# Designing Satellites for Effective Mission Operations

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**Abstract**

Design of small satellites often focuses on developing a working product from a purely engineering and scientific standpoint, instead of designing the system based on the use cases of the MOPS team. The problem with this, is, if a mission operator can not collect the data required for maintaining the satellite or conducting the science mission, then a functional satellite can not meet its mission success criteria. By designing satellites from the mission operator use cases, the design team ensures the MOPS team can collect all of the science data and maintain the satellite in the most effective manner. Procedures for conducting simple tasks can be long, convoluted, and not realistic in the mission time frame and within the data budget.

## Introduction

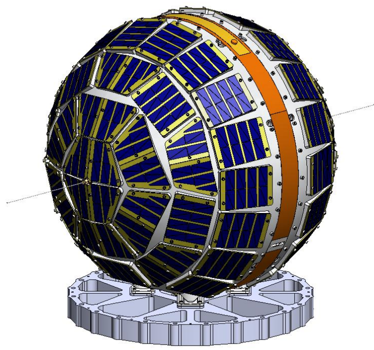

Figure 1: DANDE Satellite in Launch Configuration

The DANDE spacecraft began as a concept seven years ago, and was designed to study the near Earth drag environment. This was to be accomplished using a novel accelerometer system as well as a Wind and Temperature Sensor. During development the team focused heavily on creating a system to support the science goals, without as much concern for collection of nominal engineering data. Preparation for operations on DANDE were started one year before the satellite was put into a flight locked configuration. Due to this late start time operations had limited ability to change the satellite or ground architecture prior to launch. This large gap between development and operations contributed to the lack of data processing tools and why the operations team struggled with error debugging during the mission. DANDE launched on September 29th 2013 and on orbit operations began. Many issues became apparent once the end to end system was being used multiple times a day. Lengthy procedures became burdensome to a student team operating with limited time. Components on ground that had not been operated on flight duty cycles, especially thermal and electronics subsystem related, revealed their flaws or latch ups in ways that the team had not expected. The file system quickly became bloated, as compared to its state during ground testing rendering certain commanding ineffective. DANDEs attitude was vitally important for a successful science mission. The attitude process, which was supposed to be relatively short took, a significant amount of the DANDE mission. Many of the on-orbit problems, although challenging and unexpected, were rectified due to a responsive operations team. However, there were some configuration issues that the operations team could not address after launch. Despite all these challenges the DANDE operations team still had level 1 mission success, and met many of the mission goals.

Drag and Atmospheric Neutral Density Explorer

## Mission Timeline

In order to reach the stage where the system was ready for science operations various stages needed to be completed. DANDE launched on a SpaceX Falcon 9 v1.1 in an a inhibited state preventing operations. The first stage of operations was separation from the launch vehicle and activation of the system. On the first pass over Boulder that day DANDE beaconed and was confirmed to be live and operational. The health and status of the satellite was confirmed during this phase as tracking was verified. After this phase the team focused on removing the Lightband Adapter Bracket from DANDE shown attached to DANDE in figure 1. The goal of this was to give the satellite the spherical symmetry it needed for attitude and drag analysis. This was accomplished and visually confirmed by the Air Force Maui Optical Tracking Station on October 30th. After this time DANDE attempted to obtain a spinning attitude state and confirm proper operation of the ACS system. Unfortunately on January 9th 2014

DANDE lost contact with the ground and was only heard briefly on the 7th of February.

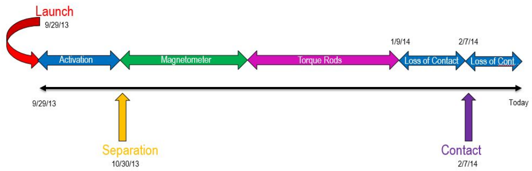


Figure 2: Time Line of the DANDE Mission

The time line shown in figure 2 will serve as a reference for events mentioned in this paper.

## Beacon

### Problem

DANDEs beacon was defined before mission operations of the satellite were clearly planned out. The problem with this approach, is that due to the nature of the mission a significant portion of data collection occurred through the beacon. A total of 3,105 beacons were downlinked by the DANDE mission operations team and through the aid of ham radio operators. This corresponds to 357,075 bytes of data. During the life time of the mission, about 1.5 million total bytes were downlinked from the satellite. This means approximately 24 percent of all data for the DANDE mission was collected through the beacon. Hence, the beacon and the bits in the beacon ended up being a significant portion of all data coverage. Part of the reason so much data was able to be downlinked through the beacon was that DANDE's beacon was able to be downlinked by ham radio operators. This vastly increased the potential areas for data collection.

We can see that the beacon was a great potential source of data for DANDE, and that the ham radio beacon data collection was able to greatly augment the potential areas for data collection. The problem with the beacon, however, was that the beacon was designed before mission operations began to play a significant role in the DANDE program. Because of this, many bytes on the beacon provided information that was not useful for satellite operations. Estimates range from 20 percent to 30 percent in regards to beacon data that did not aid in operation of the satellite.

For example one of the beacon bytes was a readout of the com status bits. During the entire course of the mission these bits only changed three times. A change in these bits simply meant there was an error in the PLL aboard the DANDE satellite. For a mission operator on the ground, this information is not very useful as the type of error is not presented. Another area that demonstrates the lack of usefulness of beacon data for mission operations is the EPS data read out. Almost every piece of EPS data was presented in the beacon. EPS data is critical to operations of the satellite. However, a significant portion data product of the EPS system was presented in the beacon, 19 bytes in total. Three bytes were key to mission operations: State of Charge of the Batteries, solar panel input power and solar panel output power. Only one of these data points was actually present in the beacon. This means a significant portion of the 115 byte beacon was presenting data that the MOPS users did not explicitly need from it. Also, while a great deal of EPS data was downlinked, the data key to mission operations was unable to be found.

The beacon contained other bytes which were definitely useful during the testing phase of the project, that were not useful for mission operators. For example, the beacon included information on whether the COM, CDH, and COM CDH boards were powered. If these boards are not powered, the flight configuration of the satellite is not capable of beaconing. Essentially, the fact that the satellite was able to beacon successfully means that these systems were powered and working.Bits such as these were critical during the testing phase to ensure different sub systems were working. During the flight phase, however, it is not very useful to get additional confirmations that everything in the beacon data path is functional. Other data points in the mission were also included that may have seemed useful in the testing phase, but which do not inform the mission operator on the ground of an issue that they can actively debug.

Another problem with the beacon was lack of data that was critical to mission operations of the satellite. One of the hardest to capture pieces of information on a satellite is the charge state of the batteries.This also turns out to be one of the most important pieces of information to capture. Although the DANDE satellite collects enough data to create a measure of how much power is being used by the system it required ground analysis to extract. There however was not enough information to construct a measure of how much charge was going into the system. Because the satellite was not operated in a flight configuration on the ground this problem was not identified until on orbit. The COM system was a system that encountered problems on DANDE. However, aside from the status bits discussed earlier, many COM status bits were not included in the beacon. The beacon did not include science data, meaning we could not augment the science mission through our beacon collection.

### Discussion

There are two ways to design a beacon. One way is for the engineers to place data that they feel is important in the beacon. The other way is for the mission operators to come up with data objects that will greatly assist with mission operations, and to inform the engineers what they require. Doing so, however, requires mission operations to be taken into account much earlier in the mission life time. However, doing so can result in improved satellite operations. The problem with engineers deciding which data to go into the beacon is that certain data products are very useful for testing and debugging a system when it is on the ground. During flight operations, these data products may not present relevant information. In addition, certain pieces of data that are key to mission operations may be overlooked by the engineers designing the system.

In order to design a beacon that helps the mission operator the most, we can use a technique taken from software engineering which is designing a system to the relevant use cases. An example use case diagram of the DANDE beacon is shown below:

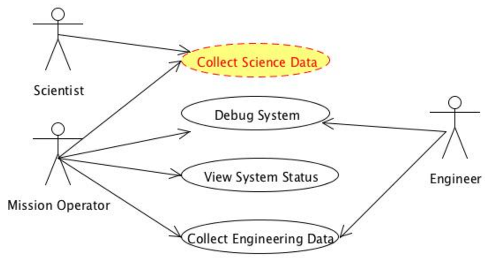


Figure 3: Dande beacon use cases

Designing to use cases is a key technique for ensuring that the end data product is satisfied. For example, if the EPS data had been designed to the use case of the mission operator, then it would have been more evident that the power in, power out, and state of charge were the key pieces of data. A great deal of time on orbit was spent ensuring that the battery state of charge was at an appropriate level to collect science and engineering measurements. If this data was in the beacon, it would have simplified the operations of the satellite. This issue highlights another problem with the engineering team designing the data products in the beacon. Without the critical data products being identified by the mission operators, there is very little motivation for the engineering team to devise methods to collect more difficult data products. State of charge of the battery is very important for understanding when science data can be collected, but it is a more difficult data point to collect from an engineering standpoint. If a mops team developed the beacon, the engineering team would understand why capturing this data point would greatly assit the mission.

A key use case for the DANDE beacon was debugging the satellite on orbit. The last contacts with the DANDE satellite consisted of just beacons. Also, there is a significant amount of repeat data points being collected in the beacon that are available to the mission operator. If more though is placed on how the mission operator will interact with this data, then this data can be used more effectively by the mission operator to debug the satellite. University nanosatellites like DANDE are typically zero fault systems, so failures to critical systems will end the mission.

One use case that was not thought of before the mission was the potential for science data collection. Part of the reason for this, was the potential for ham radio operators to collect data was unknown. The total number of successful beacons downlinked by mission operators was 807. Ham radio operators were able to successfully collect 2,298 usable beacons from ham radio operators. Ham radio operators were able to downlink beacons from the following locations:


Figure 4: Locations of Ham Radio Beacon Data Collection

We can see that Ham Radio operators were able to significantly augment our data collection potential, by providing a large range of additional ground stations. For a student satellite with limited potential passes, this data represents a significant portion of data that can be collected during the mission lifetime. Unfortunately, none of this data was used to realize the science mission of the satellite. If, the 20 percent to 30 percent of data that was not useful to the mission operator was replaced with relevant science data, then the mission could have collected an additional 100,000 bytes of data. With 1.5 million total bytes of data downlinked (including engineering data), this would have significantly increased the science potential of the DANDE mission.

The primary purpose of the satellite's beacon is to assist the satellite mission operator, and to confirm the status of the satellite. Hence we can see, careful construction of a satellite's beacon and designing a beacon for the use cases of the MOPS team has the potential to increase the scientific capability of the satellite, and ensure the satellite can be properly debugged on orbit.

## Communications

### Problem

After the launch of the DANDE mission on September 29th the task of finding the satellite and establishing communication began. The first complicating factor was that the team was unprepared for the inaccuracy of the early orbital elements, the number of objects, and the difficulty in establishing which object was DANDE. This resulted in all of the tools and procedures for this task being created in the days following the launch of the satellite. The main effects of this were to put huge demands on the time of a few individuals and to delay the establishment of reliable contact for around two weeks. While the mission timeline was designed to allow for significant activation time any loss of pass time is to be avoided and this delay shifts the entire mission timeline back as well as revealing another issue with the system. Unfortunately the DANDE system was not meant to designed to be self-sufficient for very long so the satellite was riddled with errors from an overloaded file system that resulted from the extended period of minimal contact to fix this. Shortly after DANDE was exposed to a solar storm which affected the

COM system. After this solar storm the beacon transmission time increased from 0.25 seconds to 3 seconds. This change in transmission was corrected with a reset of the satellite, which is why the team attributed the anomaly to the solar storm. This anomaly appeared to have no effect on the integrity of the data and did not appear to affect regular file transfer so the principal effect was to increase the strain on the EPS subsystem as transmission is very power-intensive. As the mission was still in the activation phase the satellite was still power-positive with the additional drain but had this anomaly occurred during a more power-intensive phase the effect would have been much more severe.

## Discussion

This anomaly, and the fact that it was also fixed ten days later by an unintended reset from a script that wasnt supposed to affect the COM subsystem, illustrated three issues with the operations. At the beginning of the anomaly there were no good theories as to what had happened or what to do about it. The team could not be expected to have a plan prepared for addressing every possible issue but this situation illustrates the need for both a procedure for determining unforeseen issues and, along with the file system issue mentioned before, a robust safe mode that ensures that the satellite will not do anything to further complicate an issue. The second issue highlighted by this issue was an issue with writing and verifying command stacks. The reset that fixed the issue was accidentally sent as there were two versions of the command stack open on two computers. The two stacks had been written as preparation for a possible reset, the first beacons of the pass would be used to determine if a reset was desired or not. Miscommunication between operators caused the incorrect stack to be sent, the reset was determined to not be needed but the stack with the reset was the one sent. While simply resetting the satellite is not a major source of risk to the mission the fact that any command was sent accidentally is a major source of concern and illustrates the need for more rigorous checks. The third issue was that the reset script called, which was intended to simply reset the processor, actually reset each subsystem and was reliant on the normal startup sequence to restart each subsystem. The script also sent requests to each subsystem to shut down gracefully before cutting power despite having killed the process that handles subsystem communication. These issues highlight the need for both rigorous testing and clear communication between developers and operators so that everyone is on the same page. This issue, along with the other reset issue of the reset intended to cycle the COM subsystem in the event of no login for 24 hours only cycling the processor, were not fixed by the time of the final loss of contact. As mentioned previously some of the issues seen during operations illustrated the need for a more robust safe mode and one that is not also used as a standby mode. A standby mode, which is what the nominally safe mode really was, would be one where the satellite is not actively engaged in any major activity (attitude, science, etc) but is still collecting subsystem buffers as normal and generally proceeding along. A true safe mode would be one where data collection was limited to a minimum, all subsystems are periodically and correctly reset, and the satellite is operating in a state designed to maximize the chances of a ground contact so that the operators could fix the issue. DANDEs safe mode does not meet these criteria for several reasons. First, the satellite could not autonomously reset COM so any major issues with the subsystem could only be fixed by a hard EPS reset as an issue with COM would preclude a commanded reset which would not be possible if COM were malfunctioning. Second, the data collectors were still fully active in safe mode and the satellite has no ability to autonomously manage files. This means that an unattended satellite would eventually generate enough files to reach a state where it was no longer operable. While this functionality was considered by the developers, and rejected as autonomous file deletion made them uneasy, the satellite needs to be able to avoid situations that are known to be fatal without any operator input. This issue ties in with the issue with the resets not working as intended as a reset of COM from longdog, which is triggered by a twenty-four hour period without a login, or backdoor, which bypasses CDH and therefore does not require a login which in turn requires an active transmitter to send the login acknowledgement, could have fixed an issue with the transmitter or even COM as a whole. As it was the only way out of a severe COM issue was to wait for something else on the satellite to go sufficiently wrong to cause a hard power reset, which could potentially be after the satellite had become inoperable due to file system troubles created in a ”safe” mode that was insufficient for allowing the satellite to survive this period of operation with no ground intervention.

# NMS

## Problem

DANDE included a neutral mass spectrometer to measure the energy, amount, and direction of travel of particles in LEO. This instrument required a variety of steps in order to ensure that it was in a operational state and collecting meaningful data. DANDE had ten modes intended for operations two for nominal operations, two to ensure ejection of the LAB, two more for attitude adjustment, and five for the use of NMS.

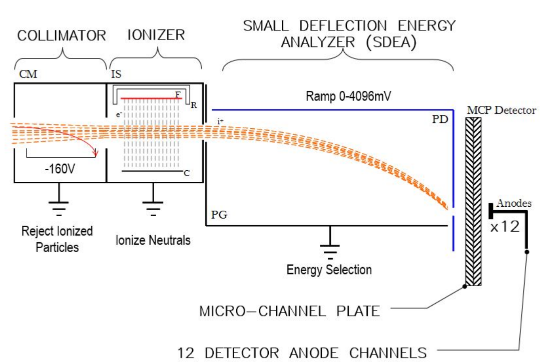


Figure 5: Design of NMS

Looking at the design of NMS shown in figure 5 a variety of components can be seen. The most important of these were the filament(ionizer) and multi-channel plate detector. The filament had a coating over it designed to protect it from becoming oxidized on the ground. It required four uninterrupted hours in order to burn off this coating and ensure the filament was in working order. Given issues seen during ADC spin-up operations where the satellite would dip below a nominal state of charge inducing safe mode this burn in would likely not have been possible. In addition the MCP required a multiple hour charge ramp in order to ensure that it would properly deflect particles at the expected energy levels. Because such an instrument requires many qualifications in order to be proven, at each of these steps a variety of mission operator defined data would need to be collected. All of these configurations would need to be verified on ground hardware before flight execution. All told the processes required to get NMS to its required science state would have taken at least a month if all went as expected with the communications and error problems. In reality the process would have likely taken three months.

### Discussion

The major lesson that was learned from the NMS system was there is not time on a mission of this duration for complex instrument set-up. The accelerometer package on DANDE was ready to be used with a single command and no additional initialization. This allowed the collection of science data to be a simple procedure requiring just hours of preparation instead of weeks or months. If possible instrumentation operation from the ground should be made as simple as possible. If complex operations are required to set up an instrument these should be performed early in the mission when the satellite is closest to its ground state as possible. These operations should also be performed primarily on the satellite and autonomous except in the case of errors. If these problems are considered early selection of proper computers, hardware, and system architecture can be created to expedite this process as much as possible.

## Commanding

### Problem

DANDE commanding was written to ensure that the mission operator could meet the science goals of the satellite. The problem was, there were often arduous procedures the MOPS team had to go through in order to obtain the appropriate data products for the satellite. For example, let us take the case of a mission operator who wishes to find when a critical error occurred in the EPS system. In order to do so on the current configuration of the DANDE Satellite the mision operator must search through the files to find the appropriate file where the error exists. Unfortunately, the mission operator does not have a way of knowing what files exist on the satellite. Instead, they must hypothesize when the error occurred and downlink all of the files in a range near that time. This is a process of trial and error, until finally the mission operator is able to obtain the relevant error data.

A much simpler solution could have been designed if errors were thought of in a different manner. If DANDE moved all files with critical errors in them to a separate staging directory automatically, then these files could have been downlinked seamlessly. On average, 20.7 minutes were spent talking to DANDE in a day. Hence, time spent talking to DANDE is a very valuable resource. Spending time searching for an error message in a large amount of files hurts the ability of the mission operations team to operate the satellite and complete the science mission.

This error also highlighted one of the problems with the day in the life testing for DANDE in regards to commanding. During day in the life testing, this issue wasn't identified as a major problem because testers could easily view all of the files on the satellite and pinpoint the exact error files to downlink. This demonstrates why designing to the flight use cases is so critical. If the simulated passes had been conducted in a manner where operators did not have additional aids, this problem would have been more obvious. Another problem with the testing of commanding during day in the life was a lack of understanding of the final state of the system. Many commands were tested without understanding the bounds of execution. For example, ground software developers would write commands to tar and downlink files from a specific directory. The ground software developers did not have an understanding that during flight these directories could have tens of thousands of files, and not the hundreds of files that were present during day in the life. This meant that command performance was bench marked in unrealistic conditions. When these commands were run on flight, their performance was too low to be useful to the mission operator.

Another key issue with commanding of the DANDE satellite was a lack of automation in the commanding process. DANDE required maintenance from the ground operator in order to be in a nominal state. This posed a problem when contact was lost with the satellite. Below, is a figure highlighting when mission operators were able to successfully login to the satellite:

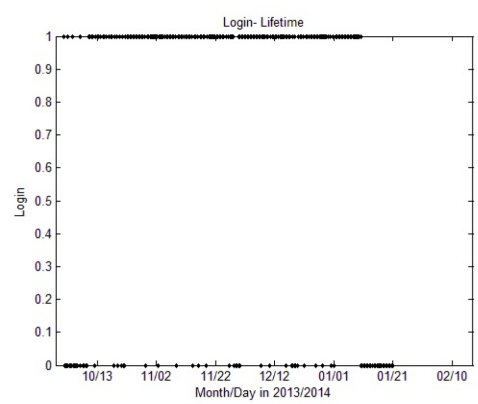


Figure 6: Succesful Login Attempts To DANDE over life time

We can see in 6 that the realities of on orbit operations meant the DANDE team had significant gaps where login was not possible. DANDE, however, was built in such a way where the satellite could not perform file system maintenance on its own. The satellite will continue to generate files until it exceeds the capacity of the SD card. The problem with this behavior is it vastly increases the load average on the DANDE satellite. As shown in the figure below, an increase in the number of files on DANDE results in a increase in the load average on the satellite.

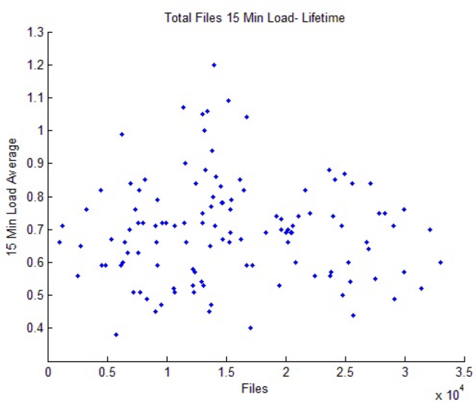


Figure 7: Load average vs total number of files on DANDE

Increasing the load average on the satellite, results in reduced performance and can prevent the satellite from allowing login attempts. A ballooning file count results in an increase in the number of file system errors. The system has more files open during periods of high load and a reset can cause a file system error to occur in files that aren't properly closed. File system errors are an end of life condition for the satellite. This highlights the critically of automation. If the DANDE team was able to get into contact with DANDE again it is likely the system would be in a very difficult state to recover from.

Another problem with DANDE commands was a lack of encapsulation. A mission operator may have wished to do a simple ADC command. In order to do this, it was required that they upload an ADC configuration file. An ADC configuration file contains a large number of configurable elements. If one of these elements is set incorrectly, then the measurement will fail and the mission operator will need to reupload another ADC file after they discover the problem. This results in a loss of two passes, which is of significant cost.

### Discussion

The mission operations of a satellite can be greatly assisted if commanding is developed from the ground up with the mission operator in mind. One way to design commands is to think what data products are useful for the mission operator. Then, develop a solution where this data can be sent to the mission operator with minimal effort. By doing so, the engineers can ensure that the mission operator is capable of operating the satellite. Automation is another reality in small satellite design. Communication can be intermittent, so if a satellite requires constant communication this can lead to the propagation of unnecessary errors. Instead, care should be taken to ensure the space environment is fully understood by the development team. The satellite's commanding should then be developed to meet those standards. In addition, the worst case operating state of the satellite should be understood. Engineers can take these requirements and ensure commands are capable of meeting performance during these scenarios. Encapsulation is another design philosophy that can assist with the development of commands. If information is hidden from the mission operator, this prevents errors that arise from a lack of understanding of that information.

## Thermal

### Problem

Although ultimately ruled out of a cause of many problems the thermal conditions observed on DANDE were unexpected. The satellite behaved as predicted for the vast majority of cases and components. It was only when the satellite was in a completely illuminated state that issues arose.

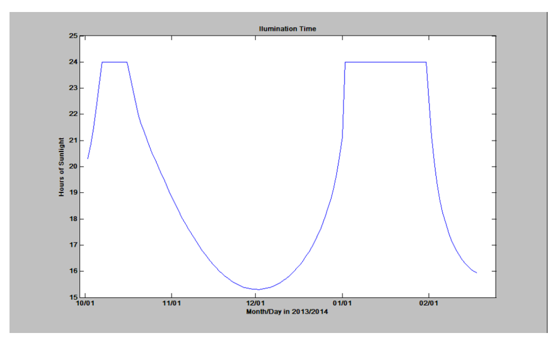


Figure 8: Illumination time in hours per day over the mission

As can be seen in figure 8 fairly early in the DANDE mission the satellite entered full illumination. This resulted in temperatures across the satellite going to steady state conditions as expected. All temperatures on the system appeared nominal with the exception of the EPS system. Although the rest of the satellite had been designed with a variety of thermal cases in mind EPS was not designed for a 100 percent duty cycle. This resulted in temperatures on EPS approaching near boundary temperatures.

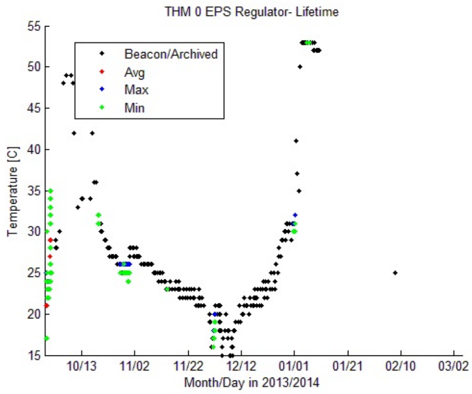


Figure 9: Regulator Temperature

In figure 9 it can be seen that early in the mission a large spike in temperature on the regulator board corresponds to the first period of full illumination on figure 8. This temperature spike tripped an onboard watchdog that was anticipating much lower temperatures. This caused a string of errors that delayed the team for a week. However this period of illumination was quite short compared to the period of illumination that would come latter in the mission. This problem was easier to identify as time went on however and the error bounds for the watchdog moved closer to the maximum bounds. This allowed the team to continue to operate the satellite while not endangering its health.

### Discussion

Although it is easy to plan for a particular case or orbit a variety of unexpected conditions may occur. For the DANDE team it was that the satellite would experience extended periods of up to a month in full illumination of the sun. Although a majority of the satellite did not struggle with this condition it was the small percentage that didn't that caused many of the problems. Even though it was concluded that elevated thermal temperatures were likely not the cause of DANDE's loss it added significant debug time that cost many passes. It also established for the DANDE team that having clear expectations of what on orbit performance should look like and what is acceptable are critical to responsive mission operations.

## Mission Operations

### Problem

One of the principal issues that contributed significantly to many of the issues seen was that the mission operations team and the engineering team were for the most part sequential and independent. This meant that the satellite was being operated by individuals who had little to no experience with the physical satellite and therefore had reached their understanding of the satellite system by reading what documentation they could find and asking questions of the engineers when they could find time for them to come in. The pre-launch testing of the ground systems was primarily handled by the responsible engineers and then turned over to the operators for use. While the operators had some experience with this as the testing was both much closer to launch time and included some training sessions on how to use the ground systems this still falls well short of what would be ideal. Watching the person who built the system, and therefore has an excellent understanding of what it does, explain it a few times hardly suffices for understanding the system. This meant that the early operations saw a fair amount of during-pass explanation of what should be happening. While the supervision of the senior engineers prevents this incomplete understanding from risking the satellite this is not an efficient or sustainable method. As pass time is precious the senior engineers tend to just take over so that the pass objectives are completed, reducing the learning for the others, and this also puts a lot of strain on those engineers as they are present for nearly every pass.

As all pre-launch communications testing was conducted either over wired RF or short-range wireless the team had no experience prior to launch in conducting operations with an unstable link. The assumption going in was that once the satellite was within range then data transfer would proceed smoothly until the satellite passed out of range.

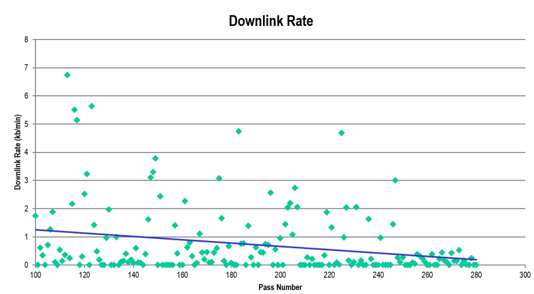


Figure 10: Downlink Rate vs. Passes

The expected data rate was 450 bytes per second and revealed itself to be just 11.9 bytes per second on average over the mission lifetime due to dropped packets. As a result of this the issue of command retry time being 10 - 20 seconds was not recognized as an issue until after launch. This retry time is the time that the ground would wait after not receiving a confirmation of receipt to resend the command. Therefore this issue could not be fixed without extensive testing that there was little time for, in addition the team struggled to perform operations as intended when commands would fail regularly. With an unstable link the operators, even more so than usual, need to be able to quickly re-prioritize commands so that the most important data is actually obtained instead of using a pass on less-important, but earlier in the command stack, data. This is best shown in figure 10 where passes that have high data rates had more stable links in comparison to the majority of passes that did not. On average it was found that data rates were lower as the mission went on owing to error cases presented by the full illumination period. The scenario of a unstable link requires that every operator, or at least one of the operators for every pass, have sufficient understanding of the current mission goals to be able to make these decisions. Many passes were essentially lost due to the operators not being able to respond to a poor-quality pass before the pass was over.

Another issue that came up, principally during ADC checkout, was the issue of unnecessary checkouts. As the satellite software was not designed to provide the desired data in a clear and concise manner numerous passes and extensive data processing and analysis were needed to obtain the desired data, which then ended up being inconclusive anyways. The mentioned issues with the actual effective pass time and realized data rates made the time to accomplish this even longer but the issue was still fundamentally with the checkout process. The difficulty in obtaining the desired data, the complexity of extracting a reasonably deterministic answer from the data, and the lack of a centralized and well informed decision making body resulted in the attitude checkout phase lasting from LAB separation at the end of October until the loss of contact over two months later.

### Discussion

One major issue the DANDE operations team experienced was a large knowledge gap between mission operators who were brought on the team during the end of the engineering phase (very few) and those who were brought on after DANDE was completed (most of the current operations team). There was not a formally defined debugging procedure for the MOPS team to follow. Instead they were required to research the subsystem and determine appropriate debugging on their own.

There was a conflict between a system that was designed for relatively quick progression through the checkout steps and a group that wanted extensive and rigorous verification of each step. As the system was not designed to provide the data that was requested the data was unlikely to be deterministic so any data collection was largely futile and then the unexpected loss of contact illustrated the fact that the mission duration is finite so any risk to the mission caused by moving too quickly needs to be weighed against the risk to the mission from an earlier than expected loss of contact. The team needs to keep in mind the larger goal and keep in mind the fact that inaction can be every bit as dangerous to the mission as taking the wrong action. The discussions of the checkout process also illustrated the need for better communication and decision-making, especially when dealing with outside help. While the mentors may be the most qualified on the subsystem in question their suggestions should be considered in the context of the mission as a whole by the senior operators as they are the ones who understand the difficulties involved in collecting/processing/interpreting any data as well as the current mission timeline.

## ADC

### Problem

After separation phase the mission continued into attitude phase. Attitude phase is where the satellite is put into a science ready attitude. This phase of the mission is where the operations team spent the rest of DANDEs lifetime. The initial instrument checkout procedure was adjusted during on-orbit operations, which increased the time required for the attitude phase significantly. By attempting to collect data that the operations time wasnt prepared to collect and process there was a large lag time between data collection and turning the data into usable information. On January 2nd, 2014, while in the attitude phase DANDE experienced a 28 day period of full illumination. During this full illumination time the operations team lost contact with the DANDE satellite. Before losing contact the team saw a sharp increase in temperature throughout the system and especially on the EPS boards. The extreme overheating of the EPS system is considered a main cause of the loss of contact. Contact was regained for one pass on February 10th, 2014. During this pass the team saw fairly nominal data in the beacon, but clearly the satellite was not in a nominal state since DANDE was never heard from again.

The initial ADC instrument checkout procedure was designed to work with an accelerated (30 day) mission timeline, so the procedure was very minimalist and didnt thoroughly check out each ADC instrument separately as well as together. Since the actual DANDE mission ended up being much longer (projected for 1.5 - 2 years) the team, with the assistance of advisors the team decided to do a more thorough checkout. This checkout started with verifying the output of the magnetometer by location mapping the data with models of the magnetic field around the earth. This task ended up being very time consuming and yielded very little proof that the magnetometer was functioning. With the general consensus being that the magnetometer was working well enough for the purposes of spin-up and alignment the team moved onto checking out the magnetorquers. The Y torque rod alone was fired for small periods of time and the team collected data to see if the spin rate was affected by the firings. The team also tried to capture the firings with the magnetometer but the induced magnetic field collapsed to quickly to catch with the magnetometer. This checkout was easier for the team to complete because the processing tools were already in place. To verify the X torque rod the team tried a similar method of firing several times and attempting to see the nutation about the X axis decrease. This change was much more difficult to see in the raw data than initially anticipated. During this time communication with DANDE started to deteriorate to the point where the team couldnt retrieve any more ADC data. While these instrument checkouts seemed straightforward it was difficult to create processing tools during on-orbit operations. By expanding on the initial plan for attitude phase the team spent a lot more time than was necessary verifying the ADC instruments which ate up valuable mission time.

### Discussion

While extensive testing and verification is absolutely needed to ensure that nothing is accidentally broken one can certainly take this too far. The issues with the duration of the ADC checkout process is a good example of this issue. The main culprit here was the magnetometer. As the magnetometer data was not intended to be vetted on-orbit there minimal toold developed to aid in the processing and interpretation of the magnetometer or what the readings were expected to look like worked through. This resulted in quite a lot of time being spent trying to process the data to even get the data to a state at which it could be used for analysis and then even more time attempting to determine if this data looked as expected. As the data was not particularly deterministic this process ended with the team assuming that the magnetometer was functioning, which was the original intention, except quite some time later. As this time could have been used on spin-up and even possibly on science this illustrates the fact that the not acting can be just as dangerous to the mission as a whole as taking the wrong action. For a situation like this, where an error could at worst complicate some later data analysis instead of actually ending the mission, moving forward is rarely the wrong action. In addition to this issue the COM performance was degraded by the post-separation satellite attitude state being such that the transmit antenna null axis would pass through the ground station, causing an unstable link mid-pass. In a nominal attitude state this would not occur so the delayed spin-up caused an extended mission period with poor COM performance, which in turn made obtaining the data requested for attitude verification more difficult. For further discussion of this data see William Sear and Caitlyn Cooke's paper on DANDE COM performance.

## Conclusion

The DANDE mission was a level one mission success unfortunately this paper does not focus on this aspect. It does however focus on what is perhaps the greatest aspect of DANDE. The DANDE project allowed the Colorado Space Grant Consortium its first experience into what it means to operate a satellite on orbit. Processes that take a few seconds on the ground turn into week long campaigns on orbit. Getting DANDE into the proper attitude although planned to take a week at most ended up lasting for a majority of the mission duration. Although the MOPS team was under the impression that all possible error cases had been investigated new problems arose from day one. Because the team had not operated a satellite on orbit and regularly used and calibrated the ground station initial checkout took much longer then expected. On small teams such as the DANDE team all members had to take full responsibility for the satellite and attempt to meet the current objectives. This architecture stressed resources and caused an already warn thin team to their limits. Looking back at the project a variety differences could have made by incorporating a MOPS perspective early in the mission. These changes although they may require more time on the ground this time is not as valuable as the time on orbit. If an additional month of time on the ground means that an on orbit operation requires only day this likely will have provided more then a month of additional time on orbit to collect science or otherwise accomplish the mission. A satellite on orbit is nothing but a machine without proper planning for mission operations. It truly becomes an instrument when the time, experience, and ease of use has been incorporated into it and allows the operator to easily and quickly obtain what is needed.