# Modeling to Improve the Risk Reduction Process for Command File Errors

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The Jet Propulsion Laboratory has learned that even innocuous errors in the spacecraft command process can have significantly detrimental effects on a space mission. Consequently, such Command File Errors (CFE), regardless of their effect on the spacecraft, are treated as significant events for which a root cause is identified and corrected. A CFE during space mission operations is often the symptom of imbalance or inadequacy within the system that encompasses the hardware and software used for command generation as well as the human experts and processes involved in this endeavor. As we move into an era of increased collaboration with other NASA centers and commercial partners, these systems become more and more complex. Consequently, the ability to thoroughly model and analyze CFEs formally in order to reduce the risk they pose is increasingly important. In this paper, we summarize the results of applying modeling techniques previously developed to the DAWN flight project. The original models were built with the input of subject matter experts from several flight projects. We have now customized these models to address specific questions for the DAWN flight project and formulating use cases to address their unique mission needs. The goal of this effort is to enhance the project's ability to meet commanding reliability requirements for operations and to assist them in managing their Command File Errors.

## Introduction

Command Errors have been documented and studied by the Jet Propulsion Laboratory (JPL) Office of Safety and Mission Success (OSMS) and our industrial partners for well over a decade [10, 11, and 12]. Initially the effort and definitions were somewhat informal but have increased in rigor with time. Since a discussion with a half dozen space operations personnel will arrive at a half dozen different ideas of what a Command Error is, JPL's OSMS adopted a formal definition for a Command File Error (CFE). A CFE is now defined in JPL's Anomaly Resolution Requirements document as:

One of the following regardless of the effect on the spacecraft:

- An error in a command file that was sent to the spacecraft
- An error in the approval, processing, or unlinking of a command file that was sent to the spacecraft
- The omission of a command file that should have been sent to the spacecraft

With the instantiation of this definition, it is possible to move from gathering raw, and sometimes intuitive, data as reported in "Improving Operations: Metrics to Results"[1] to collecting data that actually facilitates analysis and modeling of CFEs. A module, which captures information specific to CFEs, is now included in JPL's Problem Reporting System (PRS) Incident, Surprise, Anomaly (ISA) report generation tool. ISAs are the reports used to document the occurrence, analysis, and corrective action of anomalies occurring during mission operations. PRS is JPL's institutional tool for documenting both development phase and operational phase anomalies for space exploration flight projects and JPL managed instruments on non-JPL spacecraft. In addition to capturing data to categorize the CFE such as process details, a most important feature of the module is the collection of contributing, proximate, and root cause details as provided/validated by a project's Mission Operations Assurance Manager (MOAM). Study of these cause descriptions provides a valuable input for modeling CFE causes in order to determine which responses or process changes can provide the most value added for reducing the likelihood of CFEs.

The modeling approach employed two distinct approaches initially and relies upon the collection of data from subject matter experts on a number of JPL flight projects. The Probabilistic Risk Assessment (PRA) model focuses on the command process used for most mission operations by JPL flight projects. The second, a Bayesian Belief Network (BBN) captures the different types and causes of CFEs. Initial results and findings from this model

development approach were reported at the Aerospace Sciences Meeting (ASM) 2013 in "Managing the Risk of Command File Errors" [1]. As articulated in the paper, the authors came to this conclusion:

> The models that were developed are now ready for use within each of the projects to enable them to more fully assess and manage the risk of CFEs. The intent of the authors is to work individually with each of the projects that provided the input data to develop case studies of operational scenarios and associated CFE risk for each. We will address questions that are posed to the projects during reviews to provide them more insight into the modeling process and explore their options for making use of these tools and improve the CFE risk posture on their project. This will most likely require us to add depth and detail associated with each project in a customized manner for that project. The objective of this work is to assist each project in identifying the elements of the command file generation process which have the most potential for cost effectively providing an opportunity to reduce the risk of CFEs. Several projects included in this work have developed process improvement changes to reduce their vulnerability to CFEs. However, even with years of experience, it is difficult at best to take all the contributing factors for CFEs into consideration at once. The models developed here can do that and thus have the potential to identify new areas for improvement that were inadvertently missed in discussions and reviews to date. Extending the model usage and determining their value to each project is a primary direction we plan to continue with in this effort.[2]

To move forward as outlined here, the decision to work next with the Dawn project was a straight forward one. Dawn recently finished a very demanding operational period exploring the asteroid Vesta. The first of two initial questions was whether the CFEs encountered prior to and during the Vesta campaign were out of family with the rest of the mission and possibly the result of the high intensity activity. The second question was whether steps could be taken after studying Vesta to cost effectively reduce the likelihood of CFEs during the upcoming campaign at the asteroid Ceres. None of the CFEs Dawn encountered during the Vesta preparation and execution posed a serious threat to the mission. However, past experience has shown that there is risk from even innocuous errors in commanding a spacecraft.

The untimely demise of the Mars Global Surveyor (MGS) has been well documented and thoroughly studied since its failure in November 2006. There was a string of events, including CFEs that occurred to reach this unfortunate conclusion. The chain of events began in September 2005 when it was time to update the control parameters for the positioning angle of the High Gain Antenna (HGA) when in Contingency Mode. The parameters were intended to be the same on both sides of the MGS Command and Data Handling (C&DH) system. However, because the updates were done at two different times and with slightly different precision, the values were not identical (CFE – error in a command file sent to the spacecraft). A subsequent memory readout revealed that the parameters were different, and even though numerically inconsequential, the difference warranted a correction. This correction was attempted in June of 2006. A number of factors influencing the update process led to the incorrect memory address being specified for the upload. The correct parameters were sent to the wrong memory location (CFE – error in a command file sent to the spacecraft) resulting in two crucial parameters being corrupted. As described in the MGS Operations Review Board Report on the Loss of MGS:[3]

> The first parameter error allowed one solar array to be driven later against its hard stop, leading the MGS fault-protection system to incorrectly assume it had a stuck gimbal and causing MGS to enter Contingency Mode. Upon entry into Contingency Mode, the spacecraft's orientation was such that one of the batteries was directly exposed to the sun. This caused the battery to overheat, which in turn gave an indication of an overcharged battery, and led to the premature termination of battery charging on each subsequent orbit. Even though the remaining battery continued to be charged, it was not being charged sufficiently to support the full electrical load, which was normally supported by both batteries. The end result was that both batteries were depleted, probably within 12 hours. The second parameter error caused the HGA to point away from the Earth when the spacecraft was, in fact, properly oriented to communicate to Earth. Communication from the spacecraft to the ground was therefore impossible, and the unsafe thermal and power situation could not be identified by the MGS's ground controllers.

Thus, a minor error in precision for a parameter update in the fall of 2005 was followed by an unnoticed error in mid 2006, which resulted in a catastrophic event in November 2006. Because such apparently benign events can align themselves to have dire consequences, flight projects at JPL are very motivated to explore actions which can enhance their ability to avoid CFEs. Developing models to use as tools in decision making regarding which actions are the most value added is an approach we are assessing and describing in this paper. The tailoring of the models to Dawn and the results of this collaboration with the flight project are addressed in the remainder of this paper.

## Probabilistic Modeling Approach

Command File Errors are by nature probabilistic. There is no certainty about whether or not they'll occur. When they do occur, it's usually due to a sequence or combination of events. Diagnosis initially involves probabilistic analysis until further evidence leads to exact cause. Therefore they are amenable to probabilistic modeling and analysis techniques. A brief overview of the types of probabilistic analysis techniques we have used for this purpose was presented in [1]. In this paper, we demonstrate the application of these techniques to a specific flight project and present the numerical results from those studies.

### Analyzing Command File Error Rates

All spacecraft CFE errors are collected, organized and examined closely at JPL. The goal is to ensure that the error rates are kept within reasonable bounds, to address root cause of issues and to lower the rates as much as possible.

In some cases, there is a need for a more in-depth analysis. The case we are reporting in this paper is regarding the DAWN spacecraft which appeared to have an elevated CFE rate in 2012. Figure 1 shows the error rate per month.

The approach used for this analysis was to consider the error rates of comparable spacecraft during the various phases of operations and to use probabilistic distributions to assess whether or not the error rates experienced by DAWN were reasonable.

Let's assume that the long term average CFE rate for comparable spacecraft is (0.8%-1.01%) in critical phases and (0.3%-0.5%) in low activity phases [4,5]. Now the occurrence of a CFE can be considered a Bernoulli trial with a probability $p$ of error. Therefore, we can use a Binomial distribution to determine the probability of $r$ CFE's in $n$ trials. This distribution will have a mean and a standard deviation and we can use this information to determine how much the perceived error rates have deviated from their expected values in each of these intervals.

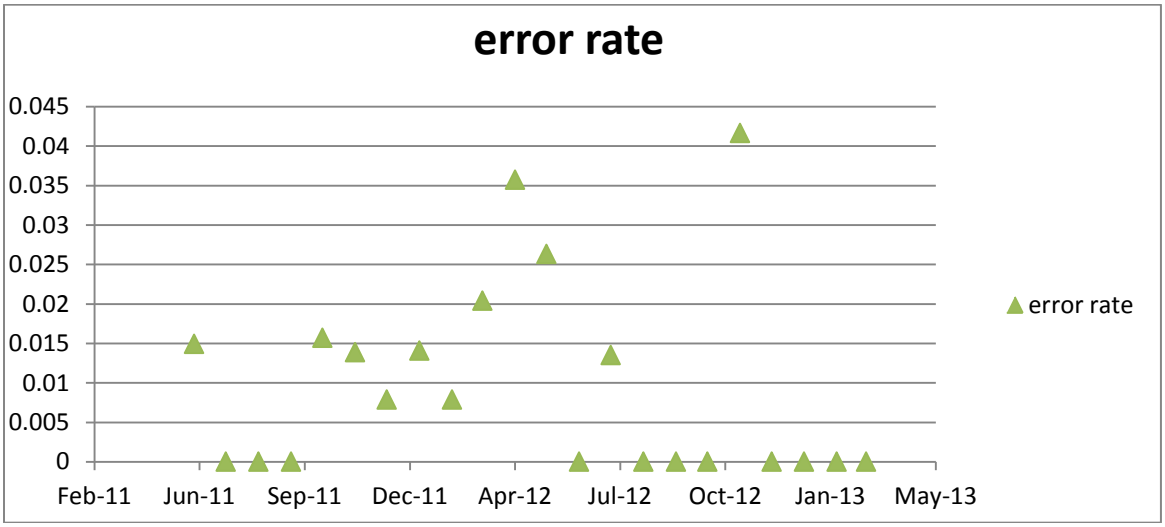


**Figure 1: Monthly Error Rates for the DAWN project**

| Month | commands | errors | Probability of errors as occurred | mean number of errors | sigma for cfe's | distance from the mean (multiples of sigma) |
|---|---|---|---|---|---|---|
| 11-Jun | 67 | 1 | 0.35 | 0.67 | 0.81 | 0.41 |
| 11-Jul | 124 | 0 | 0.28 | 1.24 | 1.10 | -1.13 |
| 11-Aug | 171 | 0 | 0.18 | 1.70 | 1.29 | -1.32 |
| 11-Sep | 127 | 0 | 0.27 | 1.27 | 1.12 | -1.13 |
| 11-Oct | 191 | 3 | 0.22 | 1.91 | 1.37 | 0.80 |
| 11-Nov | 72 | 1 | 0.35 | 0.72 | 0.84 | 0.33 |
| 11-Dec | 127 | 1 | 0.36 | 1.27 | 1.12 | -0.24 |
| 12-Jan | 142 | 2 | 0.25 | 1.42 | 1.18 | 0.49 |
| 12-Feb | 127 | 1 | 0.36 | 1.27 | 1.12 | -0.24 |
| 12-Mar | 49 | 1 | 0.30 | 0.49 | 0.69 | 0.74 |
| 12-Apr | 56 | 2 | 0.09 | 0.56 | 0.74 | 1.95 |
| 12-May | 76 | 2 | 0.14 | 0.76 | 0.86 | 1.44 |
| 12-Jun | 103 | 0 | 0.36 | 1.03 | 1.00 | -1.03 |
| 12-Jul | 74 | 1 | 0.36 | 0.74 | 0.86 | 0.30 |
| 12-Aug | 61 | 0 | 0.54 | 0.61 | 0.77 | -0.79 |
| 12-Sep | 21 | 0 | 0.80 | 0.21 | 0.46 | -0.46 |
| 12-Oct | 22 | 0 | 0.80 | 0.22 | 0.46 | -0.48 |
| 12-Nov | 24 | 1 | 0.19 | 0.24 | 0.48 | 1.58 |
| 12-Dec | 19 | 0 | 0.82 | 0.19 | 0.43 | -0.44 |
| 13-Jan | 14 | 0 | 0.87 | 0.14 | 0.37 | -0.38 |
| 13-Feb | 11 | 0 | 0.89 | 0.11 | 0.33 | -0.33 |
| 13-Mar | 59 | 0 | 0.55 | 0.59 | 0.76 | -0.78 |

**Table 1: An assessment of the monthly mean and standard deviation considering the Binomial distribution**

Table 1 shows the exact number of errors in each month, the probability that this number of errors would have occurred given a binomial distribution based on the average probability of errors for comparable missions, the mean and standard deviation for the distribution and the distance from the mean in terms of multiples of the standard deviation for each month. As it can be seen, the two months that have had the highest error rates are still within 2 standard deviations of the mean and the overall error rates are within the range of comparable missions.

The key take-away point is that some months have a very low total number of command files sent. If we merely look at the error rates within these months, it appears that they are elevated. But if we put it in the context of the appropriate Binomial probabilistic distribution, it becomes clear that the probability of their occurrence is not too low. An analogy would be rolling a dice only a few times and being concerned that the percentage of occurrence of a certain observation is more than 1/6 and thereby concluding that the dice is not a fair dice.

## Systems Analysis Using Bayesian Belief Networks

In order to manage CFE's, it's important to take into consideration all their possible causes, and the inter-relationships between these causes and each of their effects. This can be represented with a Directed Acyclic Graph (DAG). Furthermore, the probabilistic relationships between the nodes in this network can be captured and analyzed using Bayesian techniques [6, 8, and 9]. Hence the applicability of Bayesian Belief Networks (BBNs) for the systems analysis and management of CFEs.

An overarching BBN model representing the body of knowledge associated with the occurrence of CFE's was initially developed based on interviews with key experts, and assessment of existing data and knowledge bases [4,5,10]. Since it is based on knowledge and data from multiple missions, we call this the multi-mission model. In this section, we describe the model that was customized for the DAWN spacecraft based on the mission specific information for this project.

The DAWN BBN nodes represent a customized subset of the generalized, multi-mission model. Furthermore, the model nodes were regrouped into two major subsets: the mission system or hard factors and the

operator cognition or soft factors. The full model is shown in figure 2. This model has a total of 37 nodes. More legible models of each of the two branches, mission system and operator cognition are shown in figures 3 and 4 respectively.

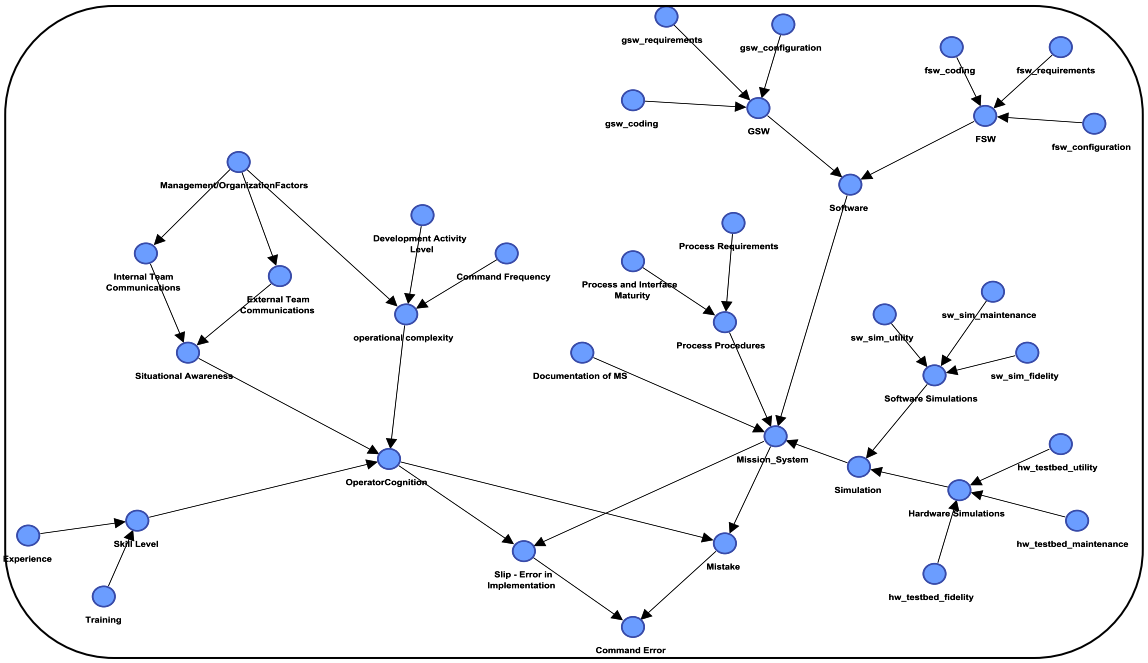


**Figure 2: Full BBN model for the DAWN CFE's.**

The root node of this model is a "Command Error" which is used as an abbreviation for a CFE. The idea is that this can be caused by a "slip" or a "mistake" [1, 2, and 3]. A slip occurs when the operators intended course of action is correct but the implementation is not. A mistake occurs when the operators intended course of action is incorrect. Both slips and mistakes can be due to soft or hard factors. Soft factors have to do with the cognitive abilities of the operator and hard factors all the external tools, processes, models, hardware or software that has an effect on the understanding the operator has of the state of the spacecraft and the best course of action associated with it.

The operator cognition, in turn, is dependent on the operators' skill level and situational awareness as well as the operational complexity of the mission. The skill level of the operator is determined by the operators experience and training. It's important to note that each of the non-leaf nodes in the BBN correspond to a conditional probability table (CPT). For instance, the CPT corresponding to "Skill Level" is shown in table 2. The states associated with "skill level" are "Novice", "Journeyman" and "Expert". The CPT shows the probability of being in each of these states for the various states of its input nodes which include "Training" and "Experience". For instance, if the training level of the operator is adequate, and the experience high, there's a 90% chance that the operator is an expert, a 10% chance the operator is a journeyman and a 0% chance the operator is a novice.

| Skill Level | | | | |
|---|---|---|---|---|
| **Training** | **Experience** | **Novice** | **Journeyman** | **Expert** |
| **Adequate** | **Low** | 80.0000 | 20.0000 | 0.0000 |
| | **High** | 0.0000 | 10.0000 | 90.0000 |
| **Inadequate** | **Low** | 100.0000 | 0.0000 | 0.0000 |
| | **High** | 10.0000 | 20.0000 | 70.0000 |

**Table 2: Conditional Probability Table (CPT) associated with the node "Skill Level".**

Each of the leaf nodes of the BBN correspond to a prior probability distribution for the associated node. The prior probability distribution for the nodes “Experience” and “Training” are shown in table 3.

| Experience | |
|---|---|
| Low | High |
| 30.0000 | 70.0000 |

| Training | |
|---|---|
| Adequate | Inadequate |
| 90.0000 | 10.0000 |

**Table 3: Prior probability distribution for the leaf nodes “Experience” and “Training”**

The situational awareness depends on the communications internally within the JPL team and the communications with the external partners outside of JPL. The adequacy of the communications then depends on the management and organizational factors. On the other hand, the operator cognition also depends on the operational complexity of the mission which in turn depends on the level of development activities as well as the command file frequency.

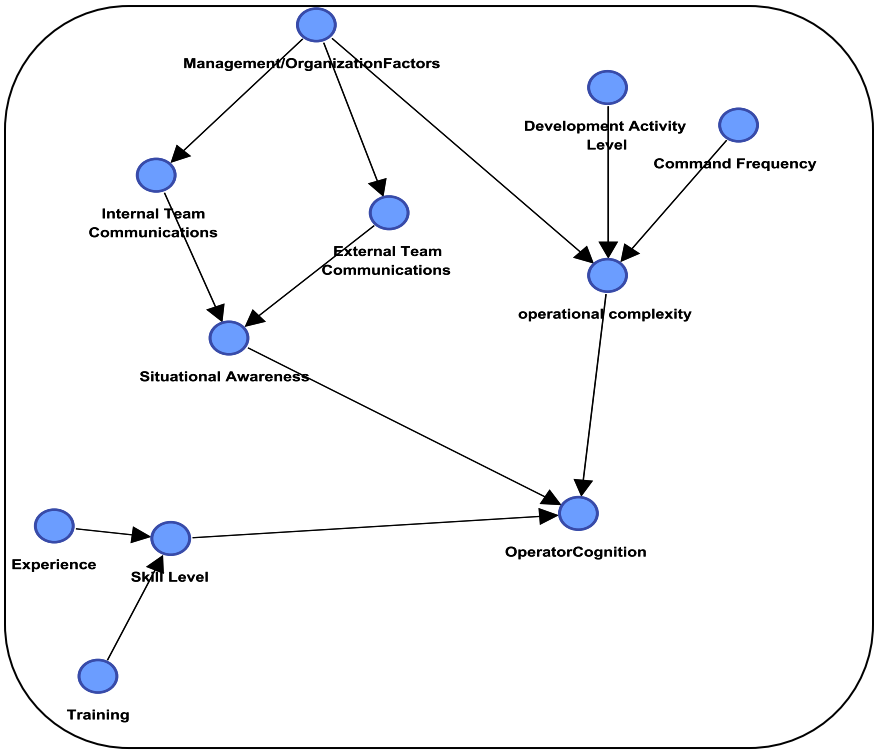


**Figure 3: Soft factors, or Operator Cognition branch of DAWN BBN.**

The hard factors or Mission System is shown in figure 4. The adequacy of the Mission System depends on the process procedures, the documentation of the flight system (note that the flight system for DAWN was developed by a contractor so the quality of the documentation is extremely important for the current JPL operators of the mission.), software and simulations. The elements feeding into the process procedures include the process requirements and process and interface maturity. The software, on the other hand, is divided into ground software and flight software. The level of adequacy of each of these depends on the state of the coding, configurations and requirements associated with them. The simulations include software and hardware simulations. As it pertains to CFE’s, the adequacy of each of these simulations depends on their level of maintenance, the fidelity of their results and their level of utility or user friendliness.

All the nodes in the BBN have multiple states associated with them. Each of the nodes with incoming arrows have CPT's associated with them and the leaf or parent nodes with no incoming arrows have prior probabilities of being in each of their corresponding states associated with them. BBN models can be used for sensitivity analysis, probabilistic root cause analysis and for anticipating CFE rates for a given set of parameters. We will now discuss several use cases to demonstrate each of these.

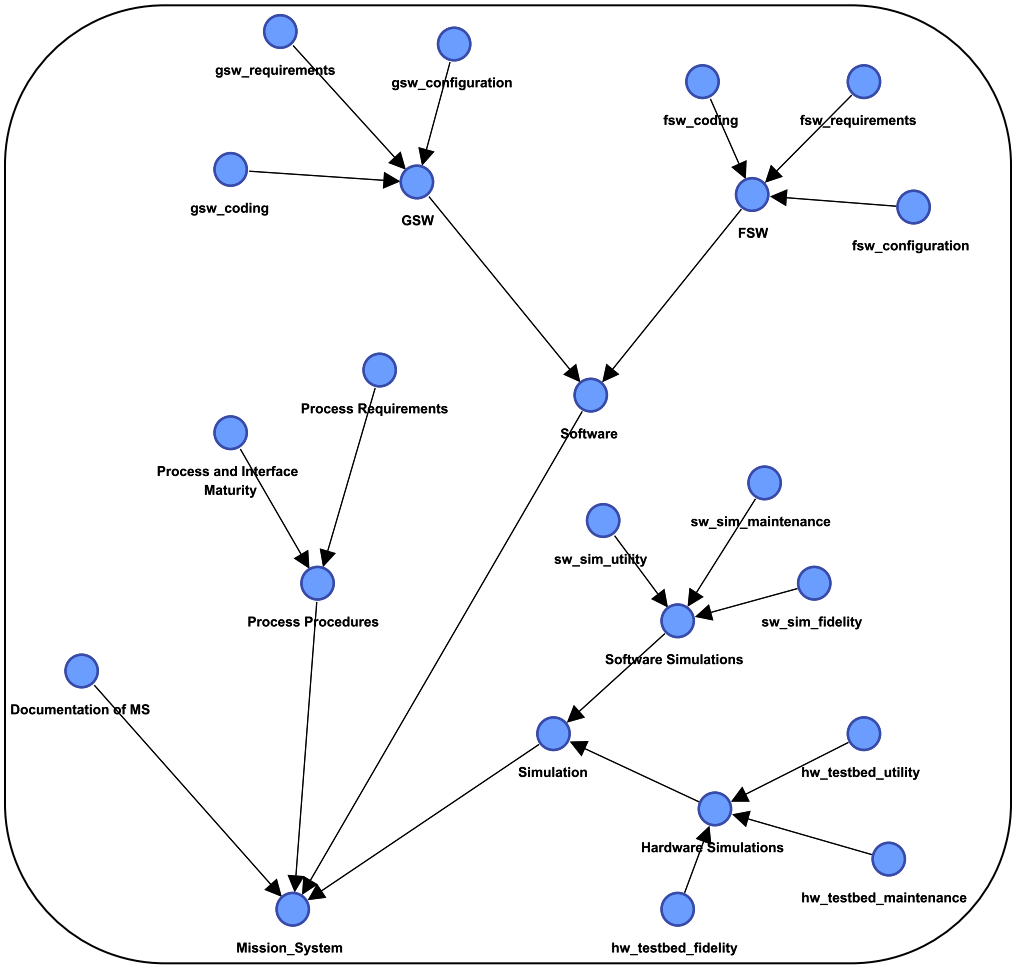


**Figure 4: Hard Factors or Mission System branch of DAWN BBN.**

### Use Case 1: Anticipating future CFE rates

The mission system or hard factors associated with DAWN are not expected to change in the near future. Therefore we consider the probabilities associated with the leaf nodes and conditional probability tables of that branch of the BBN to be constant. The variables in the soft factors branch of the BBN, though, are expected to change and by assessing their contribution to the command file error probability, the project is able to manage the risk of CFE's by planning for those changes appropriately. For this particular use case, we look at the effect of an increase in the level of the development activity and command file frequency on the probability of CFEs. For this purpose, we first set these levels to low (figure 5). For a low level of development activity and command file frequency, the operational complexity, which is a function of these variables as well as the management/organization factors , is distributed across the states (low, medium, high) by (0.88,0.0905,0.0295). The Operator Cognition which is a function of operational complexity as well as situational awareness becomes 84.79%

correct and the likelihood of a slip is 0.96% and a command file error 0.54% (note that not all slips cause command file errors as some may be caught and mitigated.)

Figure 6 shows the scenario where both the development activity and command file frequency are high and how these values ripple through their dependent variables. As can be seen, the operational complexity becomes 81% high, the operator cognition drops to only 69.16% correct and the likelihood of a slip goes up to 1.89% and the probability of a command file error goes up to 1.05%. In other words, the probability of a CFE is extremely sensitive to the level of development activity and command file frequency. These are two variables that projects are able to manage by adequately planning to distribute the development activities across time and compensating for durations of high command file frequency by increasing the workforce and such.

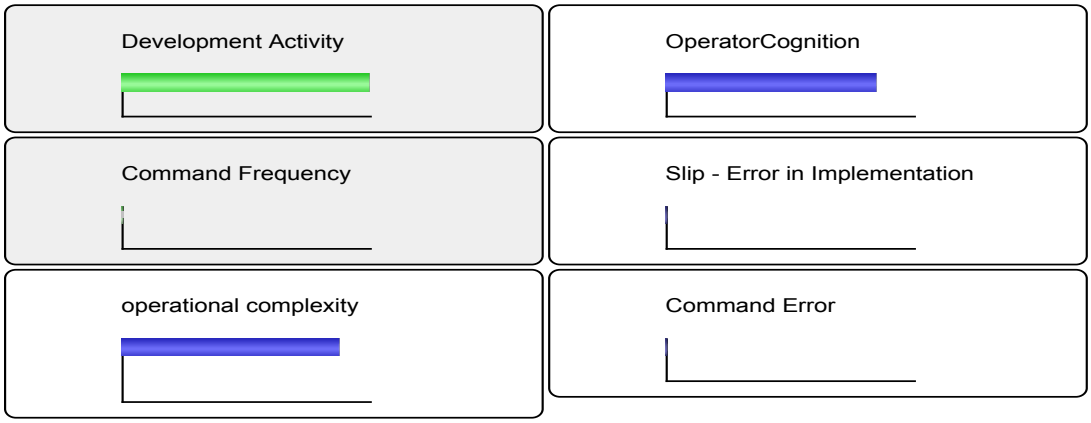


**Figure 5: CFE rates for low development, low command file frequency**

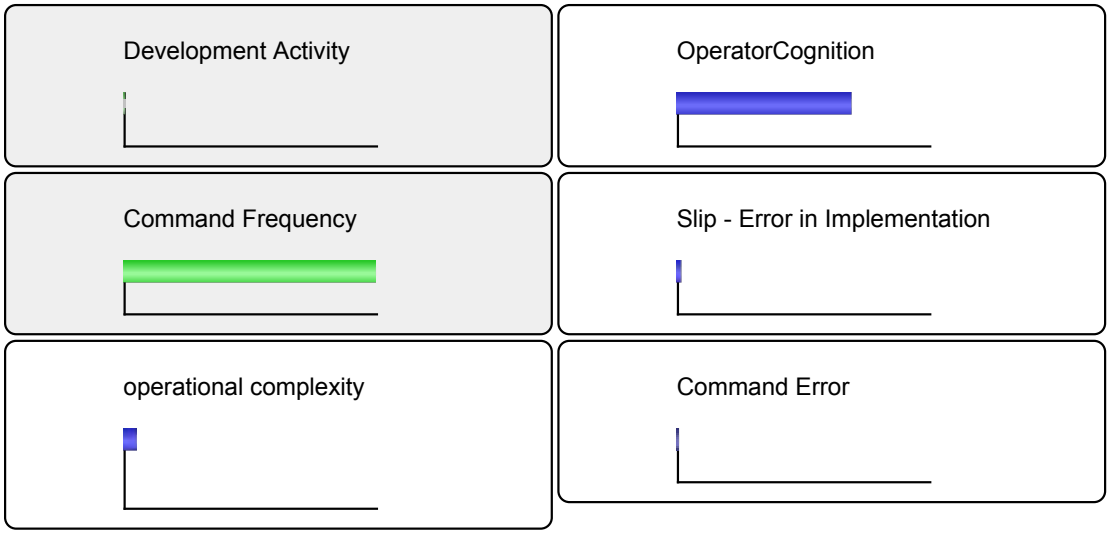


**Figure 6: CFE rates for high development activity, high command file frequency.**

### Use Case 2: Probabilistic root cause analysis

This use case deals with a scenario where we are trying to find the root cause of an issue that has occurred. So, let's assume we have evidence that the mission system is inadequate and would like to use this information to update our models and find the most likely causes for this inadequacy. For this purpose, we incrementally traverse the tree. On the first pass, we set the state of the node "Mission System" to inadequate, and the state of the node

"Operator Cognition" to correct. The parent nodes for Mission System are now updated and the probability associated with each of them being the cause of the mission system inadequacy is shown in table 4. Now suppose we have evidence that the simulations are inadequate. We set the state of this node as 100% inadequate in the model and observe the updated states of its parent nodes. Table 4 shows a full traverse of the tree based on assumptions about the evidence observed within the mission system.

| Mission System Inadequate? | Operator Cognition Incorrect? | Documentation of MS Inadequate? | Process Procedures | Simulation Inadequate? | Software |
|---|---|---|---|---|---|
| Yes | No | 85.00% | 7.00% | 7.00% | 8.11% |

| Simulation Inadequate? | Software Simulations Inadequate? | Hardware Simulations Inadequate? |
|---|---|---|
| Yes | 31.00% | 74% |

| HW Simulations Inadequate | Fidelity of Testbed Inadequate? | Maintanence Inadequate? | User Friendliness Inadequate? |
|---|---|---|---|
| Yes | 52.00% | 20.00% | 75.00% |

| SW Simulations Inadequate | Fidelity of Testbed Inadequate? | Maintenance Inadequate? | User Friendliness/Utility Inadequate? |
|---|---|---|---|
| Yes | 17% | 17.00% | 60.00% |

| Software Inadequate? | GSW Inadequate | FSW Inadequate |
|---|---|---|
| Yes | 72% | 30.00% |

| GSW Inadequate? | Coding Inadequate? | Requirements Inadequate? | Configuration Inadequate? |
|---|---|---|---|
| Yes | 21% | 44% | 21% |

| FSW Inadequate? | Coding Inadequate? | Requirements Inadequate? | Configuration Inadequate? |
|---|---|---|---|
| Yes | 9% | 0% | 0% |

**Table 4: Probabilistic root cause analysis when the mission system is inadequate**

Table 5 shows the traversal of the soft factors branch of the BBN. So here we are assuming that the evidence points to the soft factors or operator cognition being inadequate. Setting the state of the operator cognition node to 100% inadequate causes the likelihood of its parent nodes to be updated as indicated in the table. Now if the evidence further suggests that the operational complexity is high and the situational awareness low the model indicates this to be due to a low level of communication and points to 51% probability of the management and organizational factors being inadequate.

Details about the underpinnings of the management and organizational factors sub-model will be upcoming in a follow on paper.

| Mission System Inadequate? | Operator Cognition Inadequate? | Operational Complexity High? | Skill Level Low(Novice or Journeyman)? | Situational Awareness Low? |
|---|---|---|---|---|
| No | Yes | 78.00% | 40.00% | 50.00% |

| Operational Complexity High | Management/Org Adversarial? | Development Activity High? | Command Frequency Hi? |
|---|---|---|---|
| Yes | 6.00% | 67% | 66% |

| Situational Awareness Low? | External Team Communications Inadequate? | Internal Team Communications Inadequate? | |
|---|---|---|---|
| Yes | 58.00% | 48.00% | |

| Communications Inadequate? | Management/Organizational Factors Inadequate? |
|---|---|
| Yes | 51.00% |

**Table 5: Probabilistic Root Cause Analysis when the operator cognition is inadequate**

## Conclusions & Future Directions

There are multiple perspectives for assessing and investigating Command File Errors. Collecting and organizing the data associated with these errors is a first step in the direction of more in-depth statistical and probabilistic analysis. Statistical analysis of command file error rates can be used to determine if problems are occurring too frequently and in assessing the trends and behavior of the system. Systems level, probabilistic analysis leads to a more accurate understanding of the dependencies within the system and how these dependencies contribute to the CFE rates. Modeling and probabilistic analysis techniques are used as a tool to help manage the CFE error rates. The main take-away for the analyses presented in this paper is that by observing the system behavior and formalizing the relationship between the various parts of the system it is possible to identify the key factors that lead to CFEs and make informed decisions about the rates that the project is willing to tolerate and its associated trades.

BBNs can be used in a number of ways to anticipate and potentially reduce command file errors on Dawn. If-then scenarios to determine the sensitive variables and anticipating CFE rates based on the value of parameters during different phases of the mission are some of ways. Incorporation of observations about the system behavior in the form of evidence to determine ripple effects in the system and probabilistic root cause analysis is another utility of the BBN models. Most importantly perhaps is the fact that once the project starts running and updating these models on a regular basis, the learning property of the BBN will make it more and more representative of the system and the accuracy of the results will include.

While the tool used for the analysis reported in this paper was a commercial tool, we are currently exploring the possibility of using readily available and reliable free-ware for the purpose of infusion within the team. In order for the work explained in this paper to become truly useful to the project, it's important for the operations personnel to have access to a widely available and user-friendly tool as well as the underlying models and be able to update the models and run experiments with them on a regular basis.

Future direction for DAWN includes providing the team with the software and model for use within the flight project environment on a regular basis, and increasing the fidelity of the models by incorporating confidence

intervals and details about the command files that are radiated to the spacecraft. Currently, we do not distinguish between CFE's based on the number of commands within the files. We expect the results to improve in accuracy by including this information within the data.

The module associated with the effect of management and organizational factors on the cognition of the operator was added based on the initial input of the mission manager from a different flight project. Although this module is currently quite simple, there is quite a bit of sophistication embedded in it. It is based on research about the theoretical underpinnings of the effect of management on the decision making and hence error rates of engineers as well as much expert knowledge within JPL. We are currently in the process of writing up that body of research in a separate paper.

The multi-mission model that was the basis for the customized DAWN model is also being further refined to address the hard factors. The mission system is mostly constant for projects that are already in the operations phases and individual flight projects often do not have sufficient resources to improve upon some of the elements that are part of the infrastructure. Nonetheless, the Multi-Mission Ground Systems and Services (MGSS) program at JPL is meant to address issues that are of interest to multiple flight projects. The goal of our study of the hard factors associated with CFE's is to provide insight to the MGSS management for this purpose.

Another undergoing development and upcoming paper is the customization of the models to the Juno flight project.

## Acknowledgements

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The BBN modeling and analysis was conducted using the Bayesia software tool (www.bayesia.com).

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