging
HYPSO	=	Hyperspectral SmallSat for Ocean Observation
ISS	=	International Space Station
MF	=	Membership Function
MC	=	Minimal Cut Set
NA	=	NanoAvionics
NASA	=	National Aeronautics and Space Administration
NTNU	=	Norwegian University of Science and Technology
OPU	=	On-board Processing Unit
PRA	=	Probabilistic Risk Assessment
QA	=	Quality Assurance
RAD	=	Relative agreement degree
RPN	=	Risk Priority Number
SAM	=	Similarity Aggregation Method
SmallSat	=	Small Satellite
Weighing Factor	=	WF

Chapter 1

Introduction

1.1 HYPSO's Mission

Hyperspectral Small Satellite for Ocean Observation hereinafter referred to as HYPSO, is a planned satellite mission at the Norwegian University of Science and Technology (NTNU), developed at the SmallSat Laboratory. The mission, which includes multiple departments and is a collaboration among several disciplines, seeks to monitor, gather, and analyze ocean color data in near real-time observation. The mission will facilitate both low-cost and high-performance hyperspectral imaging with autonomous onboard processing which satisfies the necessary conditions and requirements for carrying out remote ocean color sensing.

One of the motivations for the HYPSO mission comes from the study of algae. Algal blooms are an innocent-looking threat that is expected to increase in both severity and frequency the coming years as a byproduct of estimated rises in sea temperature. The Norwegian aquaculture is one Norway's largest export industries with numerous fish farms scattered up and down the country's long coast. As such, the fish farming industry is directly threatened by the algal blooms as they are not only hazardous to the farmed fish, but the surrounding connected ecosystems as well.

The satellite's target is a 70 by 70km pre-defined wide area at an altitude of 500 - 550km with a roughly 90 minutes orbital period that will enable it to downlink its preliminary data within a scope of 3 hours. Its payload will be the hyperspectral camera that will take pictures with an interval of 15 to 32 frames per second, picking up light with wavelengths from 400-800nm with a 100 meter spatial resolution.

The project has a planned launch date set for Q4 of 2020, with a second mission in the early planning stages set to follow later.

1.2 Project Structure

The SmallSat Laboratory has been up and running since 2018, while HYPSO began in 2017. With support and collaboration with the Centre of Excellence (CoE), Centre for Autonomous Marine Operations and Systems (AMOS), a project was planned in order to develop a project plan in order to be able to launch a small satellite with a shared vision in transformation — to introduce an impactful change to existing procedures and solutions and possibly benefit industry.

The team behind HYPSO is a functional organization, meaning the project hierarchical structure is organized by area of expertise. Each discipline is governed loosely by a functional manager. The functional managers are working on tasks concerned with stitching it all together while sub-tasks are shared out to the different branches that sectional team members are working on either individually or in collaboration with one another. This matrix organization, where team members report both to their respective functional managers and project manager helps keep the hierarchy in a *flatter* environment where the team members are easily able to ask questions to anyone whenever they need it as opposed to a traditional stiffer hierarchical working environment.

HYPSO's team members consists of MSc. and Ph.D. students, Post.Docs. and professors. The current project manager is Evelyn Honoré-Livermore, a Ph.D. candidate at the Department of Electronic Systems with a double master's degree, who has been a part of the project since late 2017. The team itself periodically switches out most of its members as some of the students are working with HYPSO for only 6-9 months, sometimes longer when master students opt for a Ph.D. This allows the possibility for new students taking over the positions with fresh eyes and motivation, and at the same time underlines the importance of proper documentation when passing the baton for the newcomers.

1.3 CubeSats

A small satellite or SmallSat is a type of satellite with a much smaller mass and size than a conventional satellite. A «CubeSat» is such a satellite and is a fairly modern category of these satellites that has a mass of no more than 1.33 kilograms per unit U [13], which has dimensions up to 10 cm x 10 cm x 10 cm. Because of the small unit sizes making them very light, CubeSats fit well into the NanoSatellites category whose weight definition lies between 1 - 10 kilograms[14]. While a conventional communication satellite can weigh as much as 6000 kilograms or more, they are often exclusively reserved for governmental use or large private companies with a matching budget. The fact that the cost of launching anything into space is heavily influenced by weight is a major reason to why CubeSats have exploded in popularity the last years as the total cost can quickly become a fraction of their conventionally larger counterparts. This increases the availability for institutions such as universities or smaller companies that want to join the New Space movement as the lower costs offsets the reduced risk of failure [15][16]. New Space is a modern term used to describe the commercialisation of the space sector, where an increasing amount of private players are getting involved. In addition to significantly lower costs, a shorter development time due to relatively scaled-down missions offers a welcoming opportunity for a variety of projects. Making use of COTS (Commercial off-the-shelf) products that are rated and specifically made for SmallSats, the idea of constructing and launching a satellite has grown into a realistic accomplishment for many new stakeholders.

Most people think of Apollo 11's moon landing, the mighty Saturn V rocket or the futuristic space shuttles when confronted with space technology as a broader term. The popularity of satellites and specifically SmallSats, also known as NanoSats, which have a mass of less than 10 kilograms, have increased exponentially the last decade. In fact, according to NanoSats.eu as of 30th October 2019, there are 1251 and 1150 NanoSats and CubeSats launched so far respectively, with over 3000 NanoSats planned to launch in the next 6 years

CubeSats and NanoSats are used for a plethora of applications and commercial solutions, offering tremendous benefits in multiple sectors. Collecting and interpreting data to deepen our understanding of our own earth; studying human impact on deforestation, geology, the ocean or agriculture will benefit us in the long term as it allows us to improve upon existing solutions and help us create a sustainable future. Geolocation for handling ships and aircrafts in remote areas can be successfully carried out by interconnecting networks of NanoSatellites, which then offers global monitoring and live tracking, solving the logistics from space [15].

HYPSOs payload is going to be integrated into a M6P (Multi-Purpose Nano-Satellite Bus) satellite bus, which is shown in figure 1.2. The outer dimensions of the M6P frame are 10cm × 20cm × 30cm.

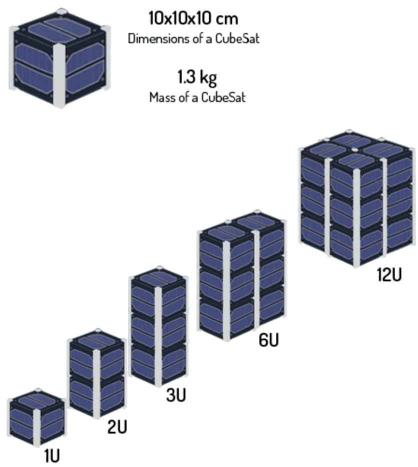


Figure 1.1: Different size of CubeSats. Courtesy of Alan space.

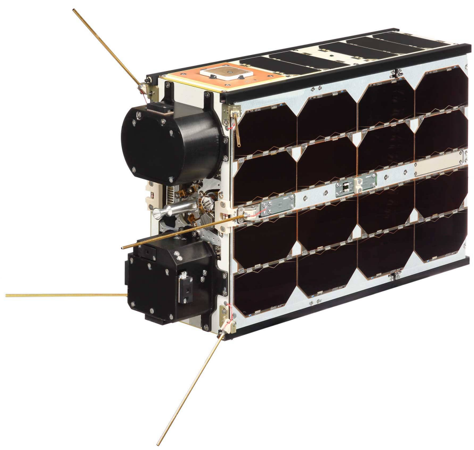


Figure 1.2: 6U modern CubeSat. Courtesy of NanoAvionics.

1.4 Satellite Reliability

Since the dawn of the space age, spaceflight and reliability became intimately interconnected due to the very nature of what you launch is what you get. There are no possible ways to change or engineer the spacecraft after it has been launched, with the exception of the International Space Station (ISS) and other major space stations. As explained in the previous chapter, satellites submit to a particular attribute of their own properties such as their small size in the New Space era or being built up of standardized unit blocks in order to carry out specific tasks, instead of being developed as a jack-of-all-trades satellite, meant to carry out multiple tasks. These satellites or spacecrafts as a general term are set to operate in a very hostile and hazardous environment that cannot be completely replicated here on earth even by today's state of the art test facilities. Hence, they are inevitably left to themselves as individual "single attempt"-missions after extensive testing.

It is critical for manufacturers to deliver systems according to the specified lifetime with the specified performance, e.g. a dependable system. It is well understood amongst engineers and scientists that nothing lasts forever. With this inevitability in mind, one should design a system that can skew the way failure will happen or delay its occurrence. Depending on the system at hand, looking at the different components that contribute to degradation and system breakdown over time is the key to a project's longevity. Which external (or internal) forces are contributing and what can be done about it? It is often possible to operate a certain appliance in a manner that will prolong its total lifetime over default expectancies. As previously established, the small satellite sector is a new and growing field. It is therefore important to move attention to the reliability question for this class of satellites as the research in this area is relatively young.

Jian Guo, Monas and Gill's paper on small satellite reliability attempts to characterize failure behaviour of these satellites by the means of statistical analysis of only in-orbit failures. A sample size of 222 anomalies from 1990 - 2010 is used and held adequate as it is a large portion of the total SmallSats launched the last decade. A custom method was implemented, Bayesian theory with Markov Chain Monte Carlo simulations to model the reliability and compare it to methods used on larger satellites (mass >500kg). Their findings show that the small satellites suffer an undoubtedly higher infant mortality rate than their larger counterparts which the authors attest to «less extensive testing methods, the use of cheaper and less reliable components and a difference in design philosophy [17].»

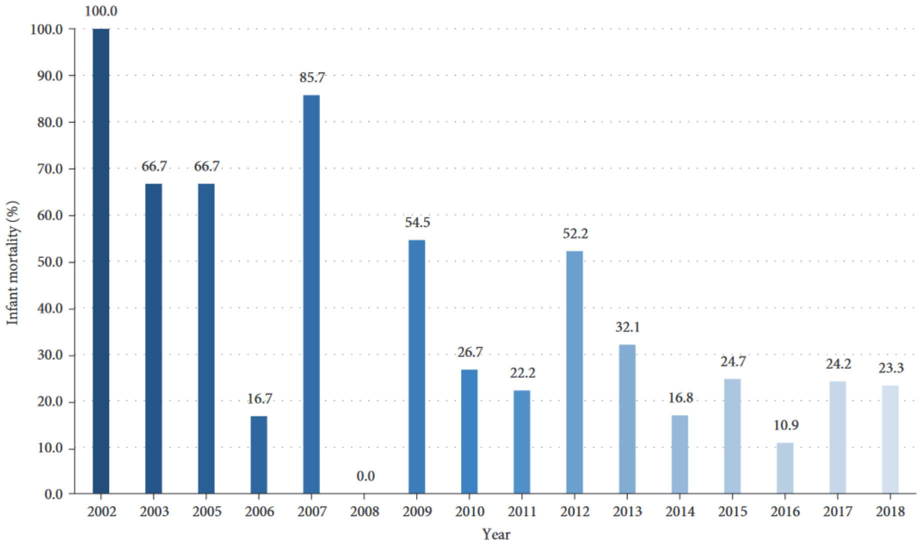


Figure 1.3: Infant mortality for CubeSats from 2002 up to May 31, 2018 (launch failures excluded) From [1]

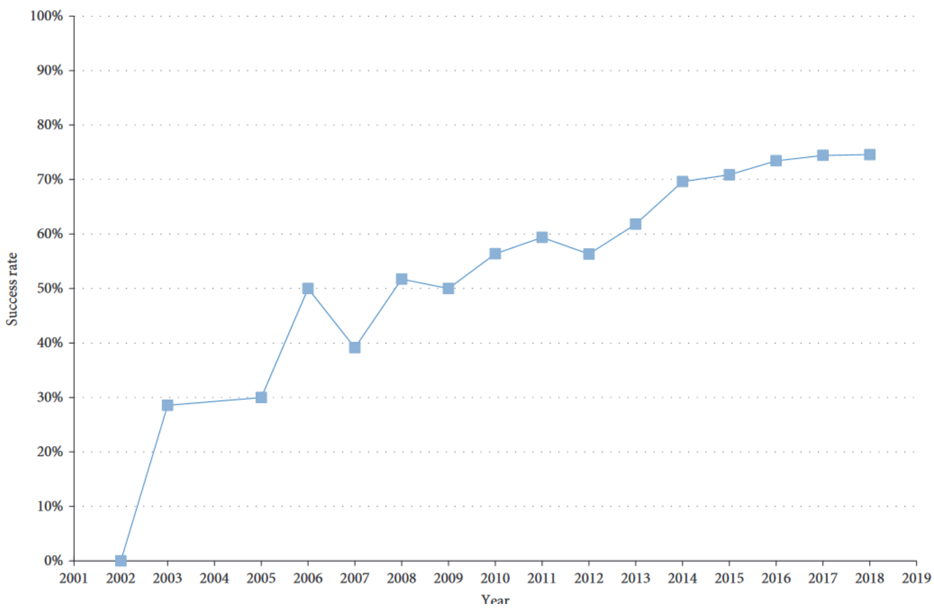


Figure 1.4: Success rate of CubeSat missions as a function of time. From [1]

General statistical model approaches investigating larger sample sizes and different elements their own probabilities of success and failures are not particularly feasible for satellites as Langer points out because the testing done on satellites are identified and corrected under different environments, which for a private project may not afford to use the same test facilities as the government has access to [18][19][20]. And the satellite is launched afterwards. Depending on different mission variables such as altitude or orbit type, involving different temperature or radiation levels through their lifespan, they will consequently face somewhat different working environments and hence, extrapolating statistical data based on success or failure at i.e. component level should be done with caution. One of the NTNU Small Sat Lab's missions is to establish the framework for "quickly" planning, designing, producing, testing and launching several SmallSats in the coming future. Which is an important feature that the industry is lacking today: a platform for mass producing SmallSats that are developed under the same identical environment with the same testing conditions - on which it would provide great benefits in terms of various data and analytical operations [21]. With strong profiles in the space industry like Elon Musk, this lack of mass producing SmallSats under identical conditions could change in the nigh future with SpaceX's Starlink project. A plan to surround Earth with 12,000 high-speed internet satellites [22].

1.5 Thesis Objectives

The main goal of this thesis is to first and foremost contribute to HYPSO and the SmallSat Lab in a meaningful way so that the approach and the results laid out in this paper can be used to help aid the current or future CubeSat missions and the teams working on them. A secondary goal is to contribute, if possible in any way, to the international scientific arena and to the growing SmallSat field.

From the previous sections, the motivation that is extracted from general SmallSat reliability and risk management procedures presented in other university projects and thesis' leaves room for the following interesting application to support a stronger reliability foundation based on the resources available:

> Applying fuzzy logic in conjunction with linguistic variables to extract numerical data from the team in order to conduct a full fault tree analysis with both qualitative and quantitative measures for the purpose of aiding risk and reliability assessments in a CubeSat project.

The aim of this paper will be to establish a framework for an effective risk assessment of HYPSO's priority failure modes. The results of which will be achieved by utilizing established or experimental methods which have been applied to other industries and fuzzy-based linguistic sets to conduct a quantitative analysis together with a qualitative one.

The detailed thesis objectives are as follows:

- Fault tree qualitative diagrams illustrating the hierarchical relationships of failure modes and the relations between their basic events
- Turning team expert knowledge into numbers representing likelihood through fuzzy theory and logic
- Evaluating the qualitative aspect from a quantitative framework
- Representing and assessing the individual quantitative identified risks

1.5.1 Anti-Objectives

The work of this master's thesis is the product of a university-based CubeSat project and all exact figures relating to reliability must be cautiously regarded as the main objective of this paper is to demonstrate the principal possibility of strengthening risk assessments when a lack of hard data is present, and not to deliver the most in-depth and detailed fault trees of the systems analyzed, nor to produce the absolute best or most practical estimations of reliability data. A critical and careful evaluation should be employed when drawing any conclusions from these data. Hence, the failure probabilities to be identified by the above method for the failure modes is the most likely estimations based on the team's evaluation and the chosen method with respect to certain limitations such as scope and time instead of deriving hard conclusive truths about likelihood and failure rates.

Chapter 2

Background

2.1 Quality Assurance and Risk Handling

Industrial and commercial satellites are typically developed over a time span between 5 and 15 years [15] with rigorous planning, testing and validation before launch. Attention to detail, reliability and risk control must devote considerably more total time, money and manpower than traditional SmallSats projects built as technology demonstrators. Still, risk mitigations and quality assurance philosophies has not laid dormant the last decade for the SmallSat sector and streamlined or dedicated approaches are actively being put to use in order to increase the chance of missions success [23].

Quality Assurance is a quality management segment centered on providing confidence that requirements and goals for a product, service or activity will be satisfied. Failure testing, statistical control and quality assessment are traditional approaches in achieving quality assurance. It is generally rooted in two principles; the commodity should be sufficient for its intended purpose and "right first time", faults should be avoided [24]. This philosophy paves the way on which the solution will be made even before said solution takes shape: "The task of engineering is to make it work once, while the task of quality assurance is to make it work all the time" [25], p. 2. In the European space sector, the European Space Agency's ESCC-Q-ST-20C is the key quality control standard in operation today.

ESA's risk management is defined in the standard ECSS-M-ST-80C [26]. Risk can be viewed as a 'project property' in addition to traditional properties such as cost, timetable and technological efficiency, including safety and reliability [27]. Over the course of a project, risk management is a highly proactive procedure that aims at optimising these beforementioned properties. Coelho [28] summarizes the most common tools applied in the space industry when investigating risks today; Failure Mode and Effect Analysis (FMEA). Sometimes, as in HYPSO's case, the extended analysis including criticality is used, abbreviated FMECA, Fault Tree Analysis (FTA) and Probabilistic Risk Assessment (PRA).

The step-wise risk management plan proposed by ESA is largely based on FMEA which will be fleshed out in greater detail in the next subsection. A reduction of risk is achieved by lowering the magnitude of said risk which can be practically achieved by either decreasing its occurrence of happening or applying preventative measures to lower the potential severity. Scores can then be applied to quantify the probability of occurrence and severity. This framework is often presented in a risk diagram or as a table when investigating the FMECA's Risk Priority Number (RPN).

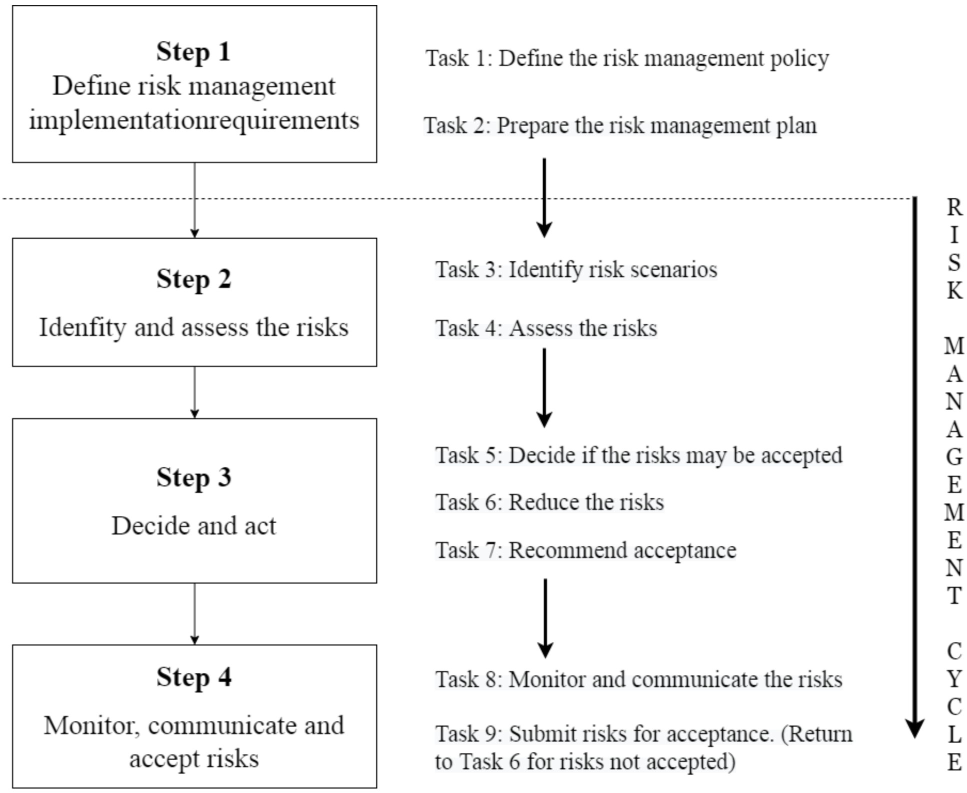


Figure 2.1: Risk guideline approach as defined by ESA [2]

From figure 2.1 we can see that the first step is left out above of the dotted line and is an initial planning stage where the type of management policy is decided upon. The risk management strategy is defined to the project's size, timeplan and constraints. Step 2 - Step 4 is a continuous cycle that repeats itself over the course of the project lifecycle. This could be beneficial to perform when there are any meaningful changes being made, either technological, management-wise or techniques. Whether this is beneficial to perform in a smaller and less complex smallsat project with less available time on a regular interval basis needs to be considered for the particular project. This is similar to the second part of NASA's risk management procedure titled "Continuous Risk Management" [3]. The risk management is a two-way approach formalized as a standard by NASA Procedural Requirements 8000.4A, required by the NASA Policy Directive.

NPR 8000.4A proposes two reciprocal processes; Risk-Informed Decision Making (RIDM) and Continuous Risk Management (CRM) that functions as their go-to risk management tool. The details surrounding this standard are not the focus of this paper, but a brief introduction as to how NASA or ESA deals with risks should be of interest to any future reader interested in smallsats and risk management. Figure 2.2 and 2.3 visualize NASA's philosophy and procedures.

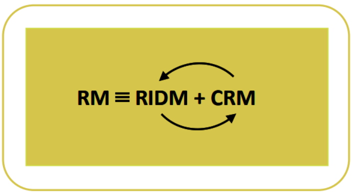


Figure 2.2: Risk management overview by from the NASA Risk Management Handbook [3]

RIDM helps avoid decision traps like confirmation bias or overconfidence when considering mitigation alternatives. By establishing a logical groundwork for decision-making, it helps ensure that the alternatives of any decision has been profoundly investigated. Then a cyclic action much like the ESA standard follows through, the CRM. Every step from "Identify" to "Control" is repeated during the development of the product and project, and fed back into the RIDM process [29]. The complete process as described in the Risk Management Handbook may not be viable for SmallSat projects.

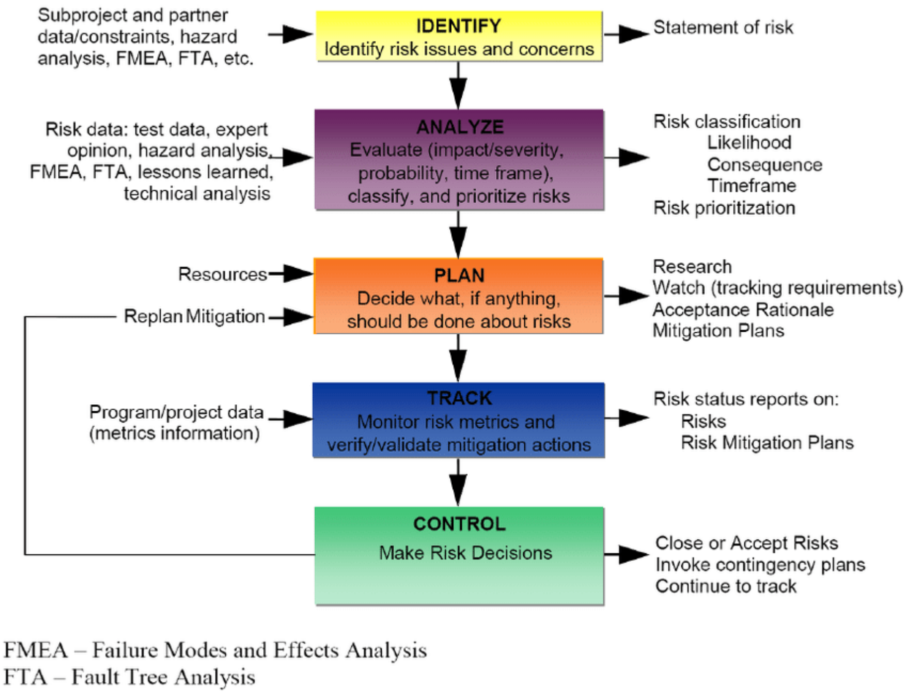


Figure 2.3: Continuous Risk Management procedure from the NASA Risk Management Handbook [3]

2.2 Risk Analysis Tools

2.2.1 Failure Mode, Effects, and Criticality Analysis

A chain is only as strong as its weakest link. Failure Modes and Effects Analysis (FMEA) is a widely used and thoroughly tested method that is used to study problems that may arise from individual faults in technical systems. It is a bottom-up inductive approach to risk assessment. By also analysing the criticality of the failure modes, we arrive at that which is abbreviated FMECA. There is usually a non-sharp difference between the two and so is of little interest in separating them but the latter tends to be preferred in both military applications and the space industry. Both tools seek to resolve and identify failure modes that could potentially become sources of process or product failure. The slight distinction is found in that the FMEA is a more qualitative tool exploring "in the case of"-scenarios, while the FMECA presents a quantitative aspect, often extrapolated from a source of known failure rates. A source containing such data can be found in The Military Handbook 217 "Reliability Prediction of Electronic Equipment" [30].

Constructing the FMECA is done in two steps: create the FMEA and then performing the criticality analysis. The FMECA is executed in the construction phase of a project and its purpose is to identify parts or attributes of a system that should be reworked and improved in order to adequately meet safety requirements or satisfactory dependability. The analysis could be performed to uncover the failure modes of a particular technical system and identify the possible causes of these modes. One may then decide the criticality of the identified failure modes and how these affect the project. The latter part is popularly done by a Risk Priority Number (RPN), which is a measure to help pinpoint critical failure modes identified from the FMECA. The RPN scales may vary, for example range from 1 (best case) to 5 (worst case). It is a product of the three following properties: severity, occurence and detectabiliy. All of which are numerical estimates.

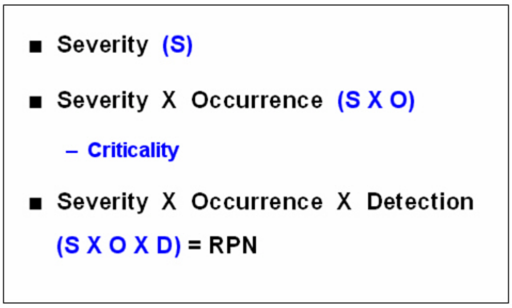


Figure 2.4: Risk Priority Number approach, from https://www.fmea-fmeca.com/ [4]

Severity (S) - is a subjective estimate of how inherently severe the specific failure's effect will be if it does occur. How damaging the effects will be for the project's goal.

Occurence (O) - how likely the specific failure mode is to actually occur during the projects or end product's lifecycle.

Detectability (D) - if the actual failure mode has occurred, how likely will it be detected and revealed what unwanted failure mode developed with the current measures installed.

The product is an overall score of danger for a particular failure mode and as such, higher RPN scores are going to be design priorities. Risk mitigation is then applied to diminish possible failures. Focusing on mitigating the risks with the highest RPN scores is a natural intuitive approach. Other mitigation strategies include:

- Change of design. Reviewing the current design of the particular subsystem in focus and looking at the various means of either switching out components, reassessing the derating data or conducting a literature review of similar previous solutions.
- Opt for a component or parts with a lower component failure rate. Given the presence and availability of these data, this may become expensive unless discovered at an early stage in the production of the project.
- Look at ways to incorporate physical redundancies of the subsystem or the component(s). Configuring the redundancy in a parallel setting means that both components have to fail together in order for the failure mode to ensue[1].
- Software redundancy. Adding watchdogs to protect and revert to a known state of the system. Timing checks and comparisons often lowers the severity of the failure modes.
- Warning system. In more general applications, a light or a buzzer could be used. In small satellite applications, regular communication checks verifying data is a viable approach.
- Classic detection and testing by inspection. Testing is really its own form of verification and it includes on various different levels unit testing, host & target testing, full system tests and more. A standardized test strategy should exist in the corporation.

The FMECA conducted for the HYPSO smallsat was developed as a part of a bachelor thesis by Moen, et al. "The task was to conduct FMECA on critical parts of the satellite and tailor a standardized approach for upcoming HYPSO satellites" [10].

[1] A real world example for scuba divers would be purchasing a scuba tank from two different vendors, adding a form of safety in so far that the two tanks are likely going to malfunction at different times.

2.2.2 Fault Tree Analysis

Fault Tree Analysis (FTA) is a deductive top-down method that was originally developed at Bell Laboratories in 1962 by H.A. Watson [31]. Fault trees are made up of event blocks and logic gates to connect a specified Top event with its underlying and determined fault cause(s). The FT do not make any assumptions themselves but ties together the perspective that could cause the event of concern. It is a well-recognized cause-and-effect tool used worldwide by many different sectors such as aerospace, automobile, electronics and nuclear industries. No complex system is completely immune to failure when it is adequately large enough. The probability of failure can be mitigated through revised system design for the relevant subsystems. It is important to keep in mind that the FT is a qualitative assessment in of itself naturally while it is free to have quantitative evaluations performed on it. One of these important qualitative insights obtained are minimal cut sets of the top event.

A cut set is defined as a combination of events that can cause the chosen top event for a particular fault tree. A minimal cut set (MCS) is intuitively then a cut set that contains the least amount of events that can cause the top event. These MCSs are resultingly important to pinpoint as one may obtain a great amount of information by studying these. For instance, a minimal cut set with a single basic event describes a particular fault which by itself can trigger the top event [32]. The quantitative perspective to a FT proposes both the introduction of probabilities of the top event and other fundamental considerations. The complete fault trees can be quantified by adding the cut set probabilities and determining the probabilities of all MCSs before sorting them thereafter. A hierarchy can be constructed to identify which dominant cut sets that contribute the most to the top event's overall probability.

Figure 2.5: Elon Musk addressing the unfortunate event surrounding SpaceX's Falcon 9 explosion in 2015.

FTA maps the relationship between potential errors, subsystems, and superfluous safety design aspects by creating a logic diagram of the complete system. This is achieved through a couple of fundamental properties, the first one being Event Blocks. Event blocks are generally divided into four types; Undeveloped Events, Basic Events, Intermediate Events, and Transfer Events. Undeveloped Events, by convention identified as an angled square, is a form of event which cannot be developed any further. This can be due to economic consolidation or simply due to the nature of the event itself has no further information available downstream. Basic Events are the lowest most events that cannot be further developed in any particular branch. They are errors or failures in a particular system and is recognized as a circle. Intermediate Events are events that occur between the top event and Basic Events and can be used to describe the former event action further leading up to the next event. Transfer Events are events that will be transferred over to another Fault Tree in which it is researched more in-depth and connected to another top event.

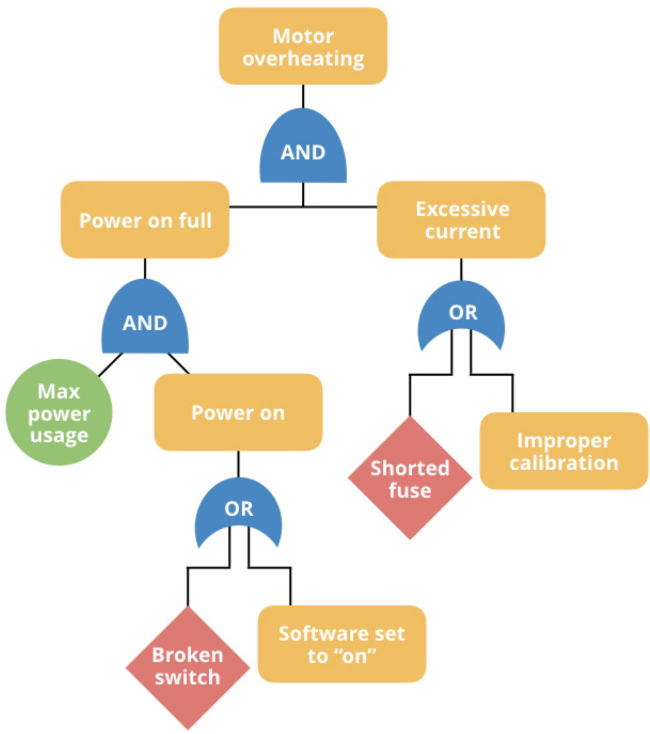


Figure 2.6: Fault Tree Example, from [5]

The second cornerstone of Fault Trees are logic symbols borrowed from digital design logic. Specifically the “AND gate” and “OR gate”. These symbols are used and applied in the same familiar way: an AND gate will output a logic high only if both inputs are also logic high. An OR gate will output a logic high either while both inputs are high, or only one of them is. An intermediate event or a top event can be caused by the fault of one or more underlying nodes, or the added combination of them all occurring at the same time.

Figure 2.2 provides insight into how such a fault tree can be used to identify which parts of a system is potentially hazardous to any particular top-event that needs to be addressed. Tracing the tree from top to bottom, one may easily pinpoint which failure modes are required particular attention and how they work together in conjunction with other failure modes to cause another problem. In this example, the top event is identified as a motor overheating. This is generally bad for most systems and processes as this can be the root cause of other unwanted hazards. We can see that this is caused by the synchronous combination of two underlying intermediate events. Using maximal power is in of itself not a problem, at least not in the short term for some processes. However, pulling excessive current is an event that should never occur in any thoroughly well-designed system and is the sum of something inherently amiss. This reasoning can be supported by looking at the causes of excessive current.

A shorted fuse is marked as an undeveloped event, perhaps its underlying cause is unclear at the time of analysing the top event, but it is an inherently unwanted property in any system. The other potential cause is identified as improper calibration whose nature is also purely unwanted. Note how potential failures such as a shorted fuse can easily be the result of a natural occurrence that might inevitability happen over time, while an improper calibration on an instrument is more suspect to human error.

Fault trees does not discriminate these in any way and should be designed such that every likely cause for a given event is listed, even when the team’s competence is undoubtedly professional. Understandably, if excessive current takes place together with enough wattage due to maximum applied voltage, the heat of the resulting total energy is potentially problematic for the electric motor.

Probability Foundation in Fault Trees

As stated, statistical probability is the tool used to work with and determine how likely the top event is likely to occur.
Assume that,

- $Q_i(t)$ = *Probability(Basic event i occurs at time t)*
- $\bar{Q}_k(t)$ = *Probability(Minimal cut set j occurs at time t)*
- $Q_0(t)$ = *Probability(Top event occurs at time t)*

Define $F_i(t)$ such that the basic event or component i is in a faulty state at time t, while not necessarily failing at precisely at time t. When all Basic Events develop at the same time, the MCS is interpreted as failed. While logic gates are used to construct an effective path of occurrences, they do not output strict binary values unlike conventional digital logic gates but rather probabilities connected to the Boolean set operations. This way, the inputs event probabilities determines the probability of a gate's output event. We assume further that the input events are statistically independent events, so that the occurrence of a single incident is not affected by the probability that the other occurs. An AND-gate will have two inputs that are unaffected by the other defined in set theory as the input event set intersection. Hence, for a single AND-gate and given *independent* basic events, the probability of the top event $Q_0(t)$ occurring is,

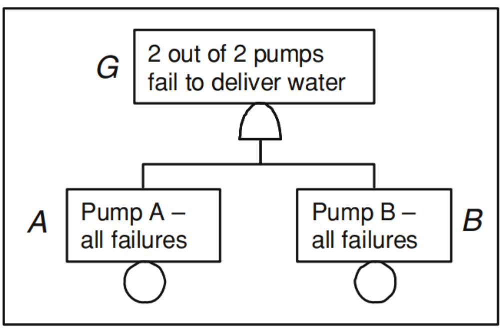
$$Q_0(t) = P(F_1(t) \cap F_2(t)) = P(F_1(t)) * P(F_2(t)) = Q_1(t) * Q_2(t) \tag{2.1}$$

as

$$P(Q_2|Q_1) = P(Q_2) \quad \text{and} \quad P(Q_1|Q_2) = P(Q_1)$$

Compactly written, an AND-gate with k basic events gives

$$Q_0(t) = \prod_{j=1}^{k} Q_j(t) \tag{2.2}$$



A	B	$G = A$ AND B $G = A \times B$
True	True	True
True	False	False
False	True	False
False	False	False

Figure 2.7: AND-gate example, from [6]

Equivalently, the OR-gate equals the union of events at the inputs. The output is then determined by the probability obtained from

$$
\begin{aligned}
Q_0(t) = P(F_1(t) \cup F_2(t)) &= P(F_1(t)) + P(F_2(t)) = Q_1(t) * Q_2(t) - P(F_1(t) \cap F_2(t)) \\
&= Q_1(t) + Q_2(t) - Q_1(t) * Q_2(t)
\end{aligned}
\tag{2.3}
$$

Giving

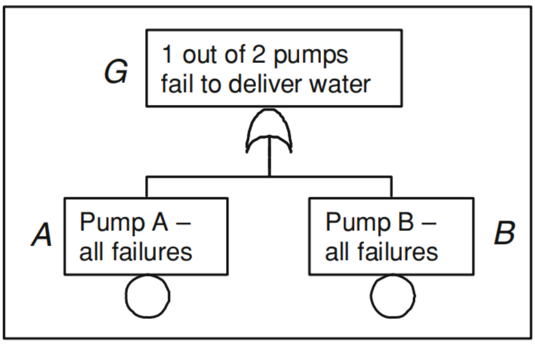
$$Q_0(t) = 1 - \prod_{j=1}^{k} 1 - Q_j(t) \tag{2.4}$$

with k basic events[33]. For very low probabilities,

$$P(F_1) \cap P(F_2)$$

is smaller compared to

$$P(F_1) \cup P(F_2)$$



A	B	$G = A$ OR B $G = A + B$
True	True	True
True	False	True
False	True	True
False	False	False

Figure 2.8: OR-gate, from [6]

While not always the case in real life, if we keep with assuming independent basic events for the minimal cut sets, the top event $Q_0(t)$ will be

$$Q_0(t) = \prod_{j=1}^{k} \bar{Q}_k(t) \tag{2.5}$$

For small values of the basic events.

2.2.3 Fuzzy Fault Trees

While conventional Fault Tree Analysis is an established method widely used by the industry, there are some drawbacks that limits its potential usefulness. The allowance of linguistic variables in the event blocks, the inclusion of human errors as a form of logic faults, dealing with uncertainties and lack of probability data are some of the obstacles likely to appear conducting this type of analysis. Instead, we introduce the use of Fuzzy Fault Tree Analysis to compensate for some of the shortcomings left by a conventional FT. Because there is a lack of hard reliable data concerning the probabilities of the chosen failure modes to conduct an FTA upon, a softer approach is applied.

The failure probabilities of each event in a quantitative assessment are considered to be exact values [34]. The numbers could sometimes be approximated e.g. using binomial probability when there is more than one outcome of a particular event but viewing only one specific outcome as important or 'Success' and concluding the remaining unwanted/non-important outcomes as 'Failure'. But when conventional FTAs treat these as sharp exact values which is inherently difficult when there are often vague characteristics of the events, the model's nature could be biased or even flawed to a lesser or greater extent [35]. Dealing with a lack of quantitative data then becomes a search for alternative database sources such as employees' experiences that is working for a company or the various team members in HYPSO's case.

The estimations carried out by HYPSO's team to help support the FTA's shortcomings on data is only going to suffer from the fact that it is not a hard measured data. Even with the help and approximate contributions from skilled programmers, designers and engineers, it is problematic determining the probabilities in an objective manner. This leads to some free leeway in applying linguistic variables like describing the probability whether a software function will lead to crashing the Onboard Processing Unit with terms like 'not likely, low, medium, probably, or very high'. Wisra & Weber [33], and Babar, Suresh & Raj [34] made foundations as to why fuzzy methods might be the only approach when there are larger variances in the parameters in the face of lacking objective data. When exact solutions are not possible to determine, approximations are the next-best thing.

The use of fuzzy logic isn't something new, even when used in conjunction with fault trees. Formally introduced in 1965 by Lotfi Zadeh[36] in the form of fuzzy sets within the field of mathematics, this type of approach have been studied since the 1920s as an infinite-valued logic. In its core, it is a type of logic rooted in the observation that individuals execute decisions based on inaccurate and non-nummerical available information. A branch developed to break down and extract nummerical data from people's vagueness and lack of objectivity in order to better represent, manipulate and work with quantitative models. This versatile tool has found its successful way into several branches, notably control theory and artificial intelligence. In 1980's, commercial applications started to appear, especially in Japan whose success with fuzzy logic prompted the establishment of the Laboratory for International Fuzzy Engineering Research by the Japanese government, a multi billion dollar program involving 50 companies over a six year period.

For example, Lin & Wang (1997)[37] united a hybrid approach between fuzzy set evaluation and probabilistic elicitation to assess the failures of the basic abnormal events of an aircraft wing drilling system. Chanda & Bhattacharjee's (1998)[38] approach in planning a transmission expansion for electric power systems examined the unpredictable nature of the components' failure rates and established new fuzzy failure rate probabilities for the components. To better assess the reliability in the chemical process industries, Khan & Abbasi (2001)[39] had developed an automated software that relied on fuzzy probability to eventually be conveyed into ordinary probability after applying the average function on the data. Both [39] and [37] used trapezoidal representations of their probabilities.

The shortcomings to address risk assessment in process plant safety was successfully handled by the use of semi-quantitative fault tree analysis to acquire probability and frequency intervals by Hauptmanns (2004)[40].

In Japan, the very term "fuzzy" was presented and used as a synonym with "efficient operation requiring minimal human intervention".[41] This is in stark contrast to the americans' view of fuzzy logic despite its formal birth in Berkeley. Zadeh, the professor that conveyed this form of logic about 55 years ago noted how "U.S. companies have yet to embrace the theory or to develop products around it, primarily because of the stigma scientists associate with imprecise theory." Expanding upon that by saying, "Our culture is based on classic truth, Aristotelian logic and black and white. Fuzzy logic is controversial in the United States because of its departure from traditional logic."
"The Japanese are going to bury us in a couple of applications. Then we are going to say, 'Uh-oh, we are going to have to play catch-up again.' " - Tom Schwartz, a Mountain View, Calif.-based consultant [42].

2.3 Applications in Other CubeSats

A review of the literature regarding the use of conventional FTA's in other CubeSat projects are readily found in numbers. For example, the HERMES CubeSat developed at the University of Colorado[43] conducted a Fault Tree Analysis while the satellite was still in its testing phase but analysed from the perspective that the satellite had already been launched and was alive and correctly functioning in orbit. HERMES approached their assessment in the same fashion that was carried out with HYPSO, the subsystems of the HERMES were investigated separately by category i.e. ADCS, EPS etc. with the basis on the previously done Failure Modes and Effects Analysis (FMEA) that was carried out by the respective design team.

The main application extrapolated from the Colorado's team of using FTA was establishing relationships between the different subsystems. How certain faults caused within a particular branch of one subsystem could lead to the fault inside another subsystem occuring. The cited paper briefly mentions towards the end that they "quantified" their fault trees to some extent using the FMEA and assigning linguistic probabilities to each event, by quoting "from «frequent» to «remote"», which the reader of this paper will hopefully recognize as treading into fuzzy logic.

Another CubeSat project, developed at the University of Florida by the Space Systems Group (SSG) is a 1U PicoSat named "SwampSat" [7]. The overall goal of this CubeSat program is a technological demonstrator — to provide a standard platform for the future continuous design and launch for new classes of Pico- and CubeSats. Also taking use of COTS, the primary objective is flight validation of a "compact three-axis attitude control system capable of rapid retargeting and precision pointing."

The team notes that due to lack of data on flight legacy for several components, their two reliability analyses were difficult to implement. By first realizing the Failure Modes, Effects and Criticality Analysis (FMECA) to gain a bottoms-up view by identifying different failure modes for their system categories, they went on to perform FTAs to solidify the SwampSats chance of success. SwampSat also applied FTA to the chosen uttermost severe of the failure modes that could cause the mission to fail. Unlike the HERMES project and the way FTA was done as later shown in this thesis, several fault trees were made according to different phases by timeline. For example, a fault tree was made to identify how things could go wrong in the launch phase alone. Then another was investigated in the deployment/start-up phase of the mission. This is an interesting way to carry out this form of analysis as it covers possible faults from the beginning to the end goal.

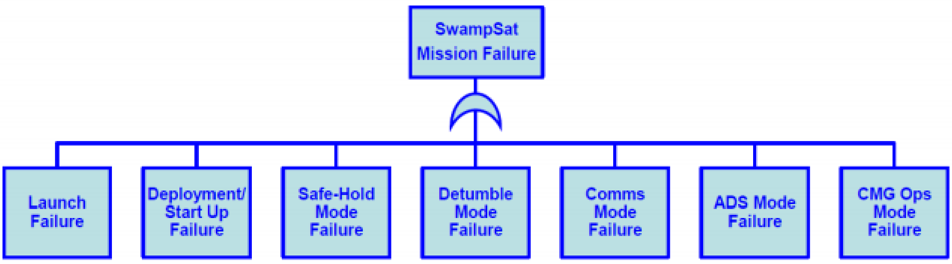


Figure 2.9: SwampSat's phase-based FTA, from [7], p.90

The different stages of the mission's overall diagram in strict fault tree analysis convention would translate into triangles which implies that the different figures each expand into their own fault trees. SwampSat did not, however, conduct any quantitative analysis of their completed fault trees and seem to have strictly applied a qualitative approach. Any mention of probability was excluded, perhaps intentionally by the author as it was outside the scope of their intended use. They identified which basic events were the root causes in the different subsystems and which potential paths could have shortest possible routes to the top event executing. Finally, they summarized which events occurred most frequently. The basic events of the tree presented had a resolution that corresponded to "Software Error" or "Cabling Error".

The resolution choice in constructing a fault tree needs to be considered. More precisely, the appropriate level of detail in describing each event will have an impact in how to deal with the tree for further analysis. The fault tree constructor can easily inquire the appropriate team working with the specific tree domain as to what level of detail is deemed fit.

For example, a project that has recently launched but experiences a major issue with the coded software soon after operating for the first time might want to look at the risk analysis that has been done. If a thorough fault tree analysis has been conducted, which is advisable for any large project especially, and the trailing error path from the relevant top node leads to a source node worded as "Software error", the next step would then be to flesh out exactly what is layered within this node. Constructing a new fault tree whose top node stems from the earlier source node "Software error" is an appropriate way of analysing what exactly went wrong, with the appropriate help from the software division.

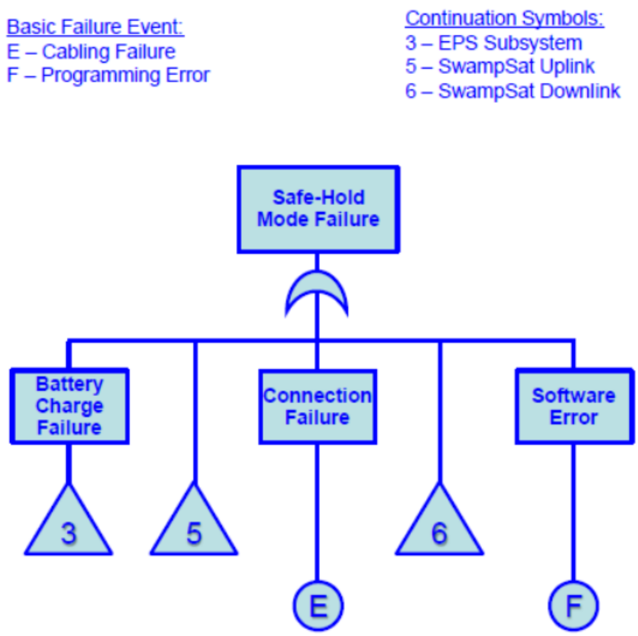


Figure 2.10: Fault Tree example from SwampSat [7], p.100. Note how nodes 'E' and 'F' are basic source nodes with umbrella terms used to describe their respective causes.

Chapter 3

Quantitative Fault Tree Analysis

> *1's and 0's dichotomies our lives, we need a bit of fuzzy logic to see the vastness of it. There is no good and bad, there is just a whole lot in between.*
>
> Rahul S. Rajan,

3.1 Motivation

Motivation to apply fuzzy logic in order to perform a quantitative study in the risk evaluation of HYPSO lies in the need to build up and contribute to a wider basis for the analysis of reliability. Providing groundwork for a better and more robust framework for future SmallSat Lab projects. The early life stage of which HYPSO currently resides in means that there are currently little no previous data on failure modes and their failure rates. Decision makers have an easier time assigning estimations by the use of words instead of precise numbers. Additionally, probability estimations by exact numbers will not have the ability to represent the ambiguity of which the decision maker is narrowing the estimation down to. Also, good risk assessment will and should include the consideration of multiple hazards. There is therefore a need to find an effective method to comply with the above elements in order to gather and collect data to help improve reliability when no previous data is unavailable.

3.2 Primer on Set Theory

3.2.1 Traditional Sets

Georg Cantor is the principal creator and father of set theory as the well established field it has evolved into. He defined it simply as - "By a set we understand any collection M of definite, distinct objects m of our perception or of our thought (which will be called the elements of M) into a whole."

Commonly referred to as a 'Crisp set', it is characterized as a container or area where elements in any particular universe is divided into those elements that belong in the set, and those who doesn't. Mathematically, this is defined with the following definition.

In the universe U, the set of elements having the property P in U is denoted by D, so that every element in the universe either has the property or not.

$$D = \{x : x \in U \quad \text{and} \quad x \text{ has the property} \quad P\} \tag{3.1}$$

If there are two sets A and B in the universe U, and if and only if $x \in A \;\Rightarrow\; x \in B$ then A is a subset of B. If the two sets A and B have the properties that $A \subset B$ and $B \subset A$, then they are equal in the universe U.

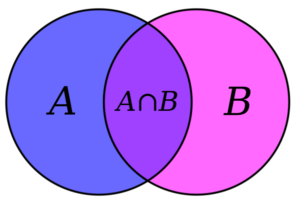


Figure 3.1: A Venn diagram illustrating the intersection between two classical crisp sets A and B.

For the readers familiarity, the null set (a set which contains no elements but is existing as a subset of every set), the set of natural numbers and the set of real numbers are all examples of crisp sets.

3.2.2 Fuzzy Sets

As introduced in chapter 2.4.3, fuzzy logic or fuzzy sets deals with the world in the opposite manner. Instead of constricting an element to either strictly belonging to a particular set or not, the element will rather have a particular *degree* of which it belongs to the set. The boundaries of the set is not precisely defined as in a classic set. Instead of representing the probability of a potential hazard with a precise number, fuzzy theory applies a range of probabilistic values to represent the likelihood of the unwanted event.

In probability space, a fuzzy set represents one or more fuzzy numbers between zero and one which can be applied to define the probability of an event [44]. This is done by taking use of different mathematical membership functions such as the triangular, trapezoidal or Gaussian functions. A fuzzy set $\tilde{A}$ in the universe U can be described as:

$$\tilde{A} \quad = \quad \{(x,\ \mu_{\tilde{A}}(x)) \mid x \in U\} \tag{3.2}$$

Where $\mu_{\tilde{A}}(x) \ =$ the degree of membership of x in $\tilde{A}$, and assumes values in the interval [0, 1]. In the case where $\mu_{\tilde{A}}(x) \ = \ 1$, then x is considered a full member of $\tilde{A}$. In the case where $\mu_{\tilde{A}}(x) \ = \ 0$, x is a non-member of $\tilde{A}$.

A fuzzy number will hold its title as a fuzzy number when the fuzzy set it belongs to is convex and normalized, and the corresponding membership function it belongs to is piece-wise continuous.

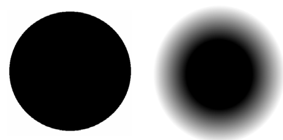


Figure 3.2: Crisp boundaries vs. fuzzy boundaries. From [8]

3.3 Fundamentals of Fuzzy Fault Tree Analysis

3.3.1 Membership Functions

The next part is how to go about choosing an adequate membership function. The designated membership functions can really have a lot of leeway in terms of shape or form as long as it correctly maps the data with a desirable degree of membership. One type of function does not fit every project and choosing the appropriate one is an acquired skill.

The choice of membership functions (MFs) depends on the project and system that is being analyzed. Deciding on how many classes in the fuzzy set are needed and the intervals between them will have a major contribution on the outcome of the fuzzy logic.

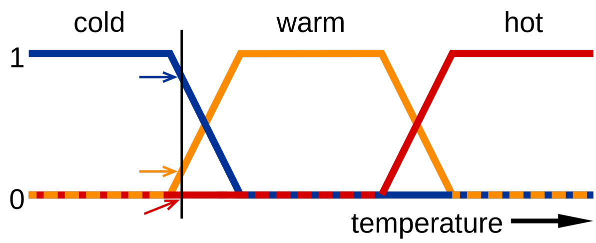


Figure 3.3: Fuzzy logic depicting the perception of temperature by trapezoidal membership functions. From https://simple.wikipedia.org/wiki/Fuzzy_logic, by *faultofstars*

The only rigorous criteria an MF must satisfy is the interval from 0 to 1. The shape will be dictated by how one one intuitively believes the different linguistic variables will covered by the function one proposes. In of itself, the MFs can be any arbitrary curve that is appropriate for our wish to capture either calculation speed, efficiency or a trade-off of both. The type of membership function then does not play an important role in determining how the final model will perform [45]. Rather, the number of classes will directly influence computational time if one chooses to simulate such a system. An optimal model scheme can be found by varying the amount of classes and type of function ("cold", "warm", "hot") in order to achieve a better performance [46].

How to choose the right membership function are readily available from various references, going about how to do so in great detail [47][48][49][50]. Modelling from a fuzzy view deals with putting aside the 0 or 1 concept. The triangular MF is a popular choice. For more complex problems when, for example, modelling a quantum mechanics problem - determining how likely a particular particle α will split off at some arbitrary time t and not looking at the other possible time-dependant split off-particles could require a special membership function. This is where familiarity with the particular situation helps.

One of, if not the most applied membership function found in literature is the triangular MF. Clearly, the triangle consist of straight linear slopes forming its shape and provides the advantage of simplicity, especially for computational purposes. One can also utilize a Gaussian function which brings smoothness, differentiability at all points and familiar, consistent notation. Both triangular and Gaussian functions has been found to perform better than most other membership functions. Zhao and B. [51] compared and found that the triangular MF is outperforming the Gaussian and about every other MF, solidifying its position as the objectively better function in many applications.

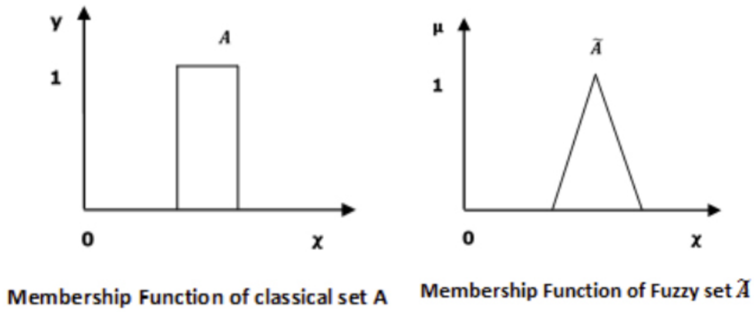


Figure 3.4: Illustrations of a classical crisp set and a fuzzy set. The first set will have a binary inclusion, while the fuzzy set on the right has a degree from 0 to absolute inclusion at 1.

When opting for a triangular MF, it is advisable to utilize a symmetric function with 50 % overlap as a starting point and tune in thereafter, according to Sadollah [45]. Due to the nature of their shapes, triangular functions represent fuzzy numbers whereas a trapezoid represents a fuzzy interval. In cases where the shape of the membership function has no specific priority for the particular project, the triangular and trapezoidal functions are easy to implement and non-complex computation-wise. Again, as long as one keeps in mind the data available when developing the model, a triangular MF is often adequate but that may not always be the case for unique data sets.

Triangular membership functions will have the following definition:
Let $x,\ a,\ b,\ c\ \in \tilde{A},\ and\ \mu_{\tilde{A}}(x) : \tilde{A} \to\ [0,1]$ A fuzzy number described by the triangular membership function will defined by:

$$\mu_{\tilde{A}}(x) = \begin{cases} 0 & x \leq a \\ \text{(x - a)/(b - a)} & a \leq x \leq c, \\ \text{(c - x)/(c - b)} & c \leq x \leq b \\ 0 & b \leq x \end{cases} \tag{3.3}$$

Where $a \leq b \leq c$. Compactly written, $\tilde{A}\ =\ (a, b, c)$ 'a' and 'c' are the lower and upper bounds of the x-axis and 'b' defines the height and maximal inclusion of the function.

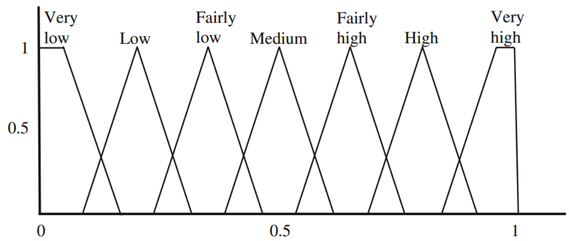


Figure 3.5: Triangular membership functions divided into 7 different classes based on linguistic descriptions.

The trapezoidal membership function will have its fully inclusive fuzzy numbers on an interval defined by the max of the function.

$$\mu_{\tilde{A}}(x) = \begin{cases} \text{(x - a)/(b - a)} & a \leq x \leq b, \\ 1 & b \leq x \leq c, \\ \text{(c - x)/(c - b)} & c \leq x \leq d \\ 0 & \text{otherwise} \end{cases} \tag{3.4}$$

So to qualify as a fuzzy number in the trapezoidal function, $\tilde{A}$ defined in U must possess the following properties [52]:

1) $\mu_{\tilde{A}}(x)$ = 0 for all $x \in (-\infty, a] \cup [d, \infty)$, $c < d$
2) $\mu_{\tilde{A}}(x)$ is strictly increasing on $[a, b]$ and strictly decreasing on [c,d] for $a \leq b \leq c \leq d$.
3) $\mu_{\tilde{A}}(x)$ = 1 for every $x \in [b, c]$, $when\ b \leq c$.

One can see that the functions in figure 3.6 has the convex property as all angles are less than 180 degrees.

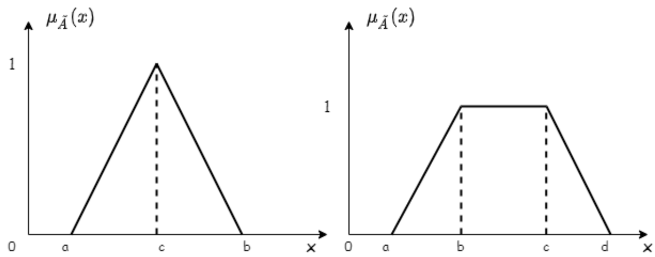


Figure 3.6: Triangular and trapezoidal membership functions.

3.3.2 Fuzzy Set Operations

The arithmetical approach and development of fuzzy numbers has been increasingly receiving a solid foundation since the 1980's and enabling this realm to make use of more complex analytical tools. The contributions have been plenty, such as Dubois and Prade [53] formulated the exact fuzzy mathematics and brought the well-known(as 'well known' as can be within this particular branch of mathematics and control systems) LR model with its corresponding notation and formulas [54]. Here, contributions are used to refer to tools like arithmetic operations and approximation methods.

Doing a quick literature review of fuzzy operations will quickly lead the reader into two primary categories to help aid in arithmetic operations. The first one being Zadeh's extension principle which plays a particularly extensive role in the fuzzy realm. Made clear, it extends operators and mapping from the formal domain of set theory to the complex domain of set theory with much of its properties and laws. In general, arithmetic operations on fuzzy numbers can either be dealt with by the direct use of membership functions through Zadeh's extension principle, or the α-cut method.

Looking at fuzzy models from a mathematical and functional point of view, the fuzzy solution partly suffers from the fact that the same algebraic properties one is familiar with do not have the same meaning or possibilities for all sorts of MFs.

3.3.3 α-cut Set

$\forall\ \alpha\ \in\ [0,1]$, an α-cut set of a fuzzy set $\tilde{A}$ is denoted by $\tilde{A}_{\alpha}$ and is a crisp set defined by

$$\tilde{A}_{\alpha} = \{x\ \in U, \mu_{\tilde{A}}(x) \geq \alpha\} \tag{3.5}$$

The $alpha$-cut set of any fuzzy set $\tilde{A}$ is a classic set that holds every value of $mu_{\tilde{A}}$ whose values are equal or greater than a specified α value. When $alpha$ is set equal to 0, the interval value corresponding is known as the "support" of the fuzzy set by notation. When α is equal to 1 in a triangular MF for example, the interval will cease to exist by the cost of a single crisp value.

Due to its interval properties, the nature of arithmetic and operations when dealing with fuzzy sets and relations will be somewhat easier than when choosing to use direct brute force evaluations as pointed out by Dutta et al [55].

3.3.4 The Extension Principle

The extension principle is one of the cornerstones of fuzzy theory. It's a foundation that presents a general method for extrapolating the classic crisp set theory concepts to better assess fuzzy numbers, allowing some algebraic operations be possible to work with.

If we define f as a function that maps any $U_1 ... U_n$ to another universe Y by $f = f(x_1,\ ...\ , x_n)$ Then thanks to the extension principle we can induce from any fuzzy sets $\tilde{A}_1, ..., \tilde{A}_n$ to a new fuzzy set $\tilde{B}$ in the universe Y through f:

$$\mu_{\tilde{B}}(y) = \begin{cases} \sup_{x_1,...x_n, y=f(x_1,...,x_n)} \quad min(\mu_{\tilde{A_1}}(x), ..., \mu_{\tilde{A_n}}(x)); \quad f^{-1}(y) \neq \Phi \\ 0, \quad f^{-1}(y) = \Phi \end{cases} \tag{3.6}$$

$f^{-1}(y)$ represents the inverted image of y, and $\mu_{\tilde{B}}(y)$ is the largest of the membership functions from $\mu_{\tilde{A_1},...\tilde{A_n}}(x_1, ..., x_n)$.

While the idea is useful and somewhat elegant, it can be complex and too difficult to use if certain operations are needed other than the very basic when compared to α-cut sets [56].

However, the following operations are easy to work with: The addition of two fuzzy numbers $\tilde{A} = (a_1, a_2, a_3) + \tilde{B} = (b_1, b_2, b_3)$ is equal to the sum of their parts respectively:

$$\tilde{A} + \tilde{B} = (a_1 + b_1, a_2 + b_2, a_3 + b_3) = \tilde{C} \tag{3.7}$$

This is true for both triangular and trapezoidal functions. The resulting addition of two fuzzy numbers will produce a new fuzzy number.

Similarly, for subtraction:

$$\tilde{A} - \tilde{B} = (a_1 - b_1, a_2 - b_2, a_3 - b_3) = \tilde{C} \tag{3.8}$$

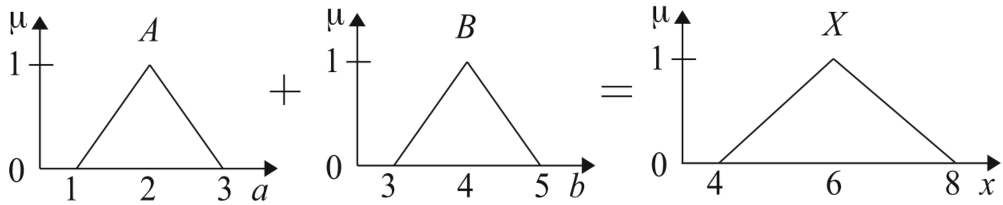


Figure 3.7: L-R Fuzzy arithmetic from [9]

Chapter 4

Method

In this chapter, a walk-through of the approach used in constructing fault trees for HYPSO's SmallSat missions are delved into. Because Fault Tree Analyses is a complementing top-down approach to a thoroughly constructed FMECA, the resulting material can be utilized for both preventative measures as well as a post-event analysis of a potential mishap. Two main foundations constitutes this functional possibility: risk analysis of hazards and the mathematical framework to aggregate risks in a hierarchical approach.

The sections in this chapter are placed in chronological order as they were executed and carried out the spring semester of 2020. First we will look at how the fault trees came to be by examining their reason for existence and their link to the FMECA and risk analysis as a whole. A dive into how the fault trees were constructed following top event identification is then looked at.

Fuzzy sets are used to represent the vague nature of linguistic probabilities as an alternative way of acquiring data. The mathematical method for quantitative analysis is examined towards the end with a specific example from the resulting data. Fuzzy logic and an agreement method is used to achieve evaluation possibilities of the aggregated scores. This way of utilizing fuzzy logic has been successfully executed in many previous engineering applications as was covered in chapter 2. A chosen method, Similarity Agreement's Method (SAM) can effectively aggregate information and has been previously successfully used in solar photovoltaic systems and fire and explosion analysis of crude oil tanks.

This thesis adopts the aformentioned method together with fuzzy set theory to produce numeric risks for the HYPSO mission as laid out in the following pages.

4.1 Identifying Top Events

As fault trees are made up of a single top event that has been chosen for analysis, the first task in carrying out this objective was to find out what exactly was going to be assessed in a fault tree analysis. Which failure modes. A literature review on the use of fuzzy logic in fault trees or even stand-alone fault tree analyses shows that a single fault tree is almost always worked with one at a time in any specific research paper.

From HYPSO's standpoint, picking out a single top event and constructing a single fault tree from that top event would likely be too narrow and too specific of a problem scope, at least in the start phase of the SmallSat Lab's lifetime projects. There are too many uncertain areas that could hide potential causes of errors just as easily as the next area, and propagate through the various sub-systems, resulting in unwanted events. From the author's perspective, as of writing this paper, focusing on a single failure event intuitively would be less beneficial overall, especially now before HYPSO have had its launch and accumulated any hours of operational lifetime or data. Reviewing the FMECA that was previously carried out reveals numerous failure events for all categories of the satellite as seen in figure 4.1.

To better cover possible risks and provide a larger supply of data for risk analysis, assessing multiple fault trees were decided upon. This is beneficial because the resulting data is spread to cover a larger part of the risk assessment of HYPSO. While likelihood is the focus of this thesis, and potential room for carrying out similar methods in cultivating additional data for other parts of the satellite is possible later, the resulting data should not only be of help by themselves, but this very paper could serve as a platform and framework into conducting similar analyses for whomever is tasked with risk analysis next.

While the possible failure modes turning into top events for the FTA were plenty to choose from, the next issue was deciding on which failures modes in particular were of interest. The authors of the FMECA had listed plenty of causes that could easily reduce the expected lifetime or one-way events immediately concluding HYPSO's mission. Determining then which categories should be prioritized is not trivial.

While the SmallSat projects are relatively young and there are increasing amounts of available data on SmallSat risk and failure analysis with each passing year, there remains nevertheless limited data and what is available is uncertain. Especially when looking which sub-system of a satellite is of most concern, failure-wise. When it comes to assessing SmallSat reliability, the devil is in the details and the details are mostly unknown.

Operational mode	Description of ope	Function	FM #	Failure Mode	Failure detection	Failure cause	Failure effect on other units	Failure effect on main function	O (1-5)	S (1-5)	D (1-5)	RPN =O*S *D	Failure minimizing measures
(J)ADCS				Attitude Determination Failure Mode	ADCS Failure Mode (total)								
Function			FM#	Failure Mode	Failure effect	Failure detection	Failure cause	Failure effect on other units	O (1-5)	S (1-5)	D (1-5)		
Estimate angular velocity			J1	Fails to estimate angular velocity			Flaw in inertial measurement unit (IMU), error in signals between IMU and AD	AC: Most tasks	2	4	2	16	
Estimate magnetic field			J2	Fails to estimate magnetic field			Flaw in magnetometers, error in signals between magnetometers and AD	AC: Detumbling, Idle	2	3	1	6	
Estimate sun vector			J3	Fails to estimate sun vector			Flaw in sun sensors, error in signals between sun sensors and AD	AC: Sun pointing	2	2	1	4	
Estimate position			J4	Fails to estimate position			Star tracker covered/blocked	AC: Any that requires pointing somewhere (sun pointing, user vector)	2	3	1	6	
Estimate attitude			J5	Fails to estimate attitude			Flaw in inertial measurement unit (IMU), error in signals between IMU and AD	Needed for all AC tasks	2	5	1	10	
(K)Power	Magne												
Operational mode	Description of operational mode	Function	FM#	Failure Mode	Failure detection	Failure cause	Failure effect on other units	Failure effect on main function	O (1-5)	S (1-5)	D (1-5)	VALUE	Failure minimizing measures
Safe Mode	Reboots EPS, happens when too much power is drawn	Convert solar energy to power											
		Reboot EPS	K1	EPS is not rebooted	No response from satellite		All units fail	Total failure	1	5	1	5	
		Store power in batteries											
		Limit discharge of batteries											
Critical Mode	Power consumption is too high, dept of discharge is too high	Distribute power to critical subsystems	K2	Subsystems do not get power					1	5	2	10	
		Convert solar energy to power	K3	Solar energy is not converted					1	5	1	5	
		Charge batteries	K4	Batteries are not charged (same as solar energy not converted?)					1	5	1	5	
		Store power in batteries	K5	Some batteries fail					2	4	1	8	
		Cut power to non-critical subsystems	K6	All batteries fail					1	5	1	5	
		Limit discharge of batteries	K7	Batteries are discharged more than depth-of-discharge					3	3	1	9	
			K8	Subsystems that are not supposed to get power in critical mode get power(sdr)					2	4	1	8	

Figure 4.1: Snippet from the HYPSO FMECA analysis. Various failure modes are shown for both the ADCS and Power categories. From [10]

In order to best determine which failure modes should be paid attention to and which should be less prioritized, the team members were the best source of information. Particular members from the team went over the FMECA and came to a final agreement on which failures posed a significant threat to the mission by re-adjusting the RPN values for each category.

To follow up the review of the RPN scores, several meetings were scheduled with the team over the course of several weeks. The meetings were held with the appropriate team members and their respective area of expertise for the operational modes. This allowed a more in-depth discussion of the various categories and if the RPN scores really reflected a realistic picture of the concerns and risks. Together with the team, 3-6 different failure modes from the subsystems Payload, Communication, ADCS, Power and Ground Station were pinpointed as the most critical.

Not only did discussing the failures modes with the team pave the way for this thesis' goal, but also strengthened and ironed out any inconsistencies or inaccuracies that were present in the FMECA. The FMECA became more detailed and fleshed out with better descriptions and notes. And if the RPN scores according to the team members did not accurately pick up the failure modes they personally felt should be of importance, that was taken into account moving forward.

Subsystems	SubSubSystem	SubSubSubSys	Reference letter	Failure Mode Candidates
Payload	HSI	OPU (on board p	A	A5 - Software crash (3-in-1) PetaLinux (3-5-1) - 15 OPU, (3-3-2) - 18 CLI (2-3-1) - 6 A17 - Deletes wrong area of memory (17)
		Imager	B	B1 - No image, software/hardware fault (12) B13 - Overexposed image (12) B6 - Permanent Lack of Focus (16)
		BOB(break out b	C	C4 - Unable to store images on SD card (18) C5 - Cannot recieve or transmit CSP data (various)
	RGB camera		F	F1 - Module uses power when it shouldnt (12)
Communication	S-band radio		G	G1/G3 - Does not send data (4 & 8) G13 - cant resume transmitting the missing packets (18) G6 - Sends corrupt data (5)
	UHF radio		H	H1 - Data from ground (Does not recieve data at all) (24) H2 - Recieves corrupt data (24) H3 - Does not 'send' data (20)
ADCS	AC		I	I12 - Magnettorquers do not dump reaction wheel momentum (12)
	AD		J	J1 - Fails to estimate angular velocity (16)
Power			K	K1 - EPS is not rebooted (5) (total failure) K2/K9 - Subsystems do not get power (10)
Ground Station	NTNU		L	L4&L5 - Too noisy or too weak signal - does not decode digital signal (18 & 24) (Lower RPN than L2, tracking wrong satellite but perhaps more severe to the mission)

Figure 4.2: HYPSO candidate failure modes. 19 failure modes were initially picked out across the different subsystems.

4.2 Constructing the Fault Trees

These candidate failure modes were the ones of most concern and importance with regards to the mission goal in mind. When the team had discussed and reviewed these, it was based off of what would hamper or in any way be of most risk in terms of the mission success criteria. As constructing 19 different failure trees would be a task more suited for a whole team, these failure modes had to be reduced into the 5 most critical failure modes, the most critical of them all in terms of severity or likelihood.

This was resolved by hosting several new meetings with the team across the categories of the subsystems and picking off the lesser concerns delicately. After reviewing again with the team, the final 5 most critical failure modes that was going to be taken forward into further analysis were presented at the Critical Design Review as:

- Payload: A5 (Software crash. OPU failing/freezing. Anything requiring restart.)
- Communication: G3 (S-band: Does not send data from ground to payload controller)
- ADCS: I17 (Reaction wheel does not spin up)
- Power: K1 (EPS is not rebooted)
- Ground Station: L4 (Gnd. station modulator: Receives too weak or too noisy signal)

In no particular order, the construction of the fault trees were randomized and built in the free online diagram software www.draw.io / diagrams.net. Most diagram or fault tree specific softwares are not free and to best benefit HYPSO in the future, the construction of these fault trees should be done with a software that can be accessed again in the future should there be a need to review these later. Other software solutions were initially used to construct the first fault tree but was eventually abandoned due to inaccessible data behind a paywall. Because diagrams.net is an open source technology built exactly for these kind of problems and is a widely-used and a familiar tool among academia and the industry, the choice was clear.

The construction of the fault trees themselves were straight forward in terms of their structure, but not trivial when looking at what leads to which node. One starts from the top and places the Top Event node that which is going to be analyzed. The fault trees are often built in such a way that the first gate input is going to be an OR-gate. This is a natural and intuitive choice instead of a particularly evaluated one. There exists often completely different paths for a top event to occur which are not triggered by one another, so the top event will in many many cases be triggered by the results of one or more events. Or several at the same time.

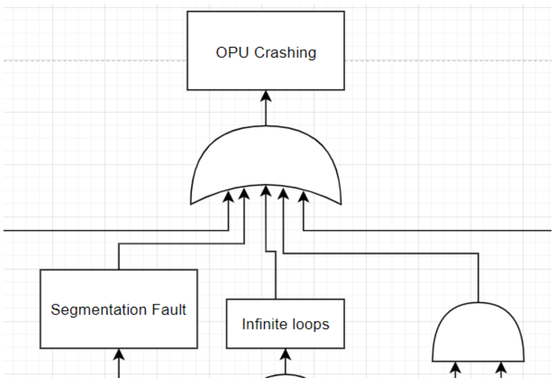


Figure 4.3: Example snippet from the OPU Crashing fault tree with an initial OR-gate. Made with draw.io

Because the team members were busy working on their own tasks and could not directly assist in constructing the trees themselves, albeit that would have been faster, they were open to aid through questions. Lacking deep knowledge about the different subsystems meant a lot of literature reviews had to be done in order to best analyse which causes lead to which events. And if there were any crosslink between the different nodes. After the initial OR-gate, the first intermediate events assigned by rectangular boxes were first causes as to how the top event could happen in any way or form, no matter how unlikely. Following these intermediate events, the question "How could this occur?" was to be asked repeatedly through each fault tree. This lead to new branches with new failure causes connected to OR-gates or AND-gates leading into the previous nodes.

During the construction of these fault trees, the respective team to which the top event belonged was used as a valuable resource in combination with the literature research. Everything had to be double-checked and reviewed with the respective team members. The resolution to which each fault tree was designed around was also reviewed with the respective teams. What would best benefit the team if they looked at the tree in the future? What made sense in terms of level of detail? The idea that the work that was being carried out should always be of benefit to HYPSO in the future was ever-present through this whole process.

After having researched potential failure causes of a particular node, the underlying nodes were created and exported picture files from draw.io was sent to the teams for inspections and validation. This process with researching, asking and validating with the teams went continuously until most, if not all the members of a subsystems group felt nothing more was needed to be added and nothing else came to mind.

The fault trees constructed in this paper are sometimes having multiple pathways from a child node leading up to several different parent nodes. This is a conscious choice. Popular alternatives would be copying the same child node at hand into different places in the tree, to accurately portray that this particular node is indeed the cause of multiple parent nodes. While the choice that was executed in this paper could be viewed as a more "spaghetti"-like structure, the intention was to better reflect and portray multiple pathways leading up from that same node, instead of copying the node elsewhere in the diagram, making the tree unnecessarily larger.

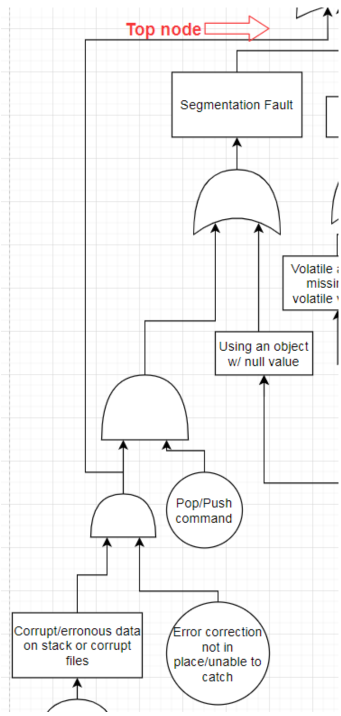


Figure 4.4: The combination of corrupt data and an error correction unable to detect said corruption is illustrated as a direct and indirect root cause of the top event.

As seen in 4.4, the AND-gate combination of having corrupt data on the stack or corrupt files, depending on how they are handled can be a direct pathway to the top event occurring, given that a watchdog is not implemented or in any way unable to detect the fault. The former is arguably an improbable pathway, the same occurrence in combination of low-level instructions run on the corrupt stack data can possibly result in one of two reasons for segmentation faults as illustrated. Which again is a possible cause for the top event.

This could also have been portrayed by making active use of the triangular symbol, representing a type of top node that will be continued on or attached in another fault tree. In cases where the same 4 or 5 error causes are repeated in different areas of the same fault tree, this could prove to present a cleaner option. If a system hierarchy has a structure where a shared intermediate event is consisting of several child nodes that is also branching out to new child nodes, and this shared intermediate event is repeated several times in the overall fault tree diagram, then this should absolutely be utilized.

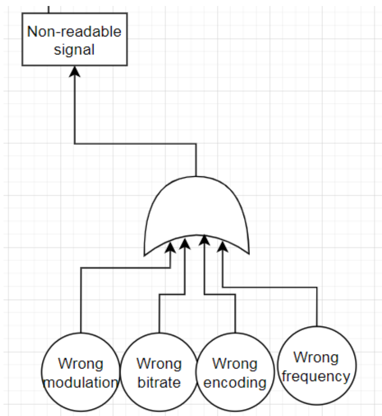


Figure 4.5: The same four source nodes, which can also be attributed "user fault" is used both in the S-Band transmitter diagram and the Ground Station diagram.

In the example illustrated in figure 4.5, figure 4.6 and figure 4.7 the same four source nodes "Wrong modulation", "Wrong bitrate", "Wrong encoding" and "Wrong frequency" are used at least two times in the fault trees. While it is not highly necessary here as the underlying child nodes are only one level deep, merging these into a triangular top node for easier re-use elsewhere could be of delight to the reader. Florida's SwampSat analysis used this illustration well. The main obstacle for this part of the analysis can be summarized to not possessing the same knowledge or experience as the designated team members working on the different parts of the subsystems.

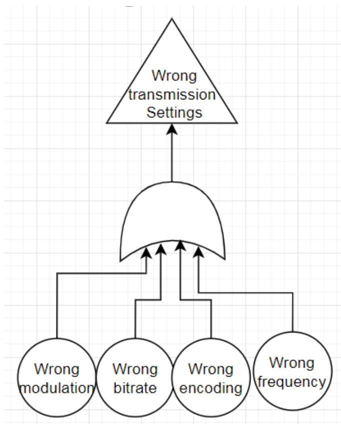


Figure 4.6: Switched out parent node to indicate a jump elsewhere in the current or another fault tree.

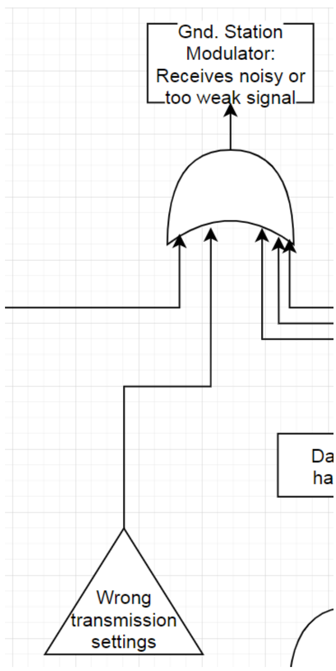


Figure 4.7: In a different fault tree, the previous four source nodes has been traded out for the triangle continuation symbol in another fault tree than the previous two figures.

4.3 Team Evaluations

After constructing the fault trees for the different chosen top events and with all teams satisfied in terms of detail level, validity and scope, the next part of applying fuzzy logic required the team's opinions on every source node of the trees. This was resolved by making a questionnaire for the team members to fill in and is also the domain of the fuzzy logic that ties in closest to the realm of psychology.

The questionnaire had to gather two things from the participants: the likelihood of which they perceived each root failure cause to happen, and the degree of experience they had surrounding the nature of the corresponding failure node. The wording of the questions had to be thought-through, especially for the degree of which the participant felt competent regarding the particular field. The important note here is that it would be counter productive if the questions were poorly worded. For example, asking "Compared with the others at your team, how competent would you rate yourself regarding failure source A?". This could trigger a subconscious decision to not accurately fill out the form in a way that truly reflected the skill level of the participant. Imposter Syndrome is known to haunt academia and the top tech companies of the world [57]. If the participants were prompted to answer in a way that sets them up for comparison either with the rest of the team or in general, a resulting answer could suffer from a lack of confidence and it would be detrimental to the goal of the questionnaire and the aim of this thesis.

The questionnaires had pre-selected answers that were available from a multiple choice type of approach. Seven different choices of likelihood were given to try capture the real probability in the best possible way. These were « Very unlikely », « Unlikely », « Doubtful », « Medium », « Possible », « Likely » and « Very likely ». Seven different pre-selected answers weren't an immediately arbitrary choice. Miller, the renowned psychologist's [58] famous paper from 1956 proposed that the average human can only hold about seven different objects or chunks of information in working memory in any given time, plus or minus two. The paper is one of psychology's most cited papers of all time. With the previous claim in mind, and to best make use of discrete fuzzy variables, it is often recommended that the number of categories be restricted to no more than seven [59].

For every source node, a question was first asked on how likely the given event could occur, no matter how unlikely the participant actually felt about it ever happening. Then, a follow-up question with a new set of 6 pre-selected answers determining the participant's expertise in the field of the source node were chosen to range from « Novice », « Developing », « Intermediate », « Proficient », « Advanced », « Expert ». This expertise scale was used to weigh the different participants opinion, scaling how much the individual's contribution to the final aggregated opinions were going to matter. Choosing which people to fill out the forms was more often than not dictated by who was available. The team itself would also help direct me to who was best suited to answer the questionnaires. Some of the subgroups like ADCS had a total of 2 or 3 people, where 2 were actively questioned due to availability. The software group is the largest and the intention was to collect data from everyone, but due to lack of time and suboptimal communication, a few were excluded. Ideally, 3 or more team members would be optimal for the chosen method.

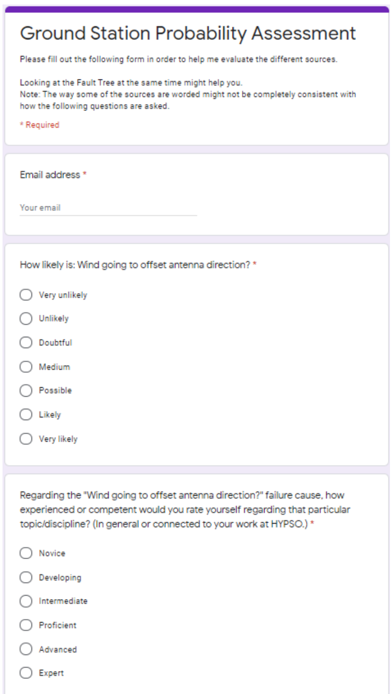
To distribute the weighing factor for each linguistic variable, given that there were set up a total of 6 different expressions, and the sum of their parts should equal 1 (100%), a simple way of dividing the total score into increasing parts was done as follows:

$$100/21 = 4.761904 \tag{4.1}$$

Where the number 4.761904 is the smallest weight given to somebody with a Novice declaration. The numerator 21 is the sum of $1 + 2 + 3 + 4 + 5 + 6$, which produces a number that can be added onto itself 5 more times to produce an increasingly greater weighing factor so that their sum equals 100.

Novice	Developing	Intermediate	Proficient	Advanced	Expert
4.761904	9.5238	14.2857	19.04761	23.8095	28.5714

There are numerous other ways to apply weight functions to different expert's opinions from literature. The proposed method is one way to achieve a difference of influence on the final fuzzy opinion. Docs.google.com was used to create the questionnaires for the fault trees.



Ground Station Probability Assessment

Please fill out the following form in order to help me evaluate the different sources.

Looking at the Fault Tree at the same time might help you.
Note: The way some of the sources are worded might not be completely consistent with how the following questions are asked.

* Required

Email address *

Your email

How likely is: Wind going to offset antenna direction? *

- Very unlikely
- Unlikely
- Doubtful
- Medium
- Possible
- Likely
- Very likely

Regarding the "Wind going to offset antenna direction?" failure cause, how experienced or competent would you rate yourself regarding that particular topic/discipline? (In general or connected to your work at HYPSO.) *

- Novice
- Developing
- Intermediate
- Proficient
- Advanced
- Expert

Figure 4.8: Example snippet from a questionnaire used to gather the opinions of team members in order to assess the fault trees.

Linguistic variable	Description
I) Likelihood	
Very unlikely (VU)	Likely not going to happen at all during the mission lifetime
Unlikely (U)	Possible, but regarded as not happening
Doubtful (D)	Not expected to happen, but could
Medium (M)	Moderate chance of happening
Possible (P)	Possibly but not particularly expected
Likely (L)	Will likely occur at some point
Very likely (VL)	Is to be expected
II) Proficiency	
Novice	Familiar with the concepts and discipline
Developing	Confident in the foundations
Intermediate	A good amount of experience with the topic
Proficient	Has experience and is often working with the specific field
Advanced	Great amount of experience and knowledge
Expert	Very experienced and is actively working within the field

4.4 Qualitative Analysis

To quote NASA [32] "*It is important to understand that a fault tree is not a model of all possible system failures or all possible causes for system failure.*" With the different chosen systems and the different selected top events to be analyzed, a number of potential basic events were identified to the point where the teams felt satisfied. In order to compute failure probability (likelihood) of the top events, fault tree analysis was performed together with fuzzy theory in a combination of qualitative and quantitative manner. The qualitative domain of the analysis was contained to the identification and relationships of basic events and identificaiton of minimal cut sets. Minimal cut sets were identified for all trees according to procedure. Boolean algebra was applied where necessary to reduce the the cut sets into the correct minimal sets. The minimal cut sets denotes which minimal routes are possible for the top event to happen. In this thesis, the minimal cut sets act more as a support to better explain and correctly analyze the fault trees.

Some of the fault trees were made with additional intermediate events to better describe what is going on. Meaning that even though some underlying child nodes and basic events could cause multiple of these description boxes, it did not matter from a pure analytical standpoint as these served more to fill out information on what could happen instead of actively influencing the calculations in any way. This was especially true for the OPU Crashing fault tree.

4.5 Quantitative Analysis

The fuzzy representation of the 7 linguistic variables established from the previous section can be quantified using triangular membership functions as follows:

$$\mu_{1stfunction}(x) = \begin{cases} 1-6x & 0 \leq x \leq \frac{1}{6}, \\ 0 & \frac{1}{6} \leq x \leq 1, \end{cases} \tag{4.2}$$

$$\mu_{2.-6.}(x) = \begin{cases} 0 & 0 \leq x \leq \frac{m-2}{6}, \\ 6x-(m-2) & \frac{m-2}{6} \leq x \leq \frac{m-1}{6} \\ m-6x & \frac{m-1}{6} \leq x \leq \frac{m}{6} \\ 0 & \frac{m}{6} \leq x \leq 1 \end{cases} \tag{4.3}$$

$$\mu_{7thfunction}(x) = \begin{cases} 0 & 0 \leq x \leq \frac{5}{6}, \\ 6x-5 & \frac{5}{6} \leq x \leq 1 \end{cases} \tag{4.4}$$

The above equations giving the triangular membership functions can be seen in figure 4.9

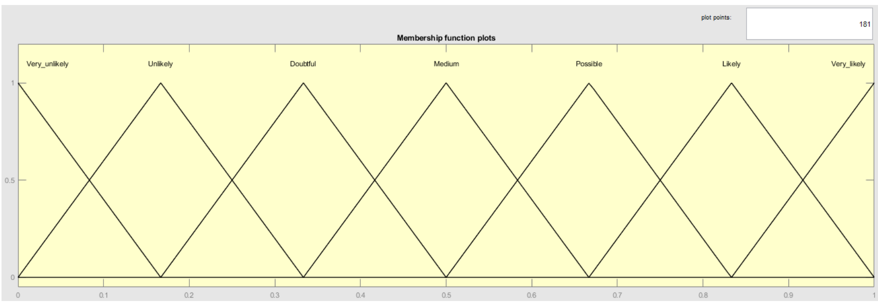


Figure 4.9: Triangular membership functions turning linguistic estimates into fuzzy numbers. Presented using MATLABR2020a, fuzzy toolbox.

Linguistic variable	Fuzzy number (interval)
Very unlikely	[0 0 0.1667]
Unlikely	[0 0.1667 0.3333]
Doubtful	[0.1667 0.3333 0.5]
Medium	[0.3333 0.5 0.6667]
Possible	[0.5 0.6667 0.8333]
Likely	[0.6667 0.8333 1]
Very likely	[0.8333 1 1]

Table 4.1: Table to test captions and labels

4.5.1 Aggregation method

The aggregation and fuzzification in this thesis was implemented by using a consistency aggregation method [60][11] which is a revised methodology of Hsu and Chen's algorithm from 1996 [12] that bypasses the restriction that the opinion of every expert given by a fuzzy number should have a common intersection. Because two or three opinions may not always overlap due to different experiences in the particular field and the total variance of opinions may be surprisingly greater than one would assume, the chosen method was a suitable choice.

The method was executed in the following way:

1. Compute the similarity degree $S(\tilde{A}_i, \tilde{A}_j)$ of the experts E_i and E_j in a pairwise fashion. $\tilde{A}_i$ and $\tilde{A}_j$ are the respective opinions of the experts.

$$S(\tilde{A}_i, \tilde{A}_j) = \begin{cases} EEval_i/EEval_j, & EEval_i \leq EEval_j \\ EEval_j/EEval_i, & EEval_j \leq EEval_i \end{cases} \tag{4.5}$$

   Where the similarity function $S(\tilde{A}_i, \tilde{A}_j)$ will produce a similarity number ∈[0,1]. $\tilde{A}_i$ and $\tilde{A}_j$ are two fuzzy numbers, $EEval_i$ and $EEval_j$ are the expectancy estimation for the opinions $\tilde{A}_i$, $\tilde{A}_j$ respectively. The expectancy estimation for a triangular fuzzy number $\tilde{A} = (a, b, c)$ is:

$$EEval(\tilde{A}) = \frac{1}{2}[E^-(\tilde{A}) + E^+(\tilde{A})] \tag{4.6}$$

   Here, $E^-(\tilde{A}) = (a + b/2)$, $E^+(\tilde{A}) = (b + c/2)$.

   Which are the first and second halves of the triangular functions respectively.

2. Then calculate the average agreement degree $AAD(E_i)$ of every expert's opinion:

$$AAD(E_i) = \frac{1}{n-1}\sum_{j=1}^{n} S(\tilde{A}_i, \tilde{A}_j), i \neq j \tag{4.7}$$

   In the cases where i = j, the similarity degree is 1.

3. Compute the relative agreement degree (RAD) for each expert i:

$$RAD_i = AAD(E_i)/\sum_{i_1}^{n} AAD(E_i) \tag{4.8}$$

4. The aggregation weight W_i given to each expert E_i is a combination of the weighing factor (WF) that was given by their own subjective expertise on any basic event and RAD_i.
$$W_i = \mu * WF(E_i) + (1 - \mu) * RAD_i, \quad i = 1, ..., n \tag{4.9}$$
μ is a slacking variable that influences how much the invidivual's expertise is going to influence the final aggregation weight compared to how similar the expert's opinion is to the others. μ is typically $\in$[0,1].

5. The final aggregated results ($\tilde{AR_i}$) of the expert's opinions is then given as:
$$\tilde{AR_i} = \sum_{i=1}^{n} W_i * \tilde{L}_{ij} \quad i = 1, .., n \tag{4.10}$$
$\tilde{AR_i}$ is the final fuzzy variable contribution result of an expert's opinion $\tilde{L}$ on a particular basic event weighted with the corresponding weight W_i.

4.5.2 Defuzzification

To go from the fuzzy domain back to the crisp domain, a defuzzification method is needed. There are plenty of methods to choose from and the mathematical differences would be another master thesis in of itself and is out of the scope of this work. However, some possible methods are [61][62]:

- BOA (bisector of area)
- CDD (constraint decision defuzzification)
- COA (center of area)
- COG (center of gravity)
- ECOA (extended center of area)
- FCD (fuzzy clustering defuzzification)
- FM (fuzzy mean)
- FOM (first of maximum)
- LOM (last of maximum)
- MeOM (mean of maxima)
- MOM (middle of maximum)

In this paper, center of area (CoA) was chosen because of its simplicity as a means to minimize error from uncertainty in probability data of basic events. Applying the fuzzy arithmetic rules as laid out in chapter 2 to estimate the fuzzy probability score (FPS) with CoA is done as described with a triangular fuzzy number. This way, the fuzzy possibility scores for all MCs are then estimated. For a triangular fuzzy number $\tilde{A} = (a, b, c)$

$$FPS = \frac{\int x * \mu_{\tilde{A}}(x)dx}{\int \mu_{\tilde{A}}(x)dx} = \frac{\int_a^b \frac{x-a}{b-a} x dx + \int_b^c \frac{c-x}{c-b} x dx}{\int_a^b \frac{x-a}{b-a} dx + \int_b^c \frac{c-x}{c-b} dx} = \frac{1}{3}(a+b+c) \quad (4.11)$$

Each basic event still has a fuzzy number given by the FPS method above so there remains a deviation and disagreement between the FPS and a real probability number. A difference between the fuzzy domain and the real domain by how the probability scores manifest. The FPS can be transformed into probability values however by the conversion function laid out by Onisawa [63]:

$$Failure\, Probability\, (FP) = \begin{cases} \frac{1}{10^{\alpha}}, & FPS \neq 0, \\ 0, & FPS = 0, \end{cases} \quad (4.12)$$

Here, $\alpha = (\frac{1}{FPS} - 1)^{\frac{1}{3}} * 2.301$.

Transforming failure probability score from the fuzzy realm into failure probability has been done for every BE with the equations 4.5 - 4.12.

The failure probability of the Top Event is defined according to probability theory as the union of the minimal cut sets (MCs) if an OR-gate is initially used:

$$P_{TopEvent} = P(MC_1 \cup MC_2 \cup MC_3 \cup MC_N) \quad (4.13)$$

where N is the total amount of minimal cut sets.

4.5.3 Fussell-Vesely Importance Measure

An important contribution for a proper reliability and risk assessment is the inclusion of an importance measure such as the Fussell-Vesely or the Birbaum Importance Measure. Hence, to help provide a rigorous and strong support for the failure probability numbers of the fault trees, Fussell-Vesely (F-V) Importance Measure has been applied to rank the most critical basic events and MCs. The method will rank the BEs or MCs according to how much the individual MC contribute to the top event's probability of occurrence as a ratio. Done for every MC will produce a priority list of which MC and hence, which BEs are the most likely to occur and the most critical. The listed priority MCs can be taken further action against to help improve reliability and reduce total risk.

First, the fuzzy numbers of each MC must be converted into a failure probability number using the above method. Next, the F-V Importance Measure is given by:

$$IM_{TE,i}^{F-V} = \frac{P_{MCs}^{i}}{P_{TE}} \tag{4.14}$$

$IM_{TE,i}^{F-V}$ is the contribution ratio to the top event of the ith minimal cut set. In the numerator, P_{MCs}^{i} is the probability of the ith MC and P_{TE} is the probability of the top event.

The motivation for an important measure ranking method is to achieve a primary goal of many risk and reliability analyses: to identify the most important or critical basic events and minimal cut sets in order to open the doors for risk assessment based on- and justified by the importance measure.

Figure 4.10 summarizes the method that has been applied procedurally for this thesis:

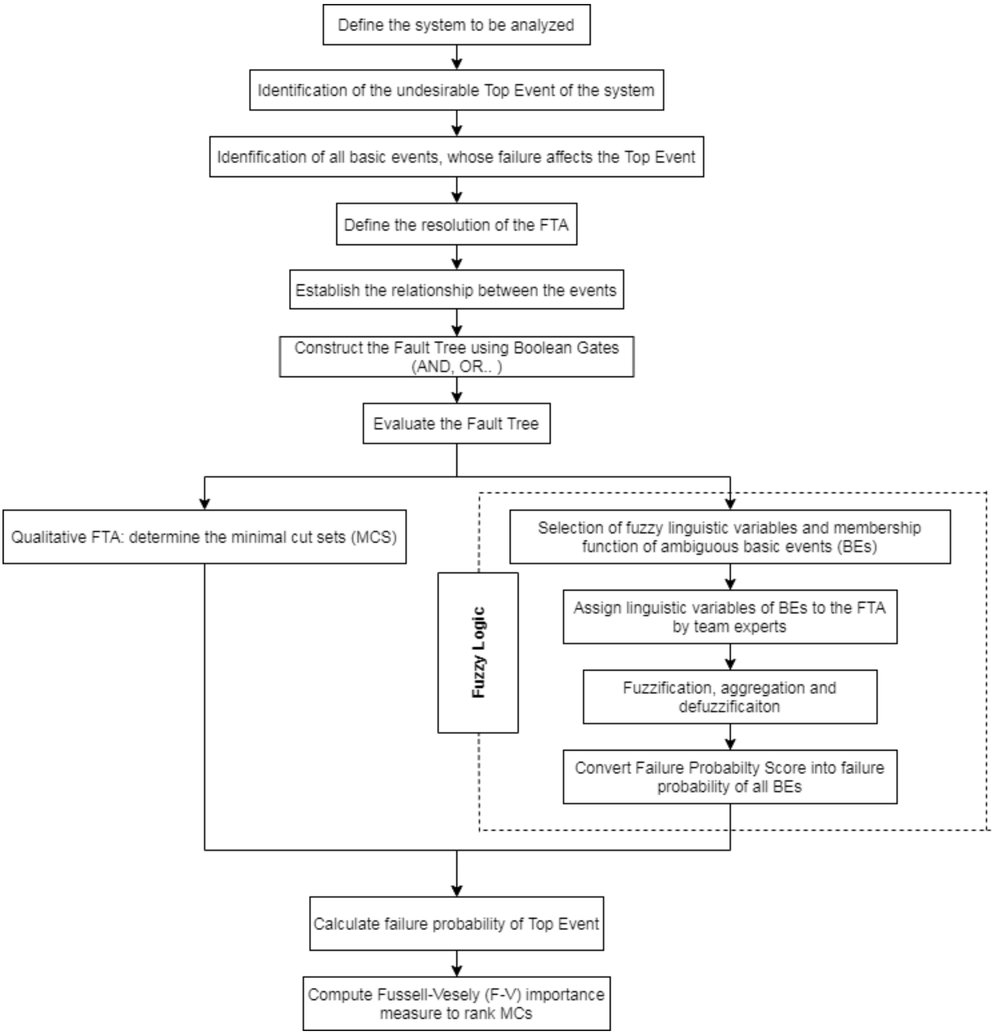


Figure 4.10: Overview of procedure, influenced by [6], [11]

Chapter 5

Work & Results

5.1 Layout

This chapter presents the results of hours with accumulated work that has been put into this thesis. A combination of qualitative and quantitative analytical results is presented as a product of the method used in the previous chapter. The resulting work presented is laid out and categorized by each subclass of the mission that was being analyzed.

While there were a total of five areas of the satellite initially opted for containing the most critical failure modes, the EPS not (re)booted failure tree and accommodating analysis was not pursued. This was because the leeway, control and customization that HYPSO have over the power supply and its use is for the purposes of this paper limited and for the most part is in the hands of the third-party vendor supplying the component. This means nobody at HYPSO possessed the necessary insight into giving an adequate reliability opinion on the basic events associated with that fault tree, and as such, the point became moot.

The chapter will show the assessment done on these failure modes:

- OPU Crashing
- Reaction Wheel Not Speeding Up
- S-Band: Data Not Sent (Gnd. To Payload)
- Ground Station Modulator receiving too noisy or weak signal.

Each category will be presented with their respective analyses done in an orderly manner.

5.2 OPU Crashing/Freezing

5.2.1 Fault Tree

The fault tree that was constructed and reviewed by the team is presented in figure 5.2

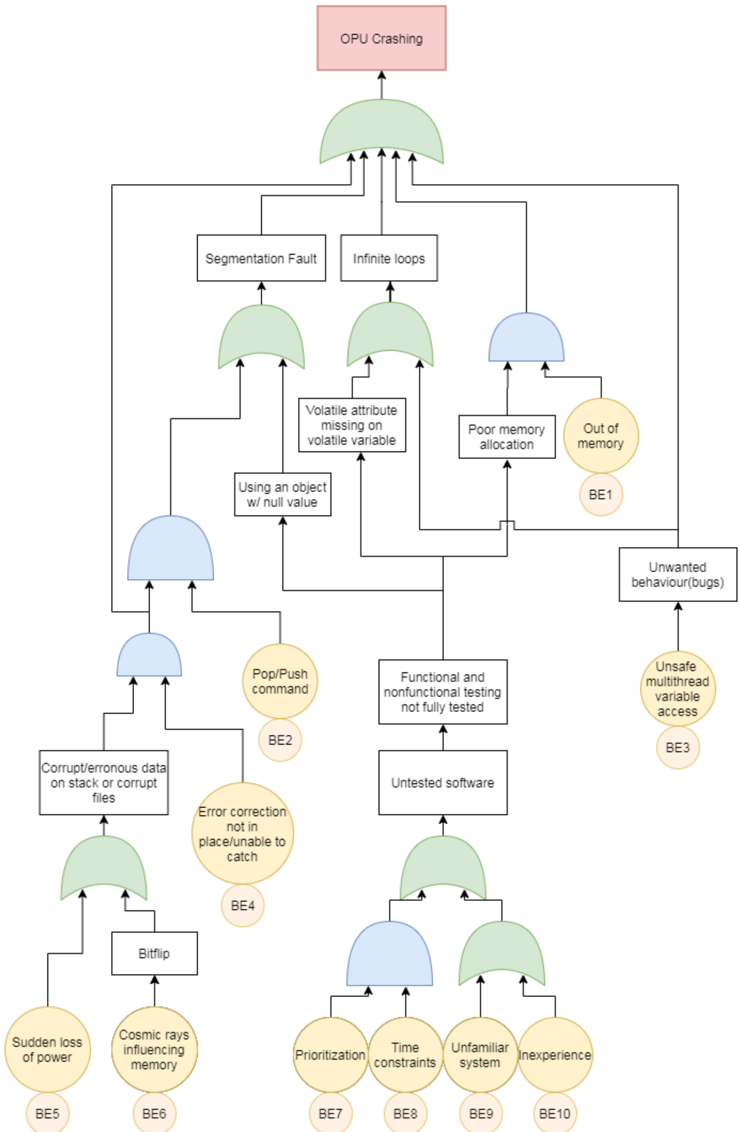


Figure 5.1: Fault Tree of OPU Crashing failure mode, made with draw.io

5.2.2 Estimation Assignments

Because the software team is the largest at HYPSO, there were many more experts providing their opinions to the risk analysis.

Expert i	BE1	BE2	BE3	BE4	BE5	BE6	BE7	BE8	BE9	BE10
Expert 1	L	N/A	P	P	N/A	N/A	P	VL	L	L
Expert 2	M	N/A	D	L	U	N/A	P	P	P	P
Expert 3	U	N/A	N/A	N/A	VL	U	L	VL	L	P
Expert 4	N/A	N/A	P	P	M	D	L	P	L	L
Expert 5	P	N/A	VU	N/A	D	N/A	L	L	L	L
Expert 6	P	N/A	L	VL	D	M	VL	L	L	L
Expert 7	L	N/A	M	VL	VL	N/A	M	L	L	L

Table 5.1: OPU linguistic assignments

Some of the experts assigned Not Applicable element to some of the basic events. This was intentional from the author's part. Due to the total number of available people to gather estimations from, it was decided that any expert with a self-proclaimed expertise rating of both Novice and Developing should be excluded in participating in the total failure probability for that particular corresponding basic event as a means to improve accuracy. BE2 was identified to be an event which would occur all the time, so the team members opinions were removed and the occurrence probability for this event was set to VL, very likely.

The remaining four expertise linguistic variables *Intermediate*, *Proficient*, *Advanced* and *Expert* had their weight scoring adjusted to the following values:

Variable	Intermediate	Proficient	Advanced	Expert
Weight	0.10	0.20	0.30	0.40

5.2.3 Aggregation, Defuzzification and Failure Probability

BEs	Aggregated fuzzy number	CoA Defuzzification	FP of BEs	Ranking
BE1	0.54 0.746 0.947	0.746	0.024	6
BE2	0.833 1 1	0.944	0.127	1
BE3	0.441 0.606 0.789	0.612	0.0105	8
BE4	0.567 0.709 0.792	0.689	0.017	7
BE5	0.415 0.585 0.695	0.565	0.00780	9
BE6	0.146 0.271 0.396	0.271	0.000633	10
BE7	0.602 0.769 0.913	0.761	0.027	5
BE8	0.668 0.835 0.955	0.819	0.040	2
BE9	0.646 0.813 0.979	0.813	0.038	3
BE10	0.622 0.789 0.95	0.789	0.033	4

Table 5.2: OPU table of failure probabilities

The failure probability of the top event can be identified as:
$P_{TE} = BE4 * (BE5 + BE6) + (BE4 * (BE5 + BE6)) * BE2 + ((BE7 * BE8) + Be9 + BE10) + ((BE7 * BE8) + BE9 + BE10) * BE1 + BE3$

If we assign $H = ((BE7 * BE8) + BE9 + BE10)$,

and $G = BE4 * (BE5 + BE6)$, then

$P_{TE} = G + G * BE2 + H + H * BE1 + BE3$

Boolean rules of algebra states that: $A + A * B = A$

Hence, the reduced expression becomes: $P_{TE} = G + H + BE3$,
and we have identified our minimal cut sets $\{G\}, \{H\}, \{BE3\}$. G and H can be further reduced to $G_{1,2} = \{BE4BE5, BE4BE6\}$ and $H_{1,2,3} = \{BE7BE8, BE9, BE10\}$

This can be easier seen with the reduced version of the fault tree:

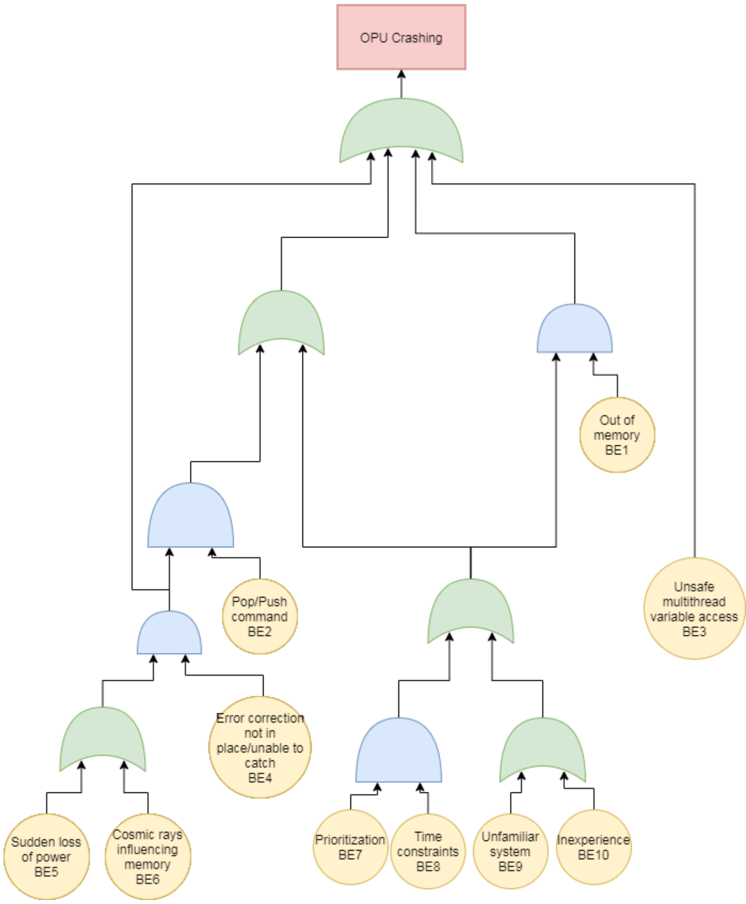


Figure 5.2: Reduced fault tree, intermediate events are removed.

MCs	FP of MCs	Fussell-Vesely IM	MCs Ranking
G_{tot}	1.455E-04	0.17%	3
H_{tot}	7.310E-02	87.21%	1
BE3	1.057E-02	12.62%	2

P(Top Event) = 8.382E-02

Table 5.3: OPU table of failure probabilities

5.3 Reaction Wheel Not Speeding Up

5.3.1 Fault Tree

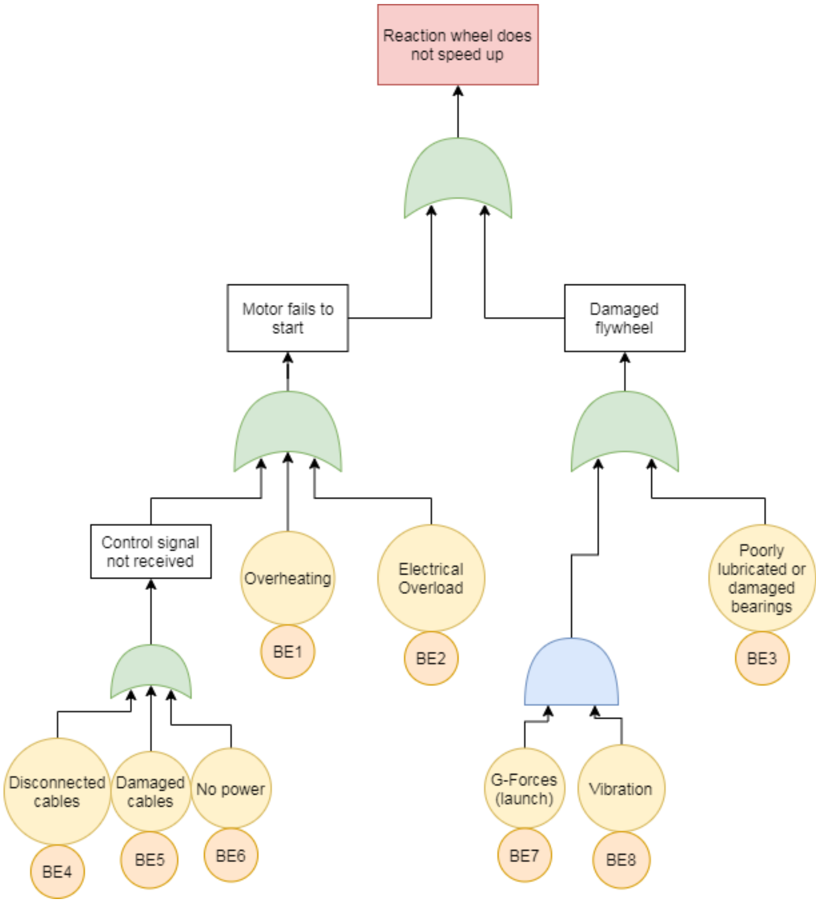


Figure 5.3: Fault Tree of reaction wheel not acquiring enough rotational speed, made with draw.io

5.3.2 Estimation Assignments

Expert i	BE1	BE2	BE3	BE4	BE5	BE6	BE7	BE8
Expert 1	U	D	D	U	D	D	VU	U
Expert 2	U	U	VU	U	D	U	VU	D

Table 5.4: ADCS linguistic assignments

5.3.3 Aggregation, Defuzzification and Failure Probability

Basic Events	Aggregated fuzzy number	CoA Defuzzification	FP of Basic Events
BE1	0 0.071 0.143	0.071	3.8E-6
BE2	0.045 0.116 0.187	0.116	2.9E-5
BE3	0.045 0.089 0.161	0.098	1.5E-5
BE4	0 0.071 0.143	0.071	3.8E-6
BE5	0.071 0.143 0.214	0.143	6.5E-5
BE6	0.045 0.116 0.187	0.116	2.9E-5
BE7	0 0 0.077	0.026	1.9E-8
BE8	0.033 0.116 0.199	0.116	2.9E-5

Table 5.5: Reaction wheel table of failure probabilities

The probability of the top event is the union of the following basic events which also consists of the MCs for this fault tree:

$$P_{TE} = BE1 + BE2 + BE3 + BE4 + BE5 + BE6 + BE7 * BE8$$

$$P_{TE} = BE1 \cup BE2 \cup BE3 \cup BE4 \cup BE5 \cup BE6 \cup BE7 \cap BE8$$

MCs	FP of MCs	Fussell-Vesely IM	MCs Ranking
BE1	3.89E-06	2.62%	5
BE2	2.97E-05	20.04%	2
BE3	1.52E-05	10.25%	4
BE4	3.89E-06	2.62%	6
BE5	6.59E-05	44.43%	1
BE6	2.97E-05	20.04%	3
BE7BE8	5.66E-13	0.00..%	7

P(Top Event) = 1.48E-04

Table 5.6: Reaction wheel not speeding up table of failure probabilities

5.4 S-Band: Data Not Sent (Gnd. To Payload)

5.4.1 Fault Tree

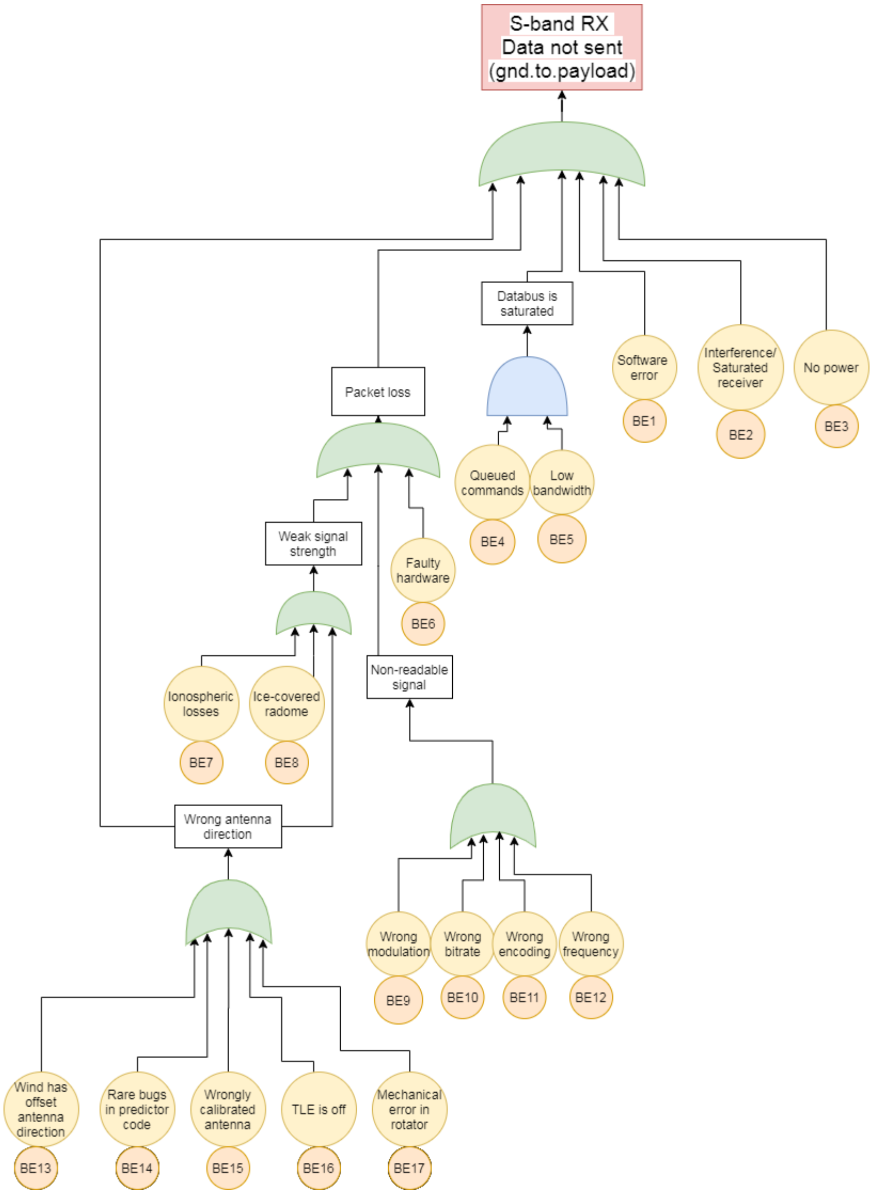


Figure 5.4: Fault Tree of data not getting send through the S-band, ground to payload. Made with draw.io

5.4.2 Estimation Assignments

Basic Events	Expert 1	Expert 2	Expert 3
BE1	P	U	D
BE2	L	M	P
BE3	P	P	D
BE4	M	D	M
BE5	U	U	P
BE6	D	P	D
BE7	VU	P	D
BE8	D	P	L
BE9	U	VU	D
BE10	U	VU	D
BE11	D	VU	D
BE12	U	VU	D
BE13	D	U	P
BE14	M	VU	D
BE15	VU	L	D
BE16	L	L	P
BE17	D	P	D

Table 5.7: S-Band linguistic assignments

5.4.3 Aggregation, Defuzzification and Failure Probability

Basic Events	Aggregated fuzzy number	CoA Defuzzification	FP of Basic Events
BE1	0.188 0.315 0.442	0.315	1.04E-03
BE2	0.394 0.521 0.648	0.521	5.78E-03
BE3	0.323 0.450 0.577	0.450	3.48E-03
BE4	0.218 0.345 0.472	0.345	1.42E-03
BE5	0.065 0.196 0.327	0.196	2.09E-04
BE6	0.216 0.351 0.486	0.351	1.50E-03
BE7	0.212 0.315 0.454	0.327	1.18E-03
BE8	0.338 0.469 0.600	0.469	4.01E-03
BE9	0.038 0.147 0.294	0.159	9.88E-05
BE10	0.038 0.147 0.294	0.159	9.88E-05
BE11	0.107 0.213 0.348	0.223	3.24E-04
BE12	0.038 0.135 0.270	0.147	7.42E-05
BE13	0.156 0.291 0.426	0.291	8.00E-04
BE14	0.161 0.262 0.389	0.271	6.27E-04
BE15	0.224 0.315 0.442	0.327	1.18E-03
BE16	0.506 0.641 0.776	0.641	1.27E-02
BE17	0.216 0.351 0.486	0.351	1.50E-03

Table 5.8: S-Band table of failure probabilities

The probability of the top event can be examined to be a sum of:

$$P_{TE} = BE1 + BE2 + BE3 + BE4 * BE5 + BE6 + BE7 + BE8 + BE9 + BE10 + BE11 + BE12 + BE13 + BE14 + BE15 + BE16 + BE17$$

MCs	FP of MCs	Fussell-Vesely IM	MCs Ranking
BE1	1.04E-03	3.03%	9
BE2	5.78E-03	16.81%	2
BE3	3.48E-03	10.11%	4
BE4BE5	2.96E-07	0.000..%	16
BE6	1.50E-03	4.37%	5
BE7	1.18E-03	3.44%	7
BE8	4.01E-03	11.66%	3
BE9	9.88E-05	0.29%	13
BE10	9.88E-05	0.29%	14
BE11	3.24E-04	0.94%	12
BE12	7.42E-05	0.22%	15
BE13	8.00E-04	2.33%	10
BE14	6.27E-04	1.82%	11
BE15	1.18E-03	3.43%	8
BE16	1.27E-02	36.90%	1
BE17	1.50E-03	4.37%	6

P(Top Event) = 3.29E-02

Table 5.9: S-Band: Data not sent table of failure probabilities

5.5 Ground Station Receiving Too Noisy Or Weak Signal

5.5.1 Fault Tree

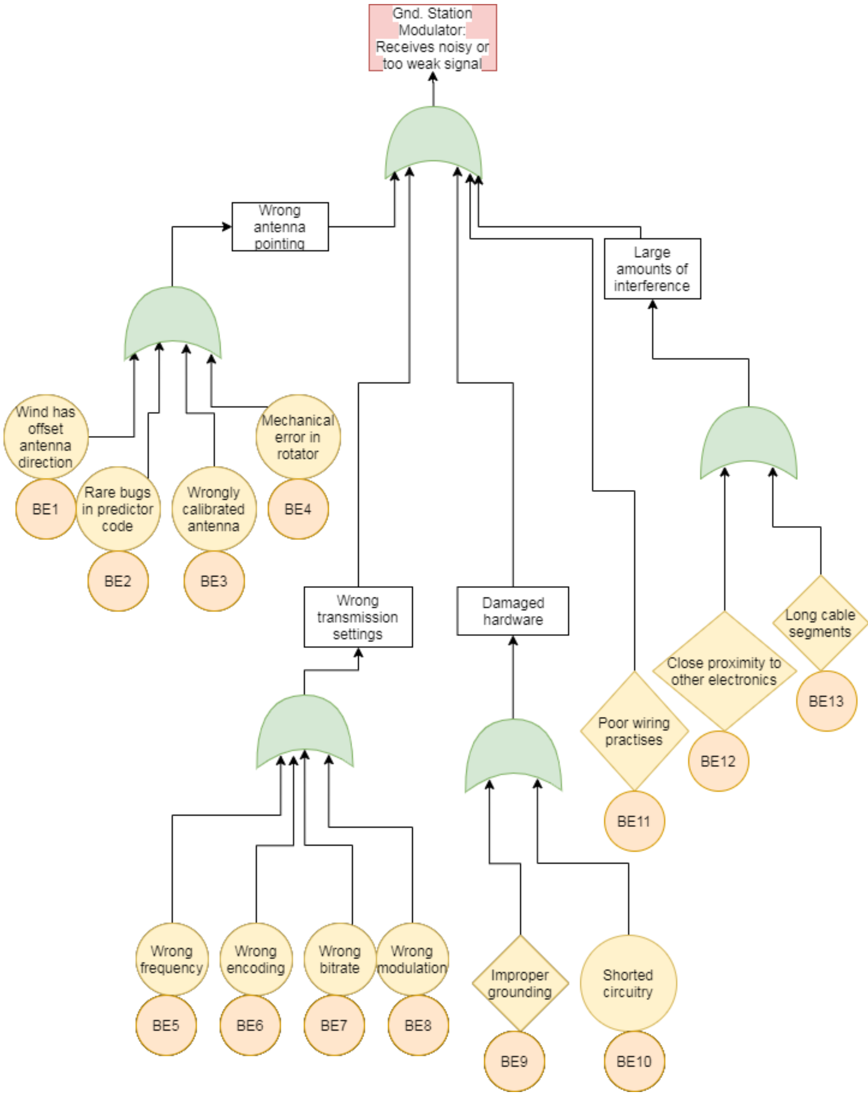


Figure 5.5: Fault Tree of data not getting send through the S-band, ground to payload. Made with draw.io

5.5.2 Estimation Assignments

Basic Events	Expert 1	Expert 2	Expert 3
BE1	U	D	P
BE2	M	M	U
BE3	M	VU	U
BE4	D	D	D
BE5	P	U	VU
BE6	U	D	U
BE7	P	U	D
BE8	D	U	D
BE9	M	U	U
BE10	P	VU	D
BE11	P	U	U
BE12	L	U	D
BE13	M	U	D

Table 5.10: Ground station linguistic assignments

5.5.3 Aggregation, Defuzzification and Failure Probability

Basic Events	Aggregated fuzzy number	CoA Defuzzification	FP of Basic Events
BE1	0.156 0.283 0.410	0.283	7.29E-04
BE2	0.189 0.308 0.427	0.308	9.68E-04
BE3	0.056 0.128 0.245	0.143	6.55E-05
BE4	0.123 0.246 0.369	0.246	4.55E-04
BE5	0.105 0.201 0.332	0.213	2.76E-04
BE6	0.052 0.183 0.313	0.183	1.61E-04
BE7	0.127 0.248 0.369	0.248	4.67E-04
BE8	0.086 0.217 0.348	0.217	2.97E-04
BE9	0.050 0.169 0.288	0.169	1.23E-04
BE10	0.133 0.222 0.353	0.236	3.95E-04
BE11	0.082 0.213 0.344	0.213	2.78E-04
BE12	0.150 0.277 0.404	0.277	6.80E-04
BE13	0.097 0.224 0.351	0.224	3.31E-04

Table 5.11: S-Band table of failure probabilities

The nature of this fault tree will result in number of MCs equal to the number of basic events as they are all connected by the union of events. So the probability of the top event will be:

$P_{TE} = BE1 + BE2 + BE3 + BE4 * BE5 + BE6 + BE7 + BE8 + BE9 + BE10 + BE11 + BE12 + BE13$

MCs	FP of MCs	Fussell-Vesely IM	MCs Ranking
BE1	7.29E-04	13.95%	2
BE2	9.68E-04	18.53%	1
BE3	6.55E-05	1.25%	13
BE4	4.55E-04	8.70%	5
BE5	2.76E-04	5.28%	10
BE6	1.61E-04	3.08%	11
BE7	4.67E-04	8.94%	4
BE8	2.97E-04	5.68%	8
BE9	1.23E-0	2.35%	12
BE10	3.95E-04	7.56%	6
BE11	2.78E-04	5.32%	9
BE12	3.31E-04	13.01%	3
BE13	3.03E-02	6.33%	7

P(Top Event) = 5.23E-03

Table 5.12: Ground station receiving poor signals table of failure probabilities

With table 5.12, this summarizes the results of the fuzzy fault tree analyses. One may see that the basic event "Rare bugs in predictor code" or predictor related unforeseen events takes the top spot according to the ranking. While still deemed unlikely, the cause of an external element such as wind affecting the antenna is ranked 2nd. on this list, perhaps a perk of being stationed in Trondheim.

The failure probabilities of the MCs for this category are identical to the failure probabilities of the individual basic events because of the fault tree's layout.

Chapter 6

Discussion

6.1 Interpretation

The findings are first provided with fault tree diagrams which show the relationships for each category between the specific events, the intermediate events, and the top event. These terms were introduced in Chapter 2.2.2, and are different ways to easier represent what is going on in the trees. The results shows that diamond-shaped basic events have been sparingly used. The reason is that they symbolize a basic event which either has no further development information available at the current time or that it is futile or meaningless looking further into them. In the future, the circular basic events can and should be examined further if they need to develop into branches of their own because of new acquired data. Having said that, the principles behind the interpretation of the various symbols for the fault trees were used slightly differently in different literature.

While fault trees offer a qualitative overview by minimal cut sets and provide insight into the cause and effect, the quantitative domain is presented with the probability of failure of each specific event. In addition, the tables show the aggregated fuzzy numbers consisting of three parts a, b, c (each position in a triangular function), the failure probabilities of the MCs, the importance measure ranking and finally, the top event probability.

6.2 On the Method

The Similarity Aggregation Method (SAM) used as a base for this approach combines triangular fuzzy numbers from a selection of experts' opinions into a single combined fuzzy number representing their combined estimations. How well the consensus between the experts' opinions measure was given by the equation

$$S(\tilde{A}_i, \tilde{A}_j) = \begin{cases} EEval_i/EEval_j, & EEval_i \leq EEval_j \\ EEval_j/EEval_i, & EEval_j \leq EEval_i \end{cases} \tag{6.1}$$

Where the similarity function $S(\tilde{A}_i, \tilde{A}_j)$ will produce a similarity number ∈[0,1].
The method, which was developed by Hsu and Chen added the premise that two triangular fuzzy numbers must have intersections or common parts, otherwise the method cannot be applied to calculate the aggregated opinions [12]. Although this assumption is still possible to achieve and comply to under certain premises, it places a greater constraint on the decision makers which is not productive and hinders the experts to fully express their true preference and estimations. Weng's adjusted method relaxes this assumption and does not force the fuzzy numbers estimated by the experts to have a common intersecting part, but still biases the expert's opinions towards the construction of the fuzzy numbers. Hsu establishes this requirement under the belief that consensus means to have complete agreement without objection. But in fact, this resembles an ideal situation which is rarely seen in real life. So in practise, the evaluations given by the experts will often contain fuzzy numbers without any intersecting parts.

This was a clear benefit when deciding on which method to go forward with. Hsu's original method proposes the use of the Delphi Method in the case where the expert's opinions initially have no intersection, in order to reach one. The Delphi method involves questionnaires sent to the experts as well, but includes re-assessing and re-sending forms back to the decision makers, which would be too time consuming for the scope of this thesis as several fault trees and a number of people are involved. This paper's chosen method by Weng deviates from the one by Hsu early. The first step of both procedures is to compute the similarity degrees. The one proposed by Weng is again shown in equation 6.1. The original method generates the similarity numbers by the proportion of the consistent area i.e $\int_x min\{\mu_{\tilde{R}_i}(x), \mu_{\tilde{R}_j}(x)\}dx$ divided to the total area $\int_x max\{\mu_{\tilde{R}_i}(x), \mu_{\tilde{R}_j}(x)\}dx$. When two experts' are identical, their estimates are consistent and the agreement degree

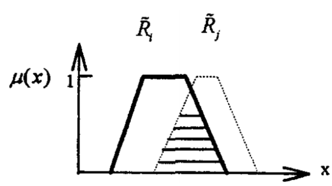


Figure 6.1: The intersection of two experts' opinions using trapezoidal functions. From Hsu [12]

obtained between them is equal to one. And in the case of two completely different estimates, we will get zero degree of agreement. In the way this paper has loud out the linguistic assigned variables, that means if Expert 1 evaluates a particular basic event to *Very Unlikely*, and Expert 2 evaluates the same event to *Doubtful*, there is zero overlap. And if this was brought forward to calculate the average agreement degree (AAD):

$$AAD(E_i) = \frac{1}{n-1}\sum_{j=1}^{n} S(\tilde{A}_i, \tilde{A}_j), i \neq j \tag{6.2}$$

We could end up with continuously dividing 0 by the total amount of expert's evaluated which would make little sense going forward. The method used in this paper allows both intersecting and non-intersecting opinions.

The aggregated final weight for each expert was determined by

$$W_i = \mu * WF(E_i) + (1-\mu) * RAD_i, \quad i = 1, ..., n \tag{6.3}$$

where μ is a slacking variable that influences how much the invidivual's expertise is going to influence the final aggregation weight compared to how similar the expert's opinion is to the others. Hsu and Weng's methods both state that the slacking variable μ can be found through either the Delphi method or by analytical hierarchy process [64]. μ allows an optimization of the two contributions to the final aggregated numbers. When μ is >0.5, there is an expressed preference towards the decision-making experts and their background; and when μ is < 0.5 there is a bias towards the common agreement between the experts rather than their background. When μ is 0.5, the risk decision making is neutral. For most of the basic events across all fault trees analyzed in this paper, the slacking variable was kept at 0.5, providing an equal weighting contribution from both expertise and relative agreement except for two cases:
1) For a few basic events in the OPU Crashing fault tree which is elaborated on in the next section and in
2) for all the computations done in the quantitative part of the ADCS fault tree: Reaction Wheel Not Speeding Up.

This change was carried out because there were only two decision making participants from that subgroup of the satellite, so the slacking variable was set to $\mu = 0.75$, giving a 75 % contribution to the expertise of the individuals and less emphasis $\mu = 0.25$ was given on their agreements. This was not a decision backed up by any particular research, but a reasoned decision on the author's part. The reason being that because there were only two experts giving estimates, a higher weighting on their background should be given as opposed to when there are many experts giving their decisions as their relative total agreement is more likely to overlap strongly with the actual probability scores. With that being said, the chosen method was simple and easy to work with. Triangular functions was used instead of the proposed trapezoidal, and while it is true they reflect a more precise estimation compared to the ambiguity allowance of the trapezoids flat top interval, the total leeway of having a total of seven fuzzy triangular/linguistic variables to choose from was a intentional form of compensation.

6.2.1 Alternative Methods

There are several available methods on aggregating information which was was briefly touched upon in Chapter 4. A potential candidate that was considered is the Dempster-Shafer method of aggregating risks. A useful aspect to this method is that it allows for the allocation of a probability to sets or intervals. Dempster-Shafer needs no assumption on the probability of the particular constituents of these sets or intervals, and is why it has some potential usefulness in estimating and evaluating risks in general engineering applications. Specifically in cases where the nature of the situation makes it impossible to obtain exact measurements from tests and experiments, or when data is obtained in the same way as described above, with linguistic estimates from expert elicitation. The combination rule used in classic Dempster-Shafer can produce acceptable results in most cases as described by Li [56], but it has also received great criticism for how it handles conflict between multiple input sources. While a potential candidate if given an in-depth evaluation, the full procedure was deemed somewhat more complex to get in and start off with.

There is no shortage of fuzzy aggregation methods. But in the light of no prior experience conducting a fuzzy fault tree analysis based on linguistic terms, and no branch-specific software used in aiding the quantitative fault tree calculations as the computations done in this paper were all done manually, the computationally easier choice was decided upon with the extra free benefits it gave.

6.3 On the Results

What do the results mean and how do they contribute to HYPSO?

First and foremost: from each of the pre-selected top events, fault trees were constructed in order to showcase how the different top events can be caused by the underlying nodes and how they relate to each other. When a number of basic events were identified as root causes and reviewed with their respective teams, and the experts' evaluations gathered from the questionnaires, tables could be generated to show the quantitative analysis next. Each of the selected sub-classes (top events) generated three tables: One showcasing how the different team members (referred to as experts) estimated the likelihood of a particular basic event happening, the second table shows the combined (aggregated) fuzzy opinion of the experts, the center of area defuzzification number used in computing the failure probabilities (see Appendix B) and the failure probabilities of the basic events themselves.

5.3.2 Estimation assignments

Expert i	BE1	BE2	BE3	BE4	BE5	BE6	BE7	BE8
Expert 1	U	D	D	U	D	D	VU	U
Expert 2	U	U	VU	U	D	U	VU	D

Table 5.4: ADCS linguistic assignments

5.3.3 Aggregation, defuzzification and failure probability

Basic Events	Aggregated fuzzy number	CoA Defuzzification	FP of Basic Events
BE1	0 0.071 0.143	0.071	3.8E-6
BE2	0.045 0.116 0.187	0.116	2.9E-5

Figure 6.2: From ADCS: Reaction Wheel Not Speeding Up analysis

Taking the ADCS as an example where the chosen top event is "Reaction Wheel Not Speeding up", we can see the variance in the experts' opinions on the different basic events, which are labeled and found in the fault tree. The ADCS group had two experts evaluating the tree, which is a possible drawback for this particular assessment. However, their likelihood estimations had little variance across the BE's as shown above. This is positive, as the closer the opinions are in terms of overlap, the more likely they will reflect the actual nature of the probabilities of these events.

Finally, the third table for every section shows the minimal cut sets, the failure probabilities of these, their percentage contribution to the top event given by the F-V Importance Measure and ranking of the most critical MCs, from most to least likely. Because the top event will occur if one of the minimal cut sets occurs, working with, and listing the resulting MCs for the fault trees is a basic and expected form of qualitative data any FTA should contain. Identifying the minimal cut sets let us pay attention to what is of importance in a fault trees and which belonging basic event should be paid attention to.

MCs	FP of MCs	Fussell-Vesely IM	MCs Ranking
BE1	3.89E-06	2.62%	5
BE2	2.97E-05	20.04%	2
BE3	1.52E-05	10.25%	4
BE4	3.89E-06	2.62%	6
BE5	6.59E-05	44.43%	1
BE6	2.97E-05	20.04%	3
BE7BE8	5.66E-13	0.00..%	7

P(Top Event) = 1.48E-04

Figure 6.3: From Chapter 5: ADCS's Reaction Wheel Not Speeding Up analysis.

Because the probability of the top event (denoted at the bottom of figure 6.3) is a sum of the minimal cut sets, these MCs are important to examine. By looking at the F-V IM column, it is easily seen which basic event(s) contribute the most to the top event's overall probability: Basic event 5, followed by BE2, BE6, BE3, and BE1 as the top five contenders in decreasing order.

Basic event 5 is described in the fault tree diagram as "Damaged cables", and both experts evaluated this event to "Doubtful", making it the highest ranked and most influential contributor to the top event at 44.43% of the MCs listed. Yet, the likelihood of this event occurring is still at 0.0000659 which is a reasonable low number. By listing the most vulnerable MCs and inspecting these, one may easier start implementing the right mitigation strategies where they are needed in order to best increase reliability. This is an additional advantage of conducting a FTA.

The top event's probability for the ADCS' fault tree was found to be 0.000148 according to the finished analysis. Compared to another failure mode inspected, such as "OPU Crashing" which had a top event probability estimated to be 0.08382, we can see that it is far more likely that the OPU will crash or freeze at some point than the reaction wheel not reaching its setpoint speed. With that being said, time is not directly taken into account for the respective basic events. The OPU will be turned off both during eclipse and when the solar panels harvest energy. This means that some of the basic events leading to the OPU crashing or freezing will not be actively contributing in certain periods of the orbit and the lifetime of the mission. Indeed, this is food for thought and could be part of an even more extensive reliability analysis.

Do the results make sense?

Inspecting the OPU Crashing analysis tables, and examining the Fussell-Vesely Importance Measure in table 5.3. One can observe that the MC contributing most to the top event's failure probability is MC H, which consists of the four basic events *Prioritization*, *Time constraints*, *Unfamiliar system* and *Inexperience*. These minimal cut sets make up 87.21 % of the top event's likelihood of happening. The weighting factor was removed when computing the probability for these four particular events. Recall from Chapter 4 than the final aggregated weighing score for any linguistic variable and opinion was a sum of the individual's own expertise and how closely his or hers opinion was that of the peers:

$$W_i = \mu * WF(E_i) + (1 - \mu) * RAD_i, \quad i = 1, ..., n$$

It was assumed that for these four basic events, everyone stood on equal ground when giving their estimation of how likely these could occur and the μ relaxation factor was set to 0, thus the final weight and aggregation for the experts' estimation on these were solely based on each individual estimation and their relative agreements. Looking at the tables 5.1, 5.2 and 5.3, we can deduce from this analysis that the most likely cause of failure justified by the the F-V IM is going to be caused by human error and the unfortunate events that software was not properly tested due to one of the four basic events BE7, BE8, BE9 or BE10.

This resonates well with the software team's own briefing on what could go wrong leading to the top event. The most common answer I received through the construction of this tree in particular was that "Everything could go wrong as long as we don't test it. If we won't catch it during testing, that's going to be a possible culprit".
Intuitively this makes sense for the software team. Humans are prone to error and software needs to be thoroughly tested in order to function completely as intended according to specifications and design. However, there is no guarantee to catch all possible bugs and errors, less so the larger and more complex the system.

In so far the way the fault trees are designed, how the wording is chosen for the various events, the size of the trees and the available expertise working with HYPSO, the probability numbers assigned to the events reflect the attention to what should not go wrong, which basic events are on the safer side and where the focus for these particular failure modes should be diverted.

Comparing the most critical MCs from the S-band RX Data Not Sent and the Ground Station Receiving Weak/Noisy Signal, the most likely events given by their F-V IM's are both related to antenna direction. Respectively, that the TLE (two-line element set) computing is off and rare bugs in predictor code. Both trees and events zoning in about the same area of communication while not comprised of the exact same experts. This helps support the notion that antenna direction and tracking the satellite is the most anticipated aspects of the communication subgroups with respect to likelihood and not necessarily severity.

6.3.1 Comparison With Previous Work

Recall from Chapter 2 that the FMECA contains Risk Priority Numbers which was the product of occurence, severity and detectability (= O x S x D). Figure 4.1 shows a snippet from various failure modes, their proposed causes, and the RPN numbers. Comparing the FMECA's occurrence ratings which was restricted to the interval of [1, 5] with the top events probability numbers derived from this paper, the following is observed:

Failure Mode	**FMECA, "O"**	**Fuzzy FTA**
OPU crashing	3	0.0838
Reaction wheels does not speed up	1	0.000148
S-Band RX: Data not sent	2	0.0329
Gnd. Station modulator receives too weak/noisy signal	1	0.00523

Table 6.1: FMECA's Occurence rating compared with the fuzzy fault tree analysis

Because the RPN scores were reviewed and assigned by a few of the team members before the construction of this thesis, and because the failure modes that was chosen to be evaluated came from the FMECA, it is natural to compare the occurrence (likelihood) rating given to the failure modes beforehand with the fuzzy approach results obtained from the above method.

As seen from table 6.1, the coarse resolution values of the Occurrence seems to be consistent with the failure probabilities found by the fuzzy approach for the same failures modes in terms of ranking. OPU Crashing was designated the highest Occurrence number from the FMECA with a rating of '3' and also came out to be the highest probability number found by the fuzzy FTA. Similarly, the two lowest designated failure mode ratings equivalently produced the two lowest fuzzy-estimated likelihood numbers.

From the above accumulated discussion on the findings, it's safe to say that the probability numbers found by the fuzzy approach makes sense. How the results and the expert's opinions compare with future data measurements remains to be seen.

Langer's CubeSat reliability analysis [65] becomes relevant when discussing the cause and effect of different failure modes as his work is one of very few addressing CubeSat reliability specifically. Drawing from a CubeSat failure database built in 2014 and finished in 2015, it consists of 178 individual CubeSat missions up to 30/06/2014 with the aim of uncovering failure and root causes of all CubeSats launched up to that date. The following six subsystems were identified as the most significant risk contributors:

- Electrical Power System (EPS)
- On-Board Computer (OBC)
- Communication System, incl. antennas (COM)
- Attitude Determination and Control System (ADCS)
- Payload (PL) Structure & Deployables (other than antennas) (STR)
- Unknown

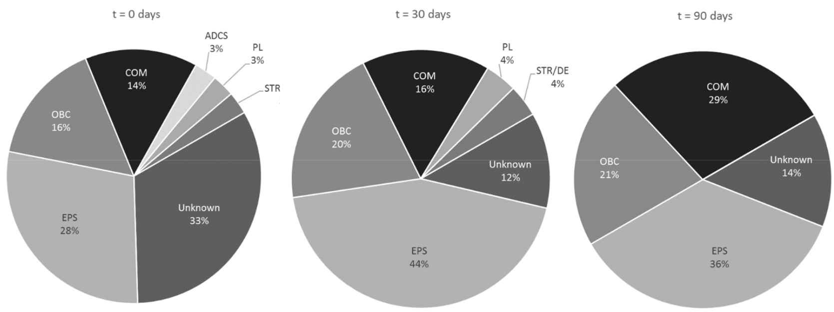


Figure 6.4: CubeSat failure causes at 0 days, 30 days and 90 days after ejection. From [10].

This information can prove valuable if conducting post-risk assessments of HYPSO or doing risk analysis and failure assessments on future projects made in the SmallSat Lab. Narrowing down the risk focus to specific areas of the satellite for which to apply mitigation strategies in order to increase reliability will help avoid the far too common Dead-On-Arrival (DOA) cases and infant mortality, which are the leading causes of CubeSat projects never reaching their minimum lifetime success goals [65]. How these findings will relate to HYPSO's potential demise in the future is an interesting path to investigate when that time comes.

6.4 Author's Thoughts

A vast literature analysis done on the construction of fault trees and scientific research where fault trees are used often have the common denominator that they analyse one single system, a single top event and hence, a single fault tree at a time. The approach used in this thesis where several different systems and fault trees were analyzed in parallel was a daunting and somewhat overwhelming task for a single student doing risk analysis. Doing it in this way had pros and cons.

The benefit from attacking multiple systems at a time is that it could give the SmallSat Lab a quicker and larger database foundation on risk management. Providing additional and accumulating information and data for designing and constructing better and more reliable systems in the future. No doubt, adding to a larger database of past work including bachelor- master- and ph.d. theses is an invaluable asset to future projects. Hopefully, the background, method and results from this thesis could add to the overall growth and success of the SmallSat Lab's future missions.

A discussable drawback from dealing with multiple fault trees at a time could be at the cost of each tree's complexity and level of depth. While I tried with the best of my abilities to double-check and reassess every assumption made with the teams, the time that was spent on multiple fault trees could have been spent on the focus of a single tree and a single failure mode, developing that further depth-wise. The opening word *discussable* is used with full intention for this paragraph. HYPSO is the first satellite made in the SmallSat Lab and data on historic satellite projects are then limited to what is available elsewhere.

Another difficulty that quickly came to attention when constructing the fault trees were the lack of deep insight into each subsystem of the satellite. As the creator of this analysis, my progress was often halted and slowed down due to lacking the area-specific knowledge to the same extent that my fellow satellite colleagues possess. This is to be expected of course, but deserves a mention. Because the team members had their hands full with tasks of their own and could not directly carry out constructing the respective trees for me, they provided assistance through answering all the questions that I had in a thorough manner. Deriving the different initial intermediate events below the first OR-gate was the easier part of constructing the fault trees. Second or third level causes and child nodes below these became increasingly harder to attach new causes to. Having assistance from a respective field expert is then highly recommended or even required. Literature review and research is the backbone of constructing these trees, but frequent evaluation from the team is needed. The work on the fault trees undoubtedly led me into gaining overall knowledge about the different subsystems and how a small satellite project functions in greater detail.

Chapter 7

Conclusion and Recommendations

7.1 Final Conclusion

Reflecting over the fault trees made and the chosen method that was approached in Chapter 4, it's acknowledged that the combination of qualitative and quantitative results were obtained for different failure modes belonging to different sub-classes of the satellite. Additionally, the importance measures of the minimal cut sets of each tree was assessed to gauge the contributions each MCs or BEs had to the fault tree's top event. From the fuzzy fault tree analysis work carried out in this thesis, a couple of conclusions can be made:

- The cause-effect hierarchy given by the fault trees of the individual events and their respective probability numbers will influence the top events differently depending on the structures of the fault trees. There are also uncertainties in the results from several sources. One of them is the fact that some systems are online and actively operating only fractions of the time compared to others. This is not directly accounted for.

- Different hazards and basic events have different relative contributions to the failure modes. The importance measure (Fussell-Vesely) of each basic event were computed to characterize and represent the various contributions to the top events explicitly. For the OPU Crashing tree, human errors had the highest importance. The ADCS tree revealed power-related causes as most important, with damaged cables at no.1 followed by electric overload and loss of power. The S-Band: Data Not Sent tables showed that the TLE deviating off is biggest contributor, then interference or a saturated receiver on the satellites part. Finally, wrong antenna pointing direction caused by predictor issues or wind were the most significant contributors to the Ground Station Modulator tree. Diverting attention to these could help reduce the top event's probabilities even further.

The fuzzy fault tree approach produces in-depth information about the expert's opinions laid out across linguistic rating scales in the form of triangular functions, as a means to attain probability numbers of the different top events of the systems. In classic FTA, such information is unknown. Using fuzzy logic, it is possible to translate an expert's idea of likelihood into a numeric interpretation with the methods laid out in Chapter 4.

The work conducted in this paper shows a framework which has the ability to deal with various numbers and types of hazards in a single analysis. The results in Chapter 5 shows examples on how natural and human-related hazards can be examined and assessed at the same time by the same structure. While that is an established method which in of itself brings nothing new to the table, this paper shows the strength and versatility of fuzzy logic in conjunction with fault tree analyses as a means to support the CubeSat industry and the HYPSO project with previously unavailable data. University CubeSat projects are an internationally growing field with an increasing number of players. When lack of data is an obstacle to make technical decisions based on reliability guidelines, extrapolating information from the people working with the satellite is a viable option.

7.2 Recommendations for Future Work

There are several possible ways to go forward with the data collected from this thesis:

- One of which is looking into uncertainty importance measures and how the sources are contributing to the total uncertainty of the fault tree analyses. Which basic events are associated with most uncertainty and how will that manifest into the upper levels of the tree when applying Boolean Algebra. Additionally, dependency degrees of the various identified basic events is another influencing variable that can add to the overall uncertainty.

- Further elaborating and exploring the fault trees constructed is another natural way to better flesh out the various failure modes and dig deeper into the causes of critical event paths. While all of the basic events established in this paper were satisfactory reviewed by the teams, it's possible and encouraged to conduct further qualitative analyses on the less developed basic events to increase the tree's overall robustness.

- Improving the weighting factors attributed to the expert's evaluations by deciding upon a standard in how these are assigned in detail will be of benefit. The way the weights were applied to the experts in this paper are somewhat subjective and not rooted in any robust objective foundation or research. Hence, more work is needed in order to apply a proper method of assigning weight factors because they contribute significantly to the final aggregated results in the risk assessment.

- Looking into failure rates, the life functions best describing these i.e. Weibull or exponential distribution, Mean Time To Failure (MTTF), mean residual life (MRL) or other reliability measures for non-repairable items.

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Appendix

Appendix A) Supporting material
Linguistic variable definitions

VU	**-**	**Very Unlikely**
U	**-**	**Unlikely**
D	**-**	**Doubtful**
M	**-**	**Medium**
P	**-**	**Possible**
L	**-**	**Likely**
VL	**-**	**Very Likely**

Appendix B) Supporting material

Rules of Boolean Algebra

Mathematical Notation	Engineering Notation	Designation
$X \cap Y = Y \cap X$	$X \cdot Y = Y \cdot X$	Commutative Law
$X \cup Y = Y \cup X$	$X + Y = Y + X$	
$X \cap (Y \cap Z) = (X \cap Y) \cap Z$	$X \cdot (Y \cdot Z) = (X \cdot Y) \cdot Z$	Associative Law
	$X(YZ) = (XY)Z$	
$X \cup (Y \cup Z) = (X \cup Y) \cup Z$	$X + (Y + Z) = (X + Y) + Z$	
$X \cap (Y \cup Z) = (X \cap Y) \cup (X \cap Z)$	$X \cdot (Y + Z) = X \cdot Y + X \cdot Z$	Distributive Law
	$X(Y + Z) = XY + XZ$	
$X \cup (Y \cap Z) = (X \cup Y) \cap (X \cup Z)$	$X + (Y \cdot Z) = (X + Y) \cdot (X + Z)$	
$X \cap X = X$	$X \cdot X = X$	Idempotent Law
$X \cup X = X$	$X + X = X$	
$X \cap (X \cup Y) = X$	$X \cdot (X + Y) = X$	Law of Absorption
$X \cup (X \cap Y) = X$	$X + (X \cdot Y) = X$	
$X \cap \bar{X} = \phi$	$X \cdot \bar{X} = \phi$	Complementation
$X \cup \bar{X} = \Omega = I$	$X + \bar{X} = \Omega = I$	
$\overline{X \cap Y} = \bar{X} \cup \bar{Y}$	$\overline{X \cdot Y} = \bar{X} + \bar{Y}$	de Morgan's Rule
$\overline{X \cup Y} = \bar{X} \cap \bar{Y}$	$\overline{X + Y} = \bar{X} \cdot \bar{Y}$	
$\phi \cap X = \phi$	$\phi \cdot X = \phi$	Operations with ϕ and Ω
$\phi \cup X = X$	$\phi + X = X$	
$\Omega \cap X = X$	$\Omega \cdot X = X$	
$\Omega \cup X = \Omega$	$\Omega + X = \Omega$	
$\bar{\phi} = \Omega$	$\bar{\phi} = \Omega$	
$\bar{\Omega} = \phi$	$\bar{\Omega} = \phi$	
$X \cup (\bar{X} \cap Y) = X \cup Y$	$X + (\bar{X} \cdot Y) = X + Y$	Other relationships
$\bar{X} \cap (X \cup \bar{Y}) = \bar{X} \cap \bar{Y}$	$\bar{X} \cdot (X + \bar{Y}) = \bar{X} \cdot \bar{Y}$	

ϕ is the empty or null set which is equal to zero
Ω or I is the universal set which is equal to one

Appendix C)
Calculations

OPU Crashing

OUT OF MEMORY	OUT OF MEMORY	OUT OF MEMORY	OUT OF MEMORY	OUT OF MEMORY	OUT OF MEMORY	OUT OF MEMORY	OUT OF MEMORY	OUT OF MEMORY	OUT OF MEMORY
	Opinions to merge:		**SD(Opi, Opj) =**	AAD(Ei) = 1/n-1 * sum(SD(Opi, Opj)	**RADi = AAD(Ei)/SUM(AAD(Ei))**	**wi = r* WF + (1-r)*RADi**	**SUM (W(i))*Li =**		
TO OG TO I SD FUNKSJON		SD1,2=	0.6000024	0.680003324	0.2965129461	0.2982564731	0.1988386429	0.2485460667	0.2982564731
Advanced 1	Likely	SD1,3=	0.19999982						
Advanced 2	Medium	SD1,4=	0.8000072				0.08070083621	0.1210524648	0.1614040935
		SD1,5=	0.8000072						
Advanced 3	Unlikely	SD1,6=	1				0	0.03124152288	0.06248240844
Proficient 4	Possible								
		SD2,1=	0.6000024	0.6066658	0.1842098594	0.2421049297	0.1046558748	0.1395418641	0.1744257602
Intermediate 5	Possible	SD2,3=	0.3333317						
Intermediate 6	Likely	SD2,4=	0.74999625				0.07965587476	0.1062083641	0.1327592602
		SD2,5=	0.74999625						
		SD2,6=	0.6000024				0.06572254642	0.08215244365	0.09858332671
		SD3,1=	0.19999982	0.246665278	0.0748981996	0.1874490998	Sum (a,b,c) =		
		SD3,2=	0.3333317				**0.5295737751**	**0.7287427262**	**0.9279113221**
		SD3,4 =	0.249997525						
		SD3,5=	0.249997525						
		SD3,6=	0.19999982						
		SD4,1=	0.8000072	0.720001635	0.218623499	0.2093117495			
		SD4,2=	0.74999625						
		SD4,3=	0.249997525						
		SD4,5=	1						
		SD4,6=	0.8000072						
		SD5,1=	0.8000072	0.720001635	0.218623499	0.1593117495			
		SD5,2=	0.74999625						
		SD5,3=	0.249997525						
		SD5,4	1						
		SD5,6=	0.8000072						
		SD6,1=	1						
		SD6,2=	0.6000024	0.32000288	0.09716665342	0.09858332671			
		SD6,3=	0.19999982						
		SD6,4=	0.8000072						
		SD6,5=	0.8000072						

UNSAFE MULTITHREAD		UNSAFE MULTITHREAD		UNSAFE MULTITHREAD			UNSAFE MULTITHREAD	UNSAFE MULTITHREAD	UNSAFE MULTITHREAD
		SD(EEi, EEj)=		**AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)**	**RADi = AAD(Ei)/SUM(AAD(Ei))**	**wi = r* WF + (1-r)*RADi**	**SUM (W(i))*Li =**		
Advanced 1 0.3	Possible	SD1,2=	0.4999925	0.6222991285	0.2176543861	0.2588271931	0.1294135965	0.1725523248	0.2156884648
Proficient 2 0.2	Doubtful	SD1,3=	1						
Proficient 3 0.2	Possible	SD1,4=	0.0614996925						
Proficient 4 0.2	Very unlikely	SD1,5=	0.8000072						
Proficient 5 0.2	Likely	SD1,6=	0.74999625						
Intermediate 6 0.1	Medium								
		SD2,1=	0.4999925	0.4382894816	0.153295455	0.1766477275	0.02944187674	0.05888198701	0.08832386375
		SD2,3=	0.4999925						
		SD2,4=	0.124801248						
		SD2,5=	0.39999616						
		SD2,6=	0.666665						
		SD3,1=	1	0.6222991285	0.2176543861	0.2088271931	0.1044135965	0.1392188248	0.1740219648
		SD3,2=	0.4999925						
		SD3,4 =	0.0614996925						
		SD3,5=	0.8000072						
		SD3,6=	0.74999625						
		SD4,1=	0.0614996925	0.0762268866	0.02666099862	0.1133304993	0	0	0.01888845433
		SD4,2=	0.124801248						
		SD4,3=	0.0614996925						
		SD4,5=	0.0500003						
		SD4,6=	0.0833335						
		SD5,1=	0.8000072	0.530002652	0.1853729124	0.1926864562	0.1284582798	0.1605714046	0.1926864562
		SD5,2=	0.39999616						
		SD5,3=	0.8000072						
		SD5,4	0.0500003						
		SD5,6=	0.6000024						
		SD6,1=	0.74999625	0.56999868	0.1993618617	0.1496809308	0.04989314468	0.07484046542	0.09978778616
		SD6,2=	0.666665				**SUM a,b,c**		
		SD6,3=	0.74999625				**0.4416204942**	**0.6060650066**	**0.7893969901**
		SD6,4=	0.0833335	Very unlikely/Medium					
		SD6,5=	0.6000024	Medium/Likely					

Error CORRECTION				ERROR CORRECTION					
		SD(EEi, EEj)=		**AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)**	**RADi = AAD(Ei)/SUM(AAD(Ei))**	**wi = r* WF + (1-r)*RADi**	SUM (W(i))*Li =		
Proficient 0.2	Possible	SD1,2=	0.8000072	0.7979506518	0.1964589096	0.1982294548	0.0991147274	0.1321536306	0.1651905516
Intermediate 0.1	Likely	SD1,3=	1						
Intermediate 0.1	Possible	SD1,4=	0.6958977035						
Proficient 0.2	Very likely	SD1,5=	0.6958977035						
Intermediate 0.1	Very likely								
		SD2,1=	0.8000072	0.8349357503	0.2055648012	0.1527824006	0.101855443	0.1273181579	0.1527824006
		SD2,3=	0.8000072						
		SD2,4=	0.8698643006						
		SD2,5=	0.8698643006						
		SD3,1=	1	0.7979506518	0.1964589096	0.1482294548	0.0741147274	0.09882013063	0.1235240516
		SD3,2=	0.8000072						
		SD3,4 =	0.6958977035						
		SD3,5=	0.6958977035						
		SD4,1=	0.6958977035	0.8154149269	0.2007586898	0.2003793449	0.1669821195	0.2003793449	0.2003793449
		SD4,2=	0.8698643006						
		SD4,3=	0.6958977035						
		SD4,5=	1						
		SD5,1=	0.6958977035	0.8154149269	0.2007586898	0.1503793449	0.1253156195	0.1503793449	0.1503793449
		SD5,2=	0.8698643006						
		SD5,3=	0.6958977035				**SUM a,b,c:**		
		SD5,4	1				0.5673826368	0.709050609	0.7922556935

SUDDEN LOSS OF POWER		SUDDEN LOSS OF POWER					SUDDEN LOSS OF POWER		
		SD(EEi, EEj)=		**AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)**	**RADi = AAD(Ei)/SUM(AAD(Ei))**	wi = r* WF + (1-r)*RADi	SUM (W(i))*Li =		
Intermediate 0.1	Unlikely								
Proficient 0.2	Very likely	SD1,2=	0.1739727035	0.3362549414	0.1128337299	0.1064168649	0	0.0177361477	0.03547193359
Intermediate 0.1	Medium	SD1,3=	0.3333317						
Intermediate 0.1	Doubtful	SD1,4=	0.4999988						
Advanced 0.3	Doubtful	SD1,5=	0.4999988						
Proficient 0.2	Very likely	SD1,6=	0.1739727035						
		SD2,1=	0.1739727035	0.4783571712	0.1605175633	0.1802587816	0.1502150505	0.1802587816	0.1802587816
		SD2,3=	0.5219206681						
		SD2,4=	0.3479462422						
		SD2,5=	0.3479462422						
		SD2,6=	1						
		SD3,1=	0.3333317	0.5421006072	0.1819073148	0.1409536574	0.04698408262	0.0704768287	0.09396957478
		SD3,2=	0.5219206681						
		SD3,4 =	0.666665						
		SD3,5=	0.666665						
		SD3,6=	0.5219206681						
		SD4,1=	0.4999988	0.5725112569	0.2288456625	0.1644228312	0.02740435328	0.05480706234	0.08221141562
		SD4,2=	0.3479462422						
		SD4,3=	0.666665						
		SD4,5=	1						
		SD4,6=	0.3479462422						
		SD5,1=	0.4999988	0.5725112569	0.1921119144	0.2460559572	0.04101014638	0.08201783221	0.1230279786
		SD5,2=	0.3479462422						
		SD5,3=	0.666665						
		SD5,4	1						
		SD5,6=	0.3479462422						
		SD6,1=	0.1739727035	0.4783571712	0.1605175633	0.1802587816	0.1502150505	0.1802587816	0.1802587816
		SD6,2=	1						
		SD6,3=	0.5219206681				**SUM, a,b,c:**		
		SD6,4=	0.3479462422				0.4158286833	0.5855554342	0.6951984659
		SD6,5=	0.3479462422						

	COSMIC RAYS									
		SD(EEi, EEj)=		AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)	RADi = AAD(Ei)/SUM(AAD(Ei))	wi = r* WF + (1-r)*RADi	SUM (W(i))*Li =			
Intermediate 0.1	Unlikely									
Intermediate 0.1	Doubtful	SD1,2=	0.4999988	0.41666525	0.2777776667	0.1888888333		0	0.03148147852	0.06296231481
Advanced 0.3	Medium	SD1,3=	0.3333317							
		SD2,1=	0.4999988	0.5833319	0.3888891	0.24444455		0.04074157315	0.08148070185	0.122222275
		SD2,3=	0.666665							
		SD3,1=	0.3333317	0.49999835	0.3333332333	0.3166666167		0.1055544833	0.1583333083	0.2111121333
		SD3,2=	0.666665							
							Sum, a,b,c:			
								0.1462960565	0.2712954887	0.3962967231
	PRIORITIZATION									
		SD(EEi, EEj)=		AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)	RADi = AAD(Ei)/SUM(AAD(Ei))	wi = r* WF + (1-r)*RADi	SUM (W(i))*Li =			
Expert 0.4	Possible									
	Possible	SD1,2=	1	0.8076525923	0.1457562707	0.1457562707		0.07287813537	0.09717133301	0.1214630731
	Likely	SD1,3=	0.8000072							
	Likely	SD1,4=	0.8000072							
	Likely	SD1,5=	0.8000072							
	Very likely	SD1,6=	0.6958977035							
	Medium	SD1.7=	0.74999625							
		SD2,1=	1	0.8076525923	0.1457562707	0.1457562707		0.07287813537	0.09717133301	0.1214630731
		SD2,3=	0.8000072							
		SD2,4=	0.8000072							
		SD2,5=	0.8000072							
		SD2,6=	0.6958977035							
		SD2,7=	0.74999625							
		SD3,1=	0.8000072	0.8449801834	0.1524927445	0.1524927445		0.101662338	0.1270767788	0.1524927445
		SD3,2=	0.8000072							
		SD3,4 =	1							
		SD3,5=	1							
		SD3,6=	0.8698643006							
		SD3,7=	0.6000024							
		SD4,1=	0.8000072	0.8449801834	0.1524927445	0.1524927445		0.101662338	0.1270767788	0.1524927445
		SD4,2=	0.8000072							
		SD4,3=	1							
		SD4,5=	1							
		SD4,6=	0.8698643006							
		SD4,7=	0.6000024							
		SD5,1=	0.8000072	0.8449801834	0.1524927445	0.1524927445		0.101662338	0.1270767788	0.1524927445
		SD5,2=	0.8000072							
		SD5,3=	1							
		SD5,4	1							
		SD5,6=	0.8698643006							
		SD5,7=	0.6000024							
		SD6,1=	0.6958977035	0.7538848295	0.1360528554	0.1360528554		0.113376926	0.1360528554	0.1360528554
		SD6,2=	0.6958977035							
		SD6,3=	0.8698643006							
		SD6,4=	0.8698643006							
		SD6,5=	0.8698643006							
		SD6,7=	0.5219206681							
		SD7,1=	0.74999625	0.636986728	0.1149563697	0.1149563697		0.03831840671	0.05747818485	0.07663796299
		SD7,2=	0.74999625							
		SD7,3=	0.6000024				**SUM a,b,c:**			
		SD7,4=	0.6000024					0.6024386173	0.7691040425	0.913095198
		SD7,5=	0.6000024				Slacking = 0, bryr seg ikke om ekspertise.			
		SD7,6=	0.5219206681							

TIME CONSTRAINTS

Very likely	No weights	**SD(EEi, EEj)=**		**AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)**	RADi = AAD(Ei)/SUM(AAD(Ei))	wi = r* WF + (1-r)*RADi	SUM (W(i))*Li =		
Possible									
Very likely		SD1,2=	0.6958977035	0.8335647181	0.1404661834	0.1404661834	0.1170546847	0.1404661834	0.1404661834
Possible		SD1,3=	1						
Likely		SD1,4=	0.6958977035						
Likely		SD1,5=	0.8698643006						
Likely		SD1,6=	0.8698643006						
		SD1.7=	0.8698643006						
		SD2,1=	0.6958977035	0.7986361678	0.1345802816				
		SD2,3=	0.6958977035			0.1345802816	0.06729014078	0.0897206363	0.112149786
		SD2,4=	1						
		SD2,5=	0.8000072						
		SD2,6=	0.8000072						
		SD2,7=	0.8000072						
		SD3,1=	1	0.8335647181	0.1404661834				
		SD3,2=	0.6958977035			0.1404661834	0.1170546847	0.1404661834	0.1404661834
		SD3,4 =	0.6958977035						
		SD3,5=	0.8698643006						
		SD3,6=	0.8698643006						
		SD3,7=	0.8698643006						
		SD4,1=	0.6958977035	0.7986361678	0.1345802816				
		SD4,2=	1			0.1345802816	0.06729014078	0.0897206363	0.112149786
		SD4,3=	0.6958977035						
		SD4,5=	0.8000072						
		SD4,6=	0.8000072						
		SD4,7=	0.8000072						
		SD5,1=	0.8698643006	0.8899571669	0.1499690233				
		SD5,2=	0.8000072			0.1499690233	0.09997984878	0.1249736862	0.1499690233
		SD5,3=	0.8698643006						
		SD5,4	0.8000072						
		SD5,6=	1						
		SD5,7=	1						
		SD6,1=	0.8698643006	0.8899571669	0.1499690233				
		SD6,2=	0.8000072			0.1499690233	0.09997984878	0.1249736862	0.1499690233
		SD6,3=	0.8698643006						
		SD6,4=	0.8000072						
		SD6,5=	1						
		SD6,7=	1						
		SD7,1=	0.8698643006	0.8899571669	0.1499690233				
		SD7,2=	0.8000072			0.1499690233	0.09997984878	0.1249736862	0.1499690233
		SD7,3=	0.8698643006						
		SD7,4=	0.8000072				**SUM, a,b,c:**		
		SD7,5=	1				0.6686291972	0.8352946981	0.9551390089
		SD7,6=	1						

UNFAMILIAR SYSTEMS			UNFAMILIAR SYSTEMS	UNFAMILIAR SYSTEMS				
	SD(EEi, EEj)=		**AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)**	RADi = AAD(Ei)/SUM(AAD(Ei))	**wi = r* WF + (1-r)*RADi**	SUM (W(i))*Li =		
Likely								
Possible	SD1,2=	0.8000072	0.9666678667	0.1464645087	0.1464645087	0.09764349403	0.1220532691	0.1464645087
Likely	SD1,3=	1						
Likely	SD1,4=	1						
Likely	SD1,5=	1						
Likely	SD1,6=	1						
Likely	SD1.7=	1						
	SD2,1=	0.8000072	0.8000072	0.1212129477	0.1212129477	0.06060647383	0.08080903581	0.1010103857
	SD2,3=	0.8000072						
	SD2,4=	0.8000072						
	SD2,5=	0.8000072						
	SD2,6=	0.8000072						
	SD2,7=	0.8000072						
	SD3,1=	1	0.9666678667	0.1464645087	0.1464645087	0.09764349403	0.1220532691	0.1464645087
	SD3,2=	0.8000072						
	SD3,4 =	1						
	SD3,5=	1						
	SD3,6=	1						
	SD3,7=	1						
	SD4,1=	1	0.9666678667	0.1464645087	0.1464645087	0.09764349403	0.1220532691	0.1464645087
	SD4,2=	0.8000072						
	SD4,3=	1						
	SD4,5=	1						
	SD4,6=	1						
	SD4,7=	1						
	SD5,1=	1	0.9666678667	0.1464645087	0.1464645087	0.09764349402	0.122053269	0.1464645087
	SD5,2=	0.8000072						
	SD5,3=	1						
	SD5,4	1						
	SD5,6=	1						
	SD5,7=	1						
	SD6,1=	1	0.9666678667	0.1464645087	0.1464645087	0.09764349402	0.122053269	0.1464645087
	SD6,2=	0.8000072						
	SD6,3=	1						
	SD6,4=	1						
	SD6,5=	1						
	SD6,7=	1						
	SD7,1=	1	0.9666678667	0.1464645087	0.1464645087	0.09764349402	0.122053269	0.1464645087
	SD7,2=	0.8000072						
	SD7,3=	1				**SUM a,b,c:**		
	SD7,4=	1				0.646467438	0.8131286501	0.9797974379
	SD7,5=	1						
	SD7,6=	1						

INEXPERIENCE		INEXPERIENCE	INEXPERIENCE					
	SD(EEi, EEj)=		**AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)**	RADi = AAD(Ei)/SUM(AAD(Ei))	**wi = r* WF + (1-r)*RADi**	SUM (W(i))*Li =		
Likely								
Possible	SD1,2=	0.8000072	0.9333357333	0.1473682416	0.1473682416	0.0982459856	0.1228063767	0.1473682416
Possible	SD1,3=	0.8000072						
Likely	SD1,4=	1						
Likely	SD1,5=	1						
Likely	SD1,6=	1						
Likely	SD1.7=	1						
	SD2,1=	0.8000072	0.8333393333	0.1315793961	0.1315793961	0.06578969806	0.08772003601	0.1096490582
	SD2,3=	1						
	SD2,4=	0.8000072						
	SD2,5=	0.8000072						
	SD2,6=	0.8000072						
	SD2,7=	0.8000072						
	SD3,1=	0.8000072	0.8333393333	0.1315793961	0.1315793961	0.06578969806	0.08772003601	0.1096490582
	SD3,2=	1						
	SD3,4 =	0.8000072						
	SD3,5=	0.8000072						
	SD3,6=	0.8000072						
	SD3,7=	0.8000072						
	SD4,1=	1	0.9333357333	0.1473682416	0.1473682416	0.0982459856	0.1228063767	0.1473682416
	SD4,2=	0.8000072						
	SD4,3=	0.8000072						
	SD4,5=	1						
	SD4,6=	1						
	SD4,7=	1						
	SD5,1=	1	0.9333357333	0.1473682416	0.1473682416	0.0982459856	0.1228063767	0.1473682416
	SD5,2=	0.8000072						
	SD5,3=	0.8000072						
	SD5,4	1						
	SD5,6=	1						
	SD5,7=	1						
	SD6,1=	1	0.9333357333	0.1473682416	0.1473682416	0.0982459856	0.1228063767	0.1473682416
	SD6,2=	0.8000072						
	SD6,3=	0.8000072						
	SD6,4=	1						
	SD6,5=	1						
	SD6,7=	1						
	SD7,1=	1	0.9333357333	0.1473682416	0.1473682416	0.0982459856	0.1228063767	0.1473682416
	SD7,2=	0.8000072						
	SD7,3=	0.8000072				**SUM a,b,c:**		
	SD7,4=	1				0.6228093241	0.7894719557	0.9561393241
	SD7,5=	1						
	SD7,6=	1						

	Basic Event (i)	Aggregated Fuzzy Number	Center of Area Defuzzification FPS = COAD(A) = 1/3(a+b+c)
Out of memory	BE1	0.5454321096 0.746296194 0.9471605959	0.7462962998
Pop/push	BE2	0.83333 1 1	0.9444433333
Unsafe Multithread	BE3	0.4416204942 0.6060650066 0.7893969901	0.6123608303
Error Correction	BE4	0.5673826368 0.709050609 0.7922556935	0.6895629798
Sudden Loss Power	BE5	0.4158286833 0.5855554342 0.6951984659	0.5655275278
Cosmic Rays	BE6	0.1462960565 0.2712954887 0.3962967231	0.2712960894
Prioritization	BE7	0.6024386173 0.7691040425 0.913095198	0.7615459526
Time constraints	BE8	0.6686291972 0.8352946981 0.9551390089	0.8196876347
Unfamiliar	BE9	0.646467438 0.8131286501 0.9797974379	0.8131311753
Inexperience	BE10	0.6228093241 0.7894719557 0.9561393241	0.7894735346

alpha = (1/FPS - 1) ^(1/3) * 2.301

alpha=	**Failure Probability = 1/ (10^alpha)**	**MCS**	**FP of MCSi**
1.605912171	0.02477923125	Æ = BE4*(BE5 + BE6)	0.0001455111078
0.894890801	0.1273823331	Ø = ((BE7*BE8)+Be9+BE10)	0.07310644087
1.975710778	0.01057521539	BE3	0.01057521539
1.763531176	0.0172372835		
2.107428216	0.00780857496		0.0001455111078
3.198545066	0.0006330746647		
1.562498036	0.02738432021		
1.389021584	0.0408299094		
1.409425201	0.03895603961		
1.48106116	0.03303230194		

P(TopEvent) = MCS Union MCS	**FUSSEL-VESELY IMPORTANCE of MCs**	
0.08382716737	F-V MC1 =	0.001735846651
	F-V MC2=	0.8721091642
	F-V MC3=	0.1261549891

Reaction Wheel Not Speeding Up

OVERHEATING				OVERHEATING	OVERHEATING	0.04761904	0.095238	0.142857	0.1904761	0.238095	0.285714
			SD(Ei,Ej) =	AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)	RADi = AAD(Ei)/SUM(AAD(Ei))		wi = r* WF + (1-r)*RADi		SUM (W(i))*Li =		
		SD1,2	1	1	0.5		0.267857075		0	0.04464285476	0.08928479881
Proficient	Unlikely										
Novice	Unlikely										
		SD2,1	1	1	0.5		0.16071428		0	0.02678571869	0.05357089095
									SUM a,b,c		
									0	0.07142857345	0.1428556898
ELECTRICAL OVERLEAD				ELECTRICAL OVERLEAD		ELECTRICAL OVERLOAD					
			SD(Ei,Ej) =	AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)	RADi = AAD(Ei)/SUM(AAD(Ei))		wi = r* WF + (1-r)*RADi		SUM (W(i))*Li =		
		SD1,2	2.0000048	2.0000048	0.5		0.267857075		0.04464373869	0.08928479881	0.1339285375
Proficient	Doubtful										
Novice	Unlikely										
		SD2,1	2.0000048	2.0000048	0.5		0.16071428		0	0.02678571869	0.05357089095
									SUM a,b,c		
									0.04464373869	0.1160705175	0.1874994285
DAMAGED BEARINGS						DAMAGED BEARINGS	0.04761904	0.095238	0.142857	0.1904761	0.238095
			SD(Ei,Ej) =	AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)	RADi = AAD(Ei)/SUM(AAD(Ei))		wi = r* WF + (1-r)*RADi		SUM (W(i))*Li =		
Proficient	Doubtful	SD1,2	0.1250005625	0.1250005625	0.5		0.267857075		0.04464373869	0.08928479881	0.1339285375
Novice	Very unlikely										
		SD2,1	0.1250005625	0.1250005625	0.5		0.16071428		0	0	0.0267857669
									SUM a,b,c		
									0.04464373869	0.08928479881	0.1607143044
DISCONNECTED CABLES						DISCONNECTED					
			SD(Ei,Ej) =	AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)	RADi = AAD(Ei)/SUM(AAD(Ei))		wi = r* WF + (1-r)*RADi		SUM (W(i))*Li =		
Proficient	Unlikely	SD1,2	1	1	0.5		0.267857075		0	0.04464285476	0.08928479881
Novice	Unlikely										
		SD2,1	1	1	0.5		0.16071428		0	0.02678571869	0.05357089095
									SUM a,b,c		
									0	0.07142857345	0.1428556898

DAMAGED CABLES					DAMAGED CABLES	0.04761904	0.095238	0.142857	0.1904761	0.238095	0.285714
			SD(Ei,Ej) =	AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)	RADi = AAD(Ei)/SUM(AAD(Ei))		wi = r* WF + (1-r)*RADi		SUM (W(i))*Li =		
Proficient	Doubtful	SD1,2	1	1	0.5		0.267857075		0.04464373869	0.08928479881	0.1339285375
Novice	Doubtful										
		SD2,1	1	1	0.5		0.16071428		0.02678624905	0.05357089095	0.08035714
									SUM a,b,c		
									0.07142998774	0.1428556898	0.2142856775
NO POWER					NO POWER						
			SD(Ei,Ej) =	AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)	RADi = AAD(Ei)/SUM(AAD(Ei))		wi = r* WF + (1-r)*RADi		SUM (W(i))*Li =		
Proficient	Doubtful	SD1,2	0.4999988	0.4999988	0.5		0.267857075		0.04464373869	0.08928479881	0.1339285375
Novice	Unlikely										
		SD2,1	0.4999988	0.4999988	0.5		0.16071428		0	0.02678571869	0.05357089095
									SUM a,b,c		
									0.04464373869	0.1160705175	0.1874994285
G FORCES					G FORCES		0.04761904	0.095238	0.142857	0.1904761	0.238095
			SD(Ei,Ej) =	AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)	RADi = AAD(Ei)/SUM(AAD(Ei))		wi = r* WF + (1-r)*RADi		SUM (W(i))*Li =		
		SD1,2	1	1	0.5		0.30357125		0	0	0.05059530952
Advanced	Very unlikely										
Developing	Very unlikely										
		SD2,1	1	1	0.5		0.16071428		0	0	0.0267857669
									SUM a,b,c		
									0	0	0.07738107643
VIBRATION					VIBRATION						
			SD(Ei,Ej) =	AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)	RADi = AAD(Ei)/SUM(AAD(Ei))		wi = r* WF + (1-r)*RADi		SUM (W(i))*Li =		
Advanced	Unlikely	SD1,2	0.4999988	0.4999988	0.5		0.30357125		0	0.05059521845	0.1011894048
Developing	Doubtful										
		SD2,1	0.4999988	0.4999988	0.5		0.1964285		0.0327387381	0.06547551191	0.09821425
									SUM a,b,c		
									0.0327387381	0.1160707304	0.1994036548

		Aggregated fuzzy numbers	(a, b, c)		P(TopEvent) = MCS Union MCS	FUSSEL-VESELY IMPORTANCE of MCs	MCS RANKING
Overheating	BE1	0	0.07142857345	0.1428556898	1.48E-04	2.62%	5
Electrical Overload	BE2	0.04464373869	0.1160705175	0.1874994285		20.04%	2
Lubricated/Damaged Bearings	BE3	0.04464373869	0.08928479881	0.1607143044		10.25%	4
Disconnected Cables	BE4	0	0.07142857345	0.1428556898		2.62%	6
Damaged Cables	BE5	0.07142998774	0.1428556898	0.2142856775		44.43%	1
No Power	BE6	0.04464373869	0.1160705175	0.1874994285		20.04%	3
G-Forces	BE7	0	0	0.07738107643		0.00%	7
Vibration	BE8	0.0327387381	0.1160707304	0.1994036548			

FPS = COAD(A) = 1/3(a+b+c)	alpha = (1/FPS - 1) ^(1/3) * 2.301	Failure Probability = 1/ (10^alpha)	MCs	FP of MCs
0.07142808774	5.410434268	0.000003886563176	BE1	3.89E-06
0.1160712282	4.527038439	0.00002971403022	BE2	2.97E-05
0.09821428063	4.818289124	0.00001519535589	BE3	1.52E-05
0.07142808774	5.410434268	0.000003886563176	BE4	3.89E-06
0.1428571183	4.181194763	0.00006588783491	BE5	6.59E-05
0.1160712282	4.527038439	0.00002971403022	BE6	2.97E-05
0.02579369214	7.720209642	0.0000000190454114	BE7*BE8	5.66E-13
0.1160710411	4.527041192	0.00002971384189		

S-Band: Data Not Sent (Gnd. To Payload)

WIND			SD(Ei,Ej) =	AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)	RADi = AAD(Ei)/SUM(AAD(Ei))	wi = r* WF + (1-r)*RADi	SUM (W(i))*Li =		
		SD1,2=	0.4999988	0.499997525	0.400000396	0.342857198	0.05714400919	0.1142845898	0.171428599
Expert	Doubtful	SD1,3=	0.49999625						
Advanced	Unlikely								
Developing	Possible	SD2,1 =	0.4999988	0.3749981625	0.300000312	0.269047656	0	0.04484128497	0.08968165517
		SD2,3 =	0.249997525						
		SD3,1 =	0.49999625	0.3749968875	0.299999292	0.149999646	0.074999823	0.100000264	0.124999205
		SD3,2 =	0.249997525						
							0.1321438322	**0.2591261388**	**0.3861094592**
RARE BUGS			SD(Ei,Ej) =	AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)	RADi = AAD(Ei)/SUM(AAD(Ei))	wi = r* WF + (1-r)*RADi	SUM (W(i))*Li =		
		SD1,2=	0.0833335	0.37499925	0.4285710306	0.3571425153	0.1190463146	0.1785712577	0.2380962007
Expert	Medium	SD1,3=	0.666665						
Proficient	Very unlikely								
Novice	Doubtful	SD2,1 =	0.0833335	0.1041670313	0.1190481633	0.1547621316	0	0	0.02579374019
		SD2,3 =	0.1250005625						
		SD3,1 =	0.666665	0.3958327813	0.4523808061	0.2261904031	0.03769915448	0.07539604705	0.1130952015
		SD3,2 =	0.1250005625						
							0.1567454691	**0.2539673047**	**0.3769851424**
ANTENNA WRONGLY CALIB			SD(Ei,Ej) =	AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)	RADi = AAD(Ei)/SUM(AAD(Ei))	wi = r* WF + (1-r)*RADi	SUM (W(i))*Li =		
		SD1,2=	0.0500003	0.08750043125	0.152174276	0.218944138	0	0	0.03649076265
Expert	Very unlikely	SD1,3=	0.1250005625						
Proficient	Likely								
Developing	Doubtful	SD2,1 =	0.0500003	0.22500045	0.3913041352	0.2670805676	0.178054602	0.2225662494	0.2670805676
		SD2,3 =	0.4000006						
		SD3,1 =	0.1250005625	0.2625005813	0.4565215888	0.2282607944	0.03804422661	0.07608617061	0.1141303972
		SD3,2 =	0.4000006						
							0.2160988286	**0.29865242**	**0.4177017274**
TLE deviating			SD(Ei,Ej) =	AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)	RADi = AAD(Ei)/SUM(AAD(Ei))	wi = r* WF + (1-r)*RADi	SUM (W(i))*Li =		
		SD1,2=	1	0.9000036	0.3461533136	0.3159336568	0.210623491	0.2632769942	0.3159336568
Expert	Likely	SD1,3=	0.8000072						
Advanced	Likely								
Developing	Possible	SD2,1 =	1	0.9000036	0.3461533136	0.2921241568	0.1947504116	0.2434358236	0.2921241568
		SD2,3 =	0.8000072						
		SD3,1 =	0.8000072	0.8000072	0.3076933728	0.1538466864	0.07692334319	0.1025649704	0.1282050592
		SD3,2 =	0.8000072						
							0.4822972458	**0.6092777882**	**0.7362628728**
MECH ERROR ROTAT			SD(Ei,Ej) =	AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)	RADi = AAD(Ei)/SUM(AAD(Ei))	wi = r* WF + (1-r)*RADi	SUM (W(i))*Li =		
		SD1,2=	0.49999625	0.749998125	0.3750004687	0.3303572344	0.05506064025	0.1101179769	0.1651786172
Expert	Doubtful	SD1,3=	1						
Advanced	Possible								
Developing	Doubtful	SD2,1 =	0.49999625	0.49999625	0.2499990625	0.2440470313	0.1220235156	0.1626988343	0.2033717126
		SD2,3 =	0.49999625						
		SD3,1 =	1	0.749998125	0.3750004687	0.1875002344	0.03125066406	0.06249945312	0.09375011719
		SD3,2 =	0.49999625						
							0.2083348199	**0.3353162644**	**0.4623004469**
WRONG FREQ			SD(Ei,Ej) =	AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)	RADi = AAD(Ei)/SUM(AAD(Ei))	wi = r* WF + (1-r)*RADi	SUM (W(i))*Li =		
		SD1,2=	0.250001725	0.3750002625	0.4285711959	0.357142598	0	0.05952377823	0.1190463422
Expert	Unlikely	SD1,3=	0.4999988						
Advanced	Very unlikely								
Developing	Doubtful	SD2,1 =	0.250001725	0.1875011438	0.2142867551	0.2261908776	0	0	0.03769855499
		SD2,3 =	0.1250005625						
		SD3,1 =	0.4999988	0.3124996812	0.357142049	0.1785710245	0.02976243265	0.05952307959	0.08928551224
		SD3,2 =	0.1250005625						
							0.02976243265	**0.1190468578**	**0.2460304094**

WRONG ENCODING			SD(Ei,Ej) =	AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)	RADi = AAD(Ei)/SUM(AAD(Ei))	wi = r* WF + (1-r)*RADi	SUM (W(i))*Li =		
		SD1,2=	0.1250005625	0.5625002813	0.44999982	0.36785691	0.06131071119	0.1226177438	0.183928455
Expert	Doubtful	SD1,3=	1						
Advanced	Very unlikely								
Developing	Doubtful	SD2,1 =	0.1250005625	0.1250005625	0.10000036	0.16904768	0	0	0.02817466968
		SD2,3 =	0.1250005625						
		SD3,1 =	1	0.5625002813	0.44999982	0.22499991	0.037500735	0.07499922	0.112499955
		SD3,2 =	0.1250005625						
							0.09881144619	0.1976169638	0.3246030797
WRONG BITRATE			SD(Ei,Ej) =	AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)	RADi = AAD(Ei)/SUM(AAD(Ei))	wi = r* WF + (1-r)*RADi	SUM (W(i))*Li =		
		SD1,2=	0.250001725	0.3750002625	0.4285711959	0.357142598	0	0.07142854694	0.1428556367
Expert	Unlikely	SD1,3=	0.4999988						
Advanced	Very unlikely								
Developing	Doubtful	SD2,1 =	0.250001725	0.1875011438	0.2142867551	0.2261908776	0	0	0.03769855499
		SD2,3 =	0.1250005625						
		SD3,1 =	0.4999988	0.3124996812	0.357142049	0.1785710245	0.02976243265	0.05952307959	0.08928551224
		SD3,2 =	0.1250005625						
							0.02976243265	0.1309516265	0.269839704
WRONG MODULATION			SD(Ei,Ej) =	AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)	RADi = AAD(Ei)/SUM(AAD(Ei))	wi = r* WF + (1-r)*RADi	SUM (W(i))*Li =		
		SD1,2=	0.250001725	0.3750002625	0.4285711959	0.357142598	0	0.07142854694	0.1428556367
Expert	Unlikely	SD1,3=	0.4999988						
Advanced	Very unlikely								
Developing	Doubtful	SD2,1 =	0.250001725	0.1875011438	0.2142867551	0.2261908776	0	0	0.03769855499
		SD2,3 =	0.1250005625						
		SD3,1 =	0.4999988	0.3124996812	0.357142049	0.2261900245	0.03769909138	0.07539592086	0.1130950122
		SD3,2 =	0.1250005625						
							0.03769909138	0.1468244678	0.293649204
IONOSPHERIC LOSS			SD(Ei,Ej) =	AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)	RADi = AAD(Ei)/SUM(AAD(Ei))	wi = r* WF + (1-r)*RADi	SUM (W(i))*Li =	0.04761904	0.095238
		SD1,2=	0.0624998125	0.0937501875	0.1363645785	0.2110392893	0	0	0.03517328522
Expert	Very unlikely	SD1,3=	0.1250005625						
Advanced	Possible								
Intermediate	Doubtful	SD2,1 =	0.0624998125	0.2812480313	0.4090900537	0.3235925269	0.1617962634	0.2157294299	0.2696593604
		SD2,3 =	0.49999625						
		SD3,1 =	0.1250005625	0.3124984063	0.4545453678	0.2987011839	0.04978452632	0.09956606562	0.1493505919
		SD3,2 =	0.49999625						
							0.2115807897	0.3152954955	0.4541832376
SNOW COVERED			SD(Ei,Ej) =	AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)	RADi = AAD(Ei)/SUM(AAD(Ei))	wi = r* WF + (1-r)*RADi	SUM (W(i))*Li =		
		SD1,2=	0.49999625	0.449998425	0.2647043253	0.2752091626	0.04586911114	0.09173547018	0.1376045813
Expert	Doubtful	SD1,3=	0.4000006						
Proficient	Possible								
Developing	Likely	SD2,1 =	0.49999625	0.650001725	0.382353045	0.2864145725	0.1432072862	0.190944003	0.2386778557
		SD2,3 =	0.8000072						
		SD3,1 =	0.4000006	0.6000039	0.3529426298	0.2240903149	0.1493942902	0.1867411821	0.2240903149
		SD3,2 =	0.8000072						
							0.3384706876	0.4694206553	0.6003727519
FALTY HARDWARE			SD(Ei,Ej) =	AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)	RADi = AAD(Ei)/SUM(AAD(Ei))	wi = r* WF + (1-r)*RADi	SUM (W(i))*Li =		
		SD1,2=	0.49999625	0.749998125	0.3750004687	0.3303572344	0.05506064025	0.1101179769	0.1651786172
Expert	Doubtful	SD1,3=	1						
Advanced	Possible								
Developing	Doubtful	SD2,1 =	0.49999625	0.49999625	0.2499990625	0.2440470313	0.1220235156	0.1626988343	0.2033717126
		SD2,3 =	0.49999625						
		SD3,1 =	1	0.749998125	0.3750004687	0.2351192344	0.03918732279	0.07837229439	0.1175596172
		SD3,2 =	0.49999625						
							0.2162714787	0.3511891057	0.4861099469

QUEUED COMMANDS			SD(Ei,Ej) =	AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)	RADi = AAD(Ei)/SUM(AAD(Ei))	wi = r* WF + (1-r)*RADi	SUM (W(i))*Li =		
		SD1,2=	0.666665	0.8333325	0.3571430102	0.3214285051	0.1071417636	0.1607142526	0.2142867415
Expert	Medium	SD1,3=	1						
Intermediate	Doubtful								
Developing	Medium	SD2,1 =	0.666665	0.666665	0.2857139796	0.2142854898	0.03571496258	0.07142778231	0.1071427449
		SD2,3 =	0.666665						
		SD3,1 =	1	0.8333325	0.3571430102	0.2261905051	0.07539608107	0.1130952526	0.150794424
		SD3,2 =	0.666665						
							0.2182528073	0.3452372874	0.4722239104
LOW BANDWIDTH			SD(Ei,Ej) =	AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)	RADi = AAD(Ei)/SUM(AAD(Ei))	wi = r* WF + (1-r)*RADi	SUM (W(i))*Li =		
		SD1,2=	1	0.6249987625	0.4166672167	0.3511906083	0	0.05853177976	0.1170623655
Expert	Unlikely	SD1,3=	0.249997525						
Proficient	Unlikely								
Developing	Possible	SD2,1 =	1	0.6249987625	0.4166672167	0.3035716583	0	0.05059528651	0.1011895409
		SD2,3 =	0.249997525						
		SD3,1 =	0.249997525	0.249997525	0.1666655667	0.1309517833	0.06547589167	0.0873016254	0.1091260496
		SD3,2 =	0.249997525						
							0.06547589167	0.1964286917	0.327377956
UNFORESEEN SW ERROR			SD(Ei,Ej) =	AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)	RADi = AAD(Ei)/SUM(AAD(Ei))	wi = r* WF + (1-r)*RADi	SUM (W(i))*Li =		
		SD1,2=	0.249997525	0.3749968875	0.299999292	0.292856646	0.146428323	0.1952387402	0.2440462288
Expert	Possible	SD1,3=	0.49999625						
Intermediate	Unlikely								
Developing	Doubtful	SD2,1 =	0.249997525	0.3749981625	0.300000312	0.221428656	0	0.03690478338	0.0738088139
		SD2,3 =	0.4999988						
		SD3,1 =	0.49999625	0.499997525	0.400000396	0.247619198	0.04127069173	0.08253890727	0.123809599
		SD3,2 =	0.4999988						
							0.1876990147	0.3146824308	0.4416646417
INTERFERENCE			SD(Ei,Ej) =	AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)	RADi = AAD(Ei)/SUM(AAD(Ei))	wi = r* WF + (1-r)*RADi	SUM (W(i))*Li =		
		SD1,2=	0.6000024	0.7000048	0.325582742	0.305648371	0.2037665995	0.254705957	0.305648371
Expert	Likely	SD1,3=	0.8000072						
Intermediate	Medium								
Developing	Possible	SD2,1 =	0.6000024	0.674999325	0.3139523202	0.2284046601	0.07613412535	0.11420233	0.1522705347
		SD2,3 =	0.74999625						
		SD3,1 =	0.8000072	0.775001725	0.3604649378	0.2278514689	0.1139257345	0.1519017388	0.1898754646
		SD3,2 =	0.74999625						
							0.3938264593	0.5208100258	0.6477943703
No power			SD(Ei,Ej) =	AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)	RADi = AAD(Ei)/SUM(AAD(Ei))	wi = r* WF + (1-r)*RADi	SUM (W(i))*Li =		
		SD1,2=	1	0.749998125	0.3750004687	0.3303572344	0.1651786172	0.2202392574	0.2752965941
Expert	Possible	SD1,3=	0.49999625						
Intermediate	Possible								
Developing	Doubtful	SD2,1 =	1	0.749998125	0.3750004687	0.2589287344	0.1294643672	0.1726200193	0.2157730822
		SD2,3 =	0.49999625						
		SD3,1 =	0.49999625	0.49999625	0.2499990625	0.1726185313	0.0287703306	0.05753893502	0.08630926563
		SD3,2 =	0.49999625						
							0.323413315	0.4503982118	0.577378942

Basic Events		**Aggregated Opinions**			**FPS = COAD(A) = 1/3(a+b+c)**	**alpha = (1/FPS - 1) ^(1/3) * 2.301**	**Failure Probability = 1/ (10^alpha)**
Unforeseen SW error	BE1	0.1876990147	0.3146824308	0.4416646417	0.3146820291	2.982565648	0.001040960744
Interference	BE2	0.3938264593	0.5208100258	0.6477943703	0.5208102852	2.237995783	0.005781016605
No Power	BE3	0.323413315	0.4503982118	0.577378942	0.4503968229	2.458864465	0.003476446374
Queued commands	BE4	0.2182528073	0.3452372874	0.4722239104	0.3452380017	2.848207173	0.001418380747
Low Bandwidth	BE5	0.06547589167	0.1964286917	0.327377956	0.1964275131	3.680082308	0.00020889002
Faulty Hardware	BE6	0.2162714787	0.3511891057	0.4861099469	0.3511901771	2.823416646	0.0015017006
Ionospheric	BE7	0.2115807897	0.3152954955	0.4541832376	0.3270198409	2.926797471	0.001183593383
Ice-covered radome	BE8	0.3384706876	0.4694206553	0.6003727519	0.4694213649	2.396876114	0.004009810847
Modulation	BE9	0.03769909138	0.1468244678	0.293649204	0.1593909211	4.005223762	0.00009880438936
Bitrate	BE10	0.03769909138	0.1468244678	0.293649204	0.1593909211	4.005223762	0.00009880438936
Encoding	BE11	0.1067481049	0.2134898051	0.3484125797	0.2228834966	3.489147736	0.0003242293037
Frequency	BE12	0.03769909138	0.1349196991	0.2698399094	0.1474862333	4.129523332	0.00007421243269
Wind affecting antenna	BE13	0.1559533322	0.2908722975	0.4257918004	0.2908724767	3.096876285	0.0008000621318
Rare bugs in predictor	BE14	0.1607138018	0.261903732	0.3888899024	0.2705024787	3.202831879	0.0006268564827
Wrongly calibrated antenna	BE15	0.2240354873	0.3145252613	0.4415112274	0.3266906587	2.928257469	0.001179621096
TLE	BE16	0.5061067458	0.641023947	0.775945214	0.6410253023	1.896616426	0.01268771966
Mechanical error rotator	BE17	0.2162714787	0.3511891057	0.4861099469	0.3511901771	2.823416646	0.0015017006
MCs	**FP of MCs**	**P(TopEvent) = MCS Union MCS**	**FUSSEL-VESELY IMPORTANCE of MCs**	**MCS RANKING**			
BE1	0.001040960744	0.03438583533	0.03027295206	9			
BE2	0.005781016605		0.1681220348	2			
BE3	0.003476446374		0.1011011174	4			
BE4*BE5	0.0000002962855826		0.000008616500945	16			
BE6	0.0015017006		0.04367206979	5			
BE7	0.001183593383		0.03442095769	7			
BE8	0.004009810847		0.1166122855	3			
BE9	0.00009880438936		0.002873403784	13			
BE10	0.00009880438936		0.002873403784	14			
BE11	0.0003242293037		0.009429153038	12			
BE12	0.00007421243269		0.002158226839	15			
BE13	0.0008000621318		0.0232672007	10			
BE14	0.0006268564827		0.01823007865	11			
BE15	0.001179621096		0.03430543665	8			
BE16	0.01268771966		0.368980993	1			
BE17	0.0015017006		0.04367206979	6			

Ground Station Receiving Too Noisy Or Weak Signal

WIND AFFECTING					Novice = 4.761904	Developing = 9.5238	Intermediate = 14.2857	Proficient = 19.04761	Advanced = 23.8095	Expert = 28.5714
			SD(Ei,Ej) =	**AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)**	**RADi = AAD(Ei)/SUM(AAD(Ei))**	**wi = r* WF + (1-r)*RADi**		**SUM (W(i))*Li =**		
		SD1,2=	0.4999988	0.3749981625	0.300000312	0.221428656		0	0.03690478338	0.0738088139
Intermediate	Unlikely	SD1,3=	0.249997525							
Expert	Doubtful									
Developing	Possible	SD2,1 =	0.4999988	0.499997525	0.400000396	0.342857198		0.05714400919	0.1142845898	0.171428599
		SD2,3 =	0.49999625							
		SD3,1 =	0.249997525	0.3749968875	0.299999292	0.197599646		0.098799823	0.131733756	0.164665713
		SD3,2 =	0.49999625					**SUM a,b,c,=**		
								0.1559438322	**0.2829231292**	**0.4099031259**
RARE BUGS						0.04761904	0.095238	0.142857	0.1904761	0.238095
			SD(Ei,Ej) =	**AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)**	**RADi = AAD(Ei)/SUM(AAD(Ei))**	**wi = r* WF + (1-r)*RADi**		**SUM (W(i))*Li =**		
Novice	Medium	SD1,2=	1	0.66666585	0.400000294	0.223809667		0.0746024763	0.1119048335	0.1492071907
Expert	Medium	SD1,3=	0.3333317							
Developing	Unlikely									
		SD2,1 =	1	0.66666585	0.400000294	0.342857147		0.1142845728	0.1714285735	0.2285725742
		SD2,3 =	0.3333317							
		SD3,1 =	0.3333317	0.3333317	0.199999412	0.147618706		0	0.02460312259	0.04920574327
		SD3,2 =	0.3333317					**SUM a,b,c**		
								0.1888870491	**0.3079365296**	**0.4269855082**
ANTENNA WRONG CALIB					ANTENNA WRONG CALIB					
			SD(Ei,Ej) =	**AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)**	**RADi = AAD(Ei)/SUM(AAD(Ei))**	**wi = r* WF + (1-r)*RADi**		**SUM (W(i))*Li =**		
Developing	Medium	SD1,2=	0.0833335	0.2083326	0.2380945292	0.1666662646		0.05555486599	0.08333313231	0.1111113986
Expert	Very unlikely	SD1,3=	0.3333317							
Developing	Unlikely									
		SD2,1 =	0.0833335	0.1666676125	0.2500013219	0.2678576609		0	0	0.04464303278
		SD2,3 =	0.250001725							
		SD3,1 =	0.3333317	0.2916667125	0.4374998992	0.2663689496		0	0.04439483381	0.08878876197
		SD3,2 =	0.250001725					SUM a,b,c		
								0.05555486599	0.1277279661	0.2445431934
MECHANICAL ERROR ROTATOR						ERROR ROTATOR				
			SD(Ei,Ej) =	**AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)**	**RADi = AAD(Ei)/SUM(AAD(Ei))**	**wi = r* WF + (1-r)*RADi**		**SUM (W(i))*Li =**		
Developing	Doubtful	SD1,2=	1	1	0.3333333333	0.2142856667		0.03571499206	0.07142784127	0.1071428333
Expert	Doubtful	SD1,3=	1							
Developing	Doubtful									
		SD2,1 =	1	1	0.3333333333	0.3095236667		0.05158830952	0.1031735238	0.1547618333
		SD2,3 =	1							
		SD3,1 =	1	1	0.3333333333	0.2142856667		0.03571499206	0.07142784127	0.1071428333
		SD3,2 =	1					SUM a,b,c,		
								0.1230182937	0.2460292064	0.3690475
WRONG FREQUENCY			WRONG FREQ			0.04761904	0.095238	0.142857	0.1904761	0.238095
			SD(Ei,Ej) =	**AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)**	**RADi = AAD(Ei)/SUM(AAD(Ei))**	**wi = r* WF + (1-r)*RADi**		**SUM (W(i))*Li =**		
Intermediate	Possible	SD1,2=	0.249997525	0.1562486688	0.2777758741	0.210316437		0.1051582185	0.1402116591	0.1752629965
Expert	Unlikely	SD1,3=	0.0624998125							
Intermediate	Very unlikely									
		SD2,1 =	0.249997525	0.249999625	0.4444445185	0.3650792593		0	0.06084655538	0.1216918695
		SD2,3 =	0.250001725							
		SD3,1 =	0.0624998125	0.1562507688	0.2777796074	0.2103183037		0	0	0.03505312072
		SD3,2 =	0.250001725					SUM a,b,c		
								0.1051582185	0.2010582145	0.3320079867

WRONG BITRATE					WRONG BITRATE					
			SD(Ei,Ej) =	**AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)**	**RADi = AAD(Ei)/SUM(AAD(Ei))**	**wi = r* WF + (1-r)*RADi**		**SUM (W(i))*Li =**		
Developing	Possible	SD1,2=	0.249997525	0.3749968875	0.2307688118	0.1630034059		0.08150170296	0.1086694806	0.1358356283
Expert	Unlikely	SD1,3=	0.49999625							
Intermediate	Doubtful									
		SD2,1 =	0.249997525	0.3749981625	0.300000312	0.292857156		0	0.04880953576	0.09761807581
		SD2,3 =	0.4999988							
		SD3,1 =	0.49999625	0.499997525	0.400000396	0.271428698		0.0452390211	0.0904753279	0.135714349
		SD3,2 =	0.4999988					**SUM a,b,c**		
								0.1267407241	**0.2479543443**	**0.3691680531**
WRONG MODULATON					WRONG MODULATION					
			SD(Ei,Ej) =	**AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)**	**RADi = AAD(Ei)/SUM(AAD(Ei))**	**wi = r* WF + (1-r)*RADi**		**SUM (W(i))*Li =**		
Intermediate	Doubtful	SD1,2=	0.4999988	0.7499994	0.37500015	0.258928575		0.0431556256	0.0863086619	0.1294642875
Expert	Unlikely	SD1,3=	1							
Intermediate	Doubtful									
		SD2,1 =	0.4999988	0.4999988	0.2499997	0.26785685		0	0.04464281726	0.08928472381
		SD2,3 =	0.4999988							
		SD3,1 =	1	0.7499994	0.37500015	0.258928575		0.0431556256	0.0863086619	0.1294642875
		SD3,2 =	0.4999988					SUM a,b,c		
								0.08631125119	0.2172601411	0.3482132988
IMPROPER GROUNDING										
			SD(Ei,Ej) =	**AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)**	**RADi = AAD(Ei)/SUM(AAD(Ei))**	**wi = r* WF + (1-r)*RADi**		**SUM (W(i))*Li =**		
Proficient	Medium	SD1,2=	0.3333317	0.16666585	0.1111107481	0.1507934241		0.05026397205	0.07539671204	0.100529452
Proficient	Unlikely	SD1,3=	0.3333317							
Novice	Unlikely									
		SD2,1 =	0.3333317	0.66666585	0.4444446259	0.317460363		0	0.05291007108	0.1058190628
		SD2,3 =	1							
		SD3,1 =	0.3333317	0.66666585	0.4444446259	0.246031833		0	0.04100531369	0.08200979088
		SD3,2 =	1					SUM a,b,c		
								0.05026397205	0.1693120968	0.2883583057
SHORTED CIRCUIT				SHORTED CIRCUIT			SHORTED CIRCUIT			
			SD(Ei,Ej) =	**AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)**	**RADi = AAD(Ei)/SUM(AAD(Ei))**	**wi = r* WF + (1-r)*RADi**		**SUM (W(i))*Li =**		
Proficient	Possible	SD1,2=	0.0624998125	0.03124990625	0.07142860204	0.130952351		0.06547617551	0.08730200385	0.1091265227
Expert	Very unlikely	SD1,3=	0.49999625							
Developing	Doubtful									
		SD2,1 =	0.0624998125	0.0937501875	0.2142868776	0.2500004388		0	0	0.04166682313
		SD2,3 =	0.1250005625							
		SD3,1 =	0.49999625	0.3124984063	0.7142845204	0.4047612602		0.06746155924	0.1349190709	0.2023806301
		SD3,2 =	0.1250005625					SUM a,b,c		
								0.1329377347	0.2222210747	0.3531739759
POOR WIRING					0.04761904	0.095238	0.142857	0.1904761	0.238095	0.285714
			SD(Ei,Ej) =	AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)	RADi = AAD(Ei)/SUM(AAD(Ei))	wi = r* WF + (1-r)*RADi		SUM (W(i))*Li =		
Proficient	Possible	SD1,2=	0.249997525	0.1249987625	0.09090843637	0.1645017182		0.08225085909	0.1096683605	0.1370842168
Advanced	Unlikely	SD1,3=	0.249997525							
Developing	Unlikely									
		SD2,1 =	0.249997525	0.6249987625	0.4545457818	0.3463203909		0	0.0577200767	0.1154389759
		SD2,3 =	1							
		SD3,1 =	0.249997525	0.6249987625	0.4545457818	0.2748918909		0	0.04581532431	0.091629714
		SD3,2 =	1					SUM a,b,c		
								0.08225085909	0.2132037615	0.3441529067

CLOSE PROXIMITY									CLOSE PROXIMITY
			SD(Ei,Ej) =	AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)	RADi = AAD(Ei)/SUM(AAD(Ei))	wi = r* WF + (1-r)*RADi	SUM (W(i))*Li =		
Proficient	Likely	SD1,2=	0.19999982	0.09999991	0.1111111444	0.1507936222	0.1005295841	0.1256608492	0.1507936222
Advanced	Unlikely	SD1,3=	0.4000006						
Developing	Doubtful								
		SD2,1 =	0.19999982	0.34999931	0.3888885889	0.3134917944	0	0.05224864286	0.1044962198
		SD2,3 =	0.4999988						
		SD3,1 =	0.4000006	0.4499997	0.5000002667	0.2976191333	0.04960418095	0.09920538571	0.1488095667
		SD3,2 =	0.4999988				SUM a,b,c		
							0.1501337651	0.2771148778	0.4040994087
LONG CABLE INTERF									
			SD(Ei,Ej) =	AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)	RADi = AAD(Ei)/SUM(AAD(Ei))	wi = r* WF + (1-r)*RADi	SUM (W(i))*Li =		
Intermediate	Medium	SD1,2=	0.3333317	0.16666585	0.1428568918	0.1428569459	0.04761850578	0.07142847296	0.09523844014
Expert	Unlikely	SD1,3=	0.666665						
Developing	Doubtful								
		SD2,1 =	0.3333317	0.41666525	0.3571427653	0.3214283827	0	0.05357140782	0.1071417228
		SD2,3 =	0.4999988						
		SD3,1 =	0.666665	0.5833319	0.5000003429	0.2976191714	0.0496041873	0.09920539841	0.1488095857
		SD3,2 =	0.4999988				SUM a,b,c		
							0.09722269308	0.2242052792	0.3511897486
WRONG ENCODING									
			SD(Ei,Ej) =	AAD(Ei) = 1/n-1 * sum(SD(Ei, EEj)	RADi = AAD(Ei)/SUM(AAD(Ei))	wi = r* WF + (1-r)*RADi	SUM (W(i))*Li =		
Intermediate	Unlikely	SD1,2=	0.4999988	0.2499994	0.1666665333	0.1547617667	0	0.02579363294	0.05158673968
Expert	Doubtful	SD1,3=	1						
Intermediate	Unlikely								
		SD2,1 =	0.4999988	0.4999988	0.3333330667	0.3095235333	0.0515882873	0.1031734794	0.1547617667
		SD2,3 =	0.4999988						
		SD3,1 =	1	0.7499994	0.5000004	0.3214287	0	0.05357146071	0.1071418286
		SD3,2 =	0.4999988				SUM a,b,c		
							0.0515882873	0.182538573	0.3134903349

Basic Events		Aggregated			FPS = COAD(A) = 1/3(a+b+c)	
WIND AFFECTING	BE1	0.1559438322	0.2829231292	0.4099031259	0.2829233624	
RARE BUGS	BE2	0.1888870491	0.3079365296	0.4269855082	0.3079363623	
ANTENNA WRONG CALIB	BE3	0.05555486599	0.1277279661	0.2445431934	0.1426086752	
MECHANICAL ERROR ROTATOR	BE4	0.1230182937	0.2460292064	0.3690475	0.2460316667	
WRONG FREQUENCY	BE5	0.1051582185	0.2010582145	0.3320079867	0.2127414732	
WRONG ENCODING	BE6	0.0515882873	0.182538573	0.3134903349	0.1825390651	
WRONG BITRATE	BE7	0.1267407241	0.2479543443	0.3691680531	0.2479543738	
WRONG MODULATON	BE8	0.08631125119	0.2172601411	0.3482132988	0.2172615637	
IMPROPER GROUNDING	BE9	0.05026397205	0.1693120968	0.2883583057	0.1693114582	
SHORTED CIRCUIT	BE10	0.1329377347	0.2222210747	0.3531739759	0.2361109285	
POOR WIRING	BE11	0.08225085909	0.2132037615	0.3441529067	0.2132025091	
CLOSE PROXIMITY	BE12	0.1501337651	0.2771148778	0.4040994087	0.2771160172	
LONG CABLE INTERF	BE13	0.09722269308	0.2242052792	0.3511897486	0.224205907	
alpha = (1/FPS - 1) ^(1/3) * 2.301	**Failure Probability = 1/ (10^alpha)**	**MCs**	**FP of MCSi**	**P(TopEvent) = MCS Union MCS**	**FUSSEL-VESELY IMPORTANCE of MCs**	**MCS RANKING**
3.137248157	0.0007290408154	BE1	0.0007290408154	0.005225629306	0.1395125396	2
3.014011956	0.0009682512006	BE2	0.0009682512006		0.1852889181	1
4.184025588	0.00006545976045	BE3	0.00006545976045		0.01252667509	13
3.342237577	0.0004547392305	BE4	0.0004547392305		0.08702095076	5
3.559084962	0.0002760037848	BE5	0.0002760037848		0.05281732949	10
3.792745315	0.0001611590448	BE6	0.0001611590448		0.0308401219	11
3.33074019	0.0004669386356	BE7	0.0004669386356		0.08935548395	4
3.52745275	0.0002968569697	BE8	0.0002968569697		0.05680788903	8
3.909914333	0.0001230511473	BE9	0.0001230511473		0.0235476227	12
3.4032043	0.0003951806761	BE10	0.0003951806761		0.07562355708	6
3.555823291	0.0002780844528	BE11	0.0002780844528		0.05321549549	9
3.167516918	0.0006799595566	BE12	0.0006799595566		0.1301201285	3
3.480297942	0.0003309040313	BE13	0.0003309040313		0.06332328833	7

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