DANDE - Operations and Implications

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The DANDE mission will characterize how wind and density variability translates to drag forces on satellites in low-earth orbit (specifically an altitude of 350-500km). Here the density of the atmosphere varies greatly due to space weather and a better understanding of drag forces/composition can help predict how quickly a satellite's orbit will change. The team has gained a unique perspective through operation of the DANDE satellite, as most of the members are undergraduate students. The team has captured some of the most important lessons learned, and will focus on what was effective, as well as how other satellite projects can implement similar systems in order to have a successful mission.

I. Introduction

The Drag & Atmospheric Neutral Density Explorer (DANDE) spacecraft launched on September 29^{th}, 2013 into a highly eccentric near polar low Earth orbit to investigate the near Earth drag environment. A novel approach is taken using a spherical microsatellite that is approximately 45cm in diameter with a mass of 42kg. The DANDE mission objective is to make measurements of thermosphere composition, temperature, wind velocity, and acceleration in both space and time. These measurements, provided by the on-board accelerometer suite and spectrometer, allow for a systematic approach to studying the full drag equation. The spherical spacecraft is spin - stabilized, minimizing attitude dependent drag variations, and the constant cross-section simplifies orbit analysis for independent validation of the drag environment. Figure (1) is a graphic of the DANDE spacecraft, including the Lightband Adapter Bracket (LAB) which was used to connect DANDE to the launch vehicle.

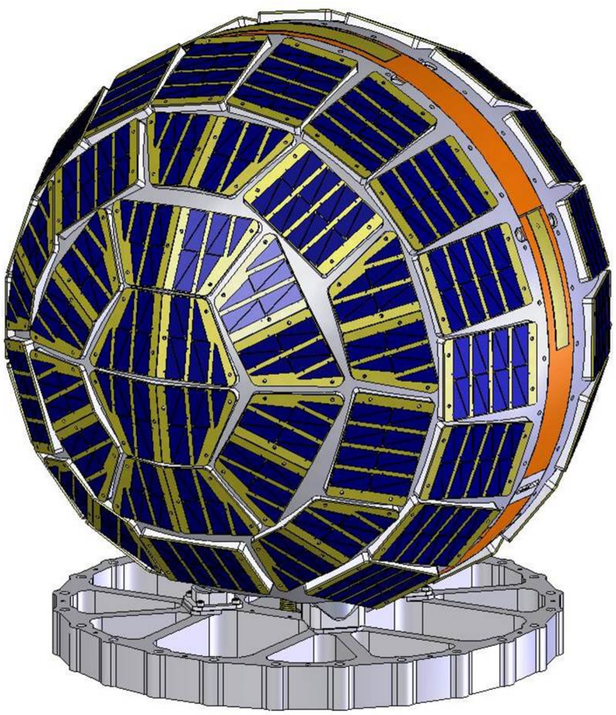

Figure 1. DANDE Sphere and Lightband Adapter Bracket

In addition to DANDE's scientific mission objectives, there is a large student education component. Over the course of design, build, and operation, 150+ graduate and undergraduate students have contributed to the team. This student led and staffed team has posed many challenges, especially considering the seven year lifespan of the DANDE project. The biggest challenge has been transferring knowledge from old "generations" of students to new team members. As most of the original design team had graduated by the time that the operations team formed, a thorough training process was critical to the success of the DANDE mission.

DANDE is a product of the partnership between NASA's Colorado Space Grant Consortium and the Department of Aerospace Engineering Sciences at the University of Colorado Boulder. This is a student designed, developed, and operated mission made possible through the Air Force Research Laboratories, and was the winner of the University Nanosatellite Program from the 5th Competition Cycle. The team also received support from the Department of Defense's Space Test Program, and the Air Force Office of Scientific Research.

II. Mission Overview

The DANDE mission is broken into several phases that encompass instrument commissioning and data collection; activation, separation, attitude, science commissioning, and science collection. Minimum mission success was accomplished by separating of the Lightband Adapter Bracket (LAB) from the main DANDE sphere over the USAF Maui Optical Tracking Station on October 30th, 2013 and receiving visual confirmation. The LAB connected DANDE to the launch vehicle (as shown in Figure (1)), and was ejected in order to return DANDE to a spherical shape. The visual confirmation was extremely important and verified separation before performing attitude maneuvers. After separating DANDE from the LAB the mission operations focus turned to attitude determination and control. This part of the mission involved commanding DANDE to change orientation and spin rate so that the spacecraft is spinning at 10 RPM and the spin axis is aligned cross-track, within a small tolerance. Both of these criteria are crucial to the science mission due to the very specific requirements of the Wind and Temperature Spectrometer (WTS). Currently the mission is in the attitude determination phase; the science instrument commissioning phase is documented and ready for execution after DANDE is in the correct orientation. Unfortunately the team lost consistent contact with the satellite in early January 2014, followed by a very brief recontact in early February. The ground station and operations team is still tracking DANDE passes and listening for the satellite. The tracking station is completely autonomous and will send an automatic notification to the operators if a beacon is received.

DANDE ground station is located on the roof of the building in which the organization resides, which makes monitoring and maintenance quick and simple. The proximity of the physical hardware to the operators during a pass, and the proximity to where the team is on a regular basis, enables any issues with the hardware to be addressed in real time and longer maintenance tasks to be performed with minimal coordination of personnel and materials. This has proved invaluable in ensuring that the ground station hardware functions as needed.

Additionally, there is a large worldwide community of amateur radio operators with equipment for listening to amateur-band satellites who can provide information on their observations of the satellite as well as providing the beacon data that they received. This provides the team with additional information on the health of the satellite communication system and a much larger telemetry set, in terms of both quantity and orbit coverage.

III. Training Undergraduates for Mission Operations

The primary goal of the DANDE mission has always been student education. Over 150 students have been a part of making this mission a reality. Although many subsystems are rooted in the work of Masters and PhD candidates, most of the construction, testing, and implementation was done by undergraduate students. This includes an exclusively undergraduate team for on-orbit operations. Many team members had never seen the satellite and had to train primarily with a "Flat Sat", which is an electrically equivalent model of the satellite. Proper training of this team was crucial to the success of the mission.

As the DANDE launch date shifted many times over the course of two years there was additional time to train mission operators and to create tools for data processing. This training process occurred three times over this interval as some students left and new students acted on the opportunity to contribute to the team. The process started with general knowledge and history of the satellite followed by a technical overview of DANDE's subsystems and the major features of its software. During the first few iterations of this training process many of the of the subsystem team leads were able work with new members to give them a better understanding. As DANDE ran Linux and used the bash scripting language, operators learned basic scripting skills as well as how to operate the custom built DANDE software features. To check understanding the operators were tested on the material in a comprehensive exam. The incentive that these skills would be necessary for operating the Flat Sat prior to launch helped motivate new members to learn the material.

The DANDE satellite operated using amateur radio frequencies for convenience. This meant that every satellite operator had to obtain their ham radio license. This test familiarized members with basics of communications as well as amateur radio regulations. All members of the team obtained this certification successfully. Due to the limited personnel the mission operations team at Space Grant also had to work as part of the data processing team. This meant working extensively with L3's InControl software, a program that handled the interpretation, graphical display, and archival of the received data; as well as all commanding. In the years leading up to launch the Ground Segment team built upon InControl to create a hub and spoke architecture for satellite projects at COSGC. DANDE, being the second project used with this software, took advantage of many graphical displays and command abilities that had already been given significant development time. This system architecture was recognized as Best Presentation at the Ground Systems Architecture Workshop, (GSAW) conference in 2013. To build on this the operators still learned to modify both the commands and data display. The software was written in Java, and students went through a month long introduction to the language that involved writing basic programs in preparation for eventual extension to the actual flight code.

Finally, the last piece of architecture students learned was the ground station architecture. This entailed learning the station configuration, how the various components operated, and how to operate the tracking software to successfully conduct a pass. As the station operates on the VHF and UHF amateur satellite bands the operators and ground station engineers were able to test the station and practice conducting passes on the numerous operational satellites that use those frequencies. The testing and practice was helped by the fact that the ground station had been constructed prior to the DANDE mission and in continuous operation for several years prior to launch. Due to this the operations teams did not need to work through the design and principal testing of the station, rather they simply needed to learn how to operate it correctly. While some changes were made during the mission to improve the utility of the station from the perspective of the operators the fundamental design remained unchanged.

Once all of the architecture had been taught to the members, procedures for operations could be rehearsed. All phases of the mission had their own procedure detailing every step that would need to be taken. The final part of formal training required members to take a practical test showing that they could successfully work all parts of the end to end system.

In addition to these areas there were many other skills that members were not formally tested on but needed to learn. Included in these is data processing of telemetry using the MATLAB scripting language and the ability to interpret the C code that much of the DANDE custom software was built with. An understanding of how the DANDE custom software was written was necessary so that team members would properly form commands and edit scripts, such as scheduling scripts. Students also needed to work with Systems Tool Kit to produce meaningful reports of pass times as well as illumination times, location information, and orbital lifetime. These reports helped develop the mission operations plan. The electrical system also needed to be examined and the Altium program was used for this purpose. The list goes on and even prior to launch the DANDE program was teaching students extensive skills that they otherwise would not even hear about until well into their professional career. This training process gave students the skills they needed to operate the DANDE satellite. More importantly however, it made them more equipped to handle complex problems, work with industry tools, and the confidence to learn new systems.

One of the most difficult areas in working with a student team is the passing of information to new team members. Students come and go as they graduate or commitments change. This is especially difficult in a project that has had a seven year life time. One way to overcome this challenge is by thorough and organized documentation of important aspects of the project. The DANDE software and Ground Segment team did this very effectively through use of the open source configuration management system TRAC. Other parts of the project did not use a formal configuration management system and that made it considerably harder to find relevant information. Since this time COSGC has migrated all projects to Redmine, a program that allows for task assignment, Wiki-like articles, and project management tools such as Gantt charts. Using a easy to use and localized resource like this and ensuring periodic updates is critical. This allows current team members to exit the team with little loss of institutional knowledge and new team members to become quickly integrated into their new project. Wiki systems are already present in many industries and are good practice when dealing with any long-term project.

The DANDE team learned many lessons about operating the satellite, mission operations management, and configuration control after launch. Test-as-you-fly is a common phrase used in the industry. This phrase means ensure that testing conditions and simulations match the flight conditions as closely as possible. The DANDE team attempted to do this but fell short in some respects. Even things that seem like trivial assumptions during testing can be mission ending. An example of this is that the EPS assembly were simulated in the thermal model as a single node, which assumed a uniform temperature for the three boards and metal housing. This turned out to be inaccurate as heat did not conduct well between the boards so one of the boards was much hotter than anticipated.

After launch the DANDE team utilized a core team of around 10 undergraduate students to staff up to four passes each day. Despite the pre-launch training, the team had never simulated an entire weeks worth of passes prior to launch. Combined with the fact that several of the tools needed for analysis were not built before launch this resulted in delays in data processing. If the team had simulated passes at a similar duty cycle to on-orbit operation then this workload would have been anticipated and the team would have been larger, with a student team assigned solely to data processing.

One of the major parts of satellite operations is being able to tell quickly if the satellite is operating within normal bounds. These bounds were monitored by watchdog processes on board the satellite that would send the satellite into safe mode if the bounds were exceeded. In addition to this automated monitoring the operators analyzed the downlinked data to assess the health of the satellite. In this analysis the long-term trends are as important as the most recent values. Once on orbit it was determined that it would be useful to compile plots of the engineering data to aid in this assessment. These showed the time series for each buffer on week, month, and mission lifetime durations. Unfortunately, the tools to process the data prior to launch were designed more for a testing environment so new tools were needed. To make these tools useful to the operators they needed to produce the desired plots with minimal user input, automatically archive the old plots, and display the data with correct engineering units and time scales. An example of the completed plots are shown below in Figure (III).

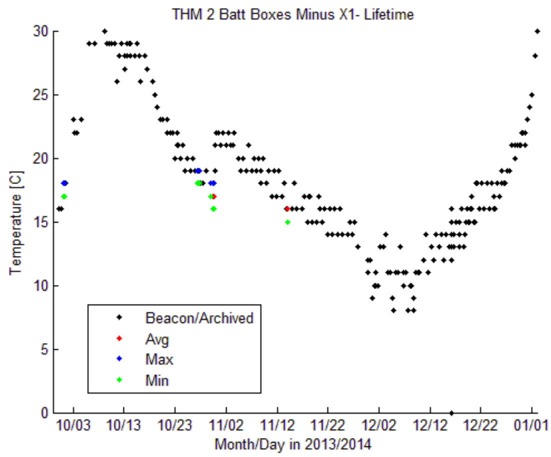

Figure 2. Engineering Data: Battery Box Temperatures

It is easy to forget about designing for the flight conditions, and the future operators, but it is essential. If the engineering team had designed for the operators from the beginning then the processing tools would not have required a significant development time after launch. Once the processing code was complete it worked very well, producing easily readable plots of the half-million data points in just a few minutes. This tool was also easily modified to handle the amateur radio operator data submitted from around the world.

IV. Mission Phases and Successes

The DANDE mission was broken into several distinct phases to provide a clear order for operations and ensure that all of the tasks that needed to be completed before starting a new phase were completed correctly and completely. The phases represent major mission milestones and have clearly defined success criteria to ensure that the mission is ready to proceed with the next phase. These phases are activation, separation, attitude determination and alignment, science commissioning, and science data collection. Each of these phases posed unique challenges and provided lessons learned.

The purpose of the first phase, activation, was to verify DANDE survived launch and was functional. To verify functionality the team gathered the most critical engineering data. This encompassed temperature, voltage and current, general health & status, as well as error log data. This data was considered the most critical because it allowed the team to check out all facets of the system. Basic temperature, voltage, and current data was in the beacon that DANDE transmitted every 15 seconds, so the team was able to easily capture this data. The health & status data gave the team a count of the files on the system, the load average of the system, and a count of the file system errors. This data was considered extremely important because it gave the team insight into CDH health. The data storage capabilities on DANDE are limited, so it was of utmost importance to make sure the system wasn't bogged down with files and becoming unstable. Timestamped error log data gave the team insight into what problems were occurring on the system.

Including critical data, (temperature, voltage, and current data) in the beacon allowed the team to collect thousands of additional data points from amateur radio operators around the world. The team set up a "beacon portal" where radio operators could submit DANDE beacon frames. These beacons provided information on the state of the satellite when DANDE was not over the team's ground station, providing a much more complete picture of the health of the satellite. Beacons were submitted from all over the world, as shown in Figure (IV).

Figure 3. Locations of Amateur Ground Stations

The addition of this data assisted not only in activation phase, when the team was performing initial system checkouts, but also in the final analysis that the team performed after loss of contact occurred. The first indication that the satellite had successfully powered on was submitted by a graduate student in Russia and the last beacon received from DANDE was submitted by an amateur operator in Oregon.

The purpose of the second phase, separation, was to eject the Lightband Adapter Bracket (LAB) from the main DANDE sphere. While the LAB made connecting to the launch vehicle possible it also affected the spherical properties of DANDE, and was therefore necessary to remove after launch. The separation procedure itself was very straightforward for the mission operations team. However, the Air Force Research Lab (AFRL) requested the separation occur over their Maui Optical Station to provide a test of their station and visually verify separation. This made the separation task more complex as now the team needed to time the separation to occur during a small window over Hawaii. The DANDE satellite does not have a GPS system, so the operation was based off DANDE system time, instead of location/-ground time based. The team was able to calculate when DANDE would approach the station (within a small tolerance) and create a scheduler file so that DANDE would enter the correct mode at the time specified. The calculation of the correct system time had to take into account orbit propagation uncertainties and internal process latencies to determine the correct time to enter the separation mode so the actual separation would occur at the correct location.

To account for all these uncertainties the team tested the separation execution script on the "Flat Sat" multiple times and calculated the script runtime. For this testing the "Flat Sat" load average, which quantifies the processor utilization, was matched to the current flight load average as closely as possible as this affects command latency. In addition to testing the actual execution script the team characterized how long it took for the system to start the separation execution script. The team used the most up to date orbital element set to calculate the time delay between the DANDE pass when the team would upload the scheduling file and when the scheduling file needed to call on the execution script. The team did calculate all these variables correctly, and the Maui Optical Station was able to observe DANDE separate from the LAB, which confirmed minimum mission success. Figure (4) shows the visual confirmation that the team received from the Maui Optical Station. There are two distinct objects very close together, one is the DANDE spacecraft and the other is the LAB.

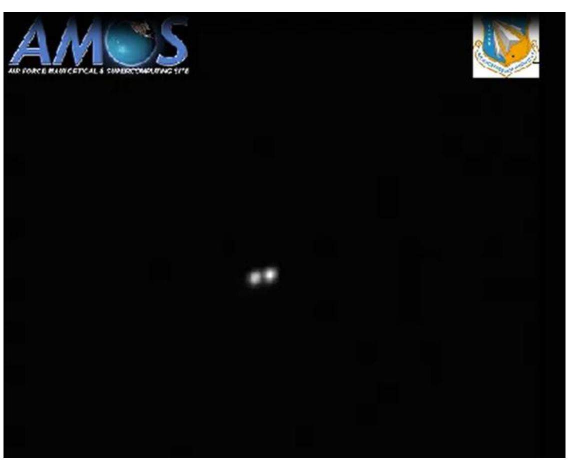

Figure 4. Image from Maui Optical Station of Two Distinct Objects; DANDE and LAB

The purpose of the third phase, attitude, was to maneuver DANDE into the correct orientation for science data collection. This phase took most of the mission and remained unfinished when the team lost contact with the DANDE satellite. The first part of the attitude phase spun DANDE up to 10 RPM, so the accelerometers could provide a low noise acceleration measurement of drag. This part of the attitude phase was closed loop. A configuration file on the satellite gave the correct spin rate bounds and the satellite would fire the magnetorquers until this spin rate was achieved. The closed loop algorithm was crucial because it allowed the system to continue the spin-up maneuver even when out of communication range. This is important, especially for satellites in low earth orbit (LEO), where commissioning time needs to be held at a minimum due to the short orbit lifetime.

However, the team did not hold to the original operations plan for this phase of the mission as the current orbit was expected to provide a longer mission lifetime than the original design. Instead of allowing the closed loop algorithm to run the team attempted to verify the magnetometer readings and torque rod actuations, tests that were not designed to occur on orbit, by reconfiguring the algorithm. The team was not always able to collect the necessary data products for verification of these instruments, which resulted in wasted time and effort as the team ended up falling back on the original plan. This experience solidified the design team's decision to make this part of the mission a closed loop operation, and taught the operations team how paramount it is to stick to the operations plan.

V. CDH

Choosing a operating system is a difficult decision for a satellite system. Some operating systems can simplify tasks that may have been complex otherwise, but they can also increase the possibility for failure. The DANDE CDH system was run on a AVR32 using a real time operating system. The operating system chosen was BusyBox Linux, an implementation specifically designed with embedded systems in mind. This allowed the DANDE team to craft the distribution to fit their need. This included using custom or public tools to improve and shape the software. Although the DANDE satellite had many of these we will focus on only the few most novel.

Through the use of the Linux ZMODEM communication protocol the DANDE team was able to eliminate the cost and development time of a project specific communication protocol. ZMODEM improved upon other communication protocols in that it did not need to wait for a confirmation to send the next packet. Instead it would resend packets only if it received a notice that the packet was not received. This reduced the communications overhead of the acknowledgment packets. The unix implementation of the protocol is highly configurable and satisfied all needs of the system. The DANDE project used this protocol exclusively for the uplink and downlink of files from the satellite. The selection of this protocol shows that often software tools already exist to handle many of the issues faced by satellite teams. By utilizing these tools when appropriate the team can save development costs and time.

As mentioned in the separation section the DANDE satellite did not include a GPS receiver. When the DANDE program began in 2007 GPS receivers were not readily available for student projects so a GPS was not included. While the main use of a GPS is for position knowledge also of considerable value is the accurate absolute time. While the lack of this source of precise timing was a particular concern due to the strict position requirements of the science mission it also caused several other systems to be necessary. The lack of absolute timing means that the system must be able to track the mission timeline, even if the system clock is reset. To address this DANDE had an epoch counter that would increment each time the CDH board reset. By tracking the system clock and epoch changes this system allows data points with the same timestamp to be correctly mapped into absolute time. As this system only provides accuracy to integer seconds the DANDE mission had an additional, much more involved, system to obtain the millisecond accuracy required for the science mission. However, the level of precision afforded by the epoch and system clock method is sufficient for most projects. As this method is quite simple to implement it is recommended for any mission. In the event of another mission finding itself in the same position of strict timing requirements and no GPS the more complex, millisecond accuracy, method requires no changes to the flight code as all of the computations for calibrating the system clock are performed by the ground software. This system was used during the DANDE mission and was demonstrated to provide the required accuracy.

VI. Autonomous Operations

An issue that nearly ended the mission after just two weeks on orbit, and is a likely reason for the final loss of contact, is how the satellite will operate in the absence of active management. When planning a mission it is normally assumed that the once the satellite separates from the launch vehicle there will be regular communications until the mission ends at a predicable time due to either reentry or radiation damage. This assumption, while making for a very clean mission, is not true enough to allow the team to ignore the issue of what will happen if the satellite is left to its own devices for an extended period. Addressing this problem is a question of autonomous software fixes and careful resets.

The current prevailing theory for the loss of contact in January and the brief recontact in February is a combination of a reset not working as intended and the satellite lacking a good safe mode. The satellite had a watchdog that was designed to reset the communications subsystem (COM) if a login had not occurred for 24 hours, on the theory that this was probably due to some issue with that subsystem that might be fixed with a reset. While the watchdog did correctly detect this timer and respond, the response actually only reset the processor and not COM. The reset was tested preflight but the verification was a check of the processor reset so did not actually verify that COM reset. This likely allowed a COM lockup in January to prevent contact for a month until a series of power resets in February. The other contributing factor to the final problem was that DANDE did not perform well in the absence of active management of a software issue. The CDH subsystem had a problem where a large number of files on the satellite would make even basic operations on the file system take such a long time that the satellite would be become nonfunctional. The main generator of files was the data collector, which had a bug that would put each data point in its own file. This had actually been fixed in a revision of the flight code but a version control error resulted in the older, bugged, code being the final code on the satellite. While this bug increased the rate of file accumulation the underlying issue was inherent in the design. The satellite had no provision in the software to check the number of files and delete files as needed to stay below the allowable number. This meant that the satellite would slowly drown itself in files in the absence of operator-commanded file deletions. Shortly after launch, when communication was unreliable due to issues with identifying which object was DANDE and inaccurate TLEs, and during the COM lockup in January the operators were unable to command these file deletions and the software became very difficult to operate. The state of the satellite software after the tracking issues at the beginning of the mission was recoverable, the state in February was not.

These events illustrate the need for rigorous testing of the resets to ensure that the reset actually works as intended. While the discussed COM reset was certainly a good idea, as it neatly addressed a likely error, its implementation resulted in it failing to actually address that issue. Also illustrated is the need for the satellite to be able to autonomously avoid fatal software situations like the file accumulation problem. If the idea of the satellite autonomously managing its own file system is concerning this issue can also be addressed by a safe mode. The detection of a threshold number of files would send the satellite into a safe mode where no, or minimal, files are generated until the operators fix the problem and command the satellite out of that mode. The safe mode can be configured so that a wide variety of problems cause the satellite to enter this mode and the satellite functionality in this mode does not exacerbate any of those problems.

VII. Communications Testing

The testing of the communications link, and the training of the operators, prior to launch was based on some assumptions that turned out to not represent the actual flight conditions. Chief among these was the assumption that the link would be stable inside of the range limits, from the signal strength, and the elevation limits, from the local topography. While the link margin was calculated to account for the antenna gains in a unfavorable attitude state, the response of the ground software and operators to a link drop was not considered. Due to this assumption there was little concern with the command re-request time and how the software would handle partial downlinks of large files. In the nominal attitude state of the satellite this would be a reasonable assumption, however the mission never progressed to this stage. As the actual attitude state of the satellite for much of the mission resulted in the null of the satellite transmit antenna pattern intersecting, or nearly intersecting, the ground station the link would drop out partway through most passes. A plot of received signal strength over the course of a pass, provided by Colin Hurst, shows this issue in Figure (5).

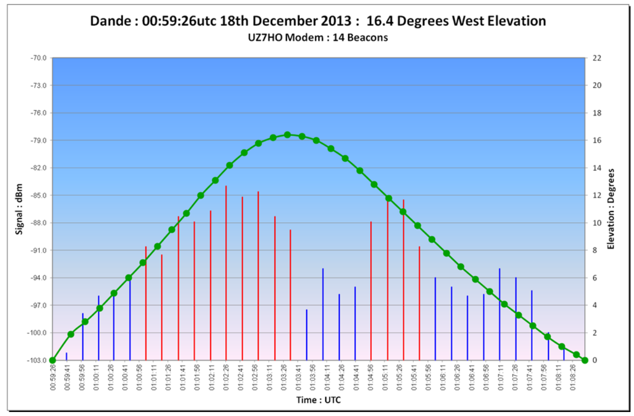

Figure 5. Received Signal Strength, Showing the Mid-Pass Link Drop

The green line is the elevation angle of the satellite and the vertical bars show the received signal strength for each beacon. A red bar indicates that the beacon was successfully decoded, a blue bar indicates a beacon that was heard but was unable to be decoded. Under normal conditions the received signal strength would be a monotonic function of the slant range, and therefore of the elevation angle. However, it can be clearly seen that this is not the case as there is a clear drop in signal strength, and a corresponding set of undecoded beacons, in the middle of the pass. While this would complicate the mission under the best of conditions the problem was exacerbated by some issues with the ground software. The ground software would wait twenty seconds before re-requesting data, i.e. if the ground station did not receive the data on the first request due to the link issue. Also, the link dropping in the middle of a large file downlink would result in the downlink needing to be restarted. These issues greatly reduced the effective data rate, more than due to the simple loss of pass time due to the link drop. As the preflight testing had not accounted for the link drop this issue was not addressed and had to be worked around for the duration of the mission. These issues could have been addressed in one of two ways. The first would have been to have written the ground software for a much shorter re-request time and to have the ability to consistently save partial files and restart a partial file in the correct place. The second would have been to have kept better track of the assumptions that went into the testing, i.e. that the satellite would be an attitude state where the peak antenna gains intersected the ground station, and to endeavor to conduct operations in the conditions tested.

VIII. Ground Station

One of the issues encountered over the course of the DANDE mission was the interface between the ground station and mission operations teams. The ground station had been developed largely independently of the satellite team. This meant that, while the station was fully functional for the mission requirements, the operation of the station was not as user-friendly as it could have been. This made it very difficult for the satellite operators to debug and repair any issues in a timely manner. The layout of the station was determined by the ground station engineers as it made sense to them, which was not a clear layout for those who hadn't built it. The other issue with the team divisions was that the operators had little "stick time" on the station, as the testing and verification of the station had been done by the ground station engineers. This contributed to the issues with the satellite operators debugging and repairing the station. Another issue encountered during operations was how to effectively conduct operations with an unstable link, as mentioned previously. As the preflight assumptions, and therefore the practice passes, had not accounted for the link dropping in the middle of the pass the operators were unprepared for how to order commands and manage the station to maximize the use of all available pass time.

A complication encountered during testing was that it is very difficult to unambiguously test the station performance. A test such as listening to another satellite is certainly useful but does not provide an absolute performance metric. While this test gives an good idea of how well the station is performing it is unknown how many beacons should have theoretically been received during that pass so one cannot compare the observed performance to the theoretical performance. This resulted in some instances where there was trouble with the link and it was difficult to identify whether it was a ground or space problem and therefore difficult to assign testing time appropriately. The best test that the team found was to track another of the university's satellites at the same time as their ground station and compare the number of packets received. While this again is not an absolute performance metric it does give a better idea of the station performance as it is unlikely that multiple ground stations would have similar problems. If there are not other local ground stations that can assist there are similar comparison tests that can be done, either by tracking other satellites with similar transmitters or by comparing to some of the global amateur satellite stations (PE0SAT and DK3WN for example). The final issue discovered during the mission was that the system clock on the ground station computer had significant drift. As the tracking and Doppler corrections require accurate knowledge of the satellite location, which requires accurate knowledge of the current time, this is a serious problem. This was easily fixed by increasing the rate at which the ground station computer would synchronize its clock with the US Navy's Tycho server but this is certainly something to check.

To help the operators several modifications were made to the ground station setup to make it more usable by students other than its designers. These consisted of rearranging the station to group like components and adding a ethernet-controlled power strip. The new station layout made it easier to troubleshoot problems, as all of the components providing information on a given task. An example of this reorganization was to place the rotator interface and rotator controller together so a quick glance could verify that both were operating correctly. This reorganization also made the setup of the station for remote passes easier as a single camera could watch multiple components. A change to the setup also fixed an issue with operations. Some of the ground station components needed to be powered in the correct order to initialize properly, which was not always done by the operators. The ethernet-controlled power strip could be programmed to turn on each port individually in a specified order and spacing, allowing the station to be correctly powered with a single command.

The last major modification that was made to the ground station was to configure the station to be operable remotely. This was particularly useful for periods such as academic breaks, when a student team is largely absent, and is also useful for debugging as it allows more of the engineering team to assist. The changes necessary to allow this functionality were to place USB cameras watching the signal strength indicator on the radio and the indicators on the rotator interface, test the ethernet-controlled power strip for remote operation, install software (TeamViewer) on the ground station computer, and set up the remote access permissions for the commanding software. These changes allowed the remote operator to see incoming data, send commands, configure the tracking software, monitor the operation of the station, and power cycle components if necessary to fix issues. While this system does not provide much debugging ability the station had reached a state of sufficient reliability that the power cycling and full control of the ground station computer was sufficient.

As the ground station for the DANDE mission encountered several issues which, while fairly minor, did interfere with the progression of the mission future teams are advised to implement some of the following suggestions. The first suggestion is to include the mission operators in the ground station as early as possible, particularly in the test/verification phase. Most of the issues with the ground station during operations were the result of operators being unfamiliar with the setup. This could be helped by having them conduct, or at least assist, much of the testing of the ground station, particularly when testing the receive capabilities against on-orbit satellites. This would provide valuable experience operating and debugging the station as well as providing a good forum for co-operatively determining a station organization that works well for all involved. The second suggestion is to deliberately interfere with the link, through attenuation of the transmit signal or deliberate introduction of noise, and modify the ground station setup in the practice passes so the operators gain experience debugging station setup/operation issues and in modifying the command sequence to work around a link drop.

IX. Conclusion

While the DANDE mission did achieve Minimum Mission Success, as it did successfully separate from the LAB, and continued for several months afterwards there are some changes the team would make if they were doing it all again. DANDE was the Colorado SpaceGrant Consortium's first on-orbit satellite project and as such it provided many lessons learned for future projects, both in what worked well and what did not work well. The main lesson learned was to integrate the satellite engineers, the ground systems engineers, and the operators as early in the mission as possible to ensure that all of the teams are working towards a robust and user-friendly finished project that meets the needs of all involved. As discussed there were a variety of relatively minor fixes and problems to work around, but all told the integration of the teams and the retention of institutional knowledge as the original team moves on were the main issues encountered as the mission progressed. The DANDE mission was a great success for the Colorado Space Grant Consortium and it is the hope of all involved that the lessons learned from this mission can be of use to future projects here and across the university satellite community.

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References

[1] Forsberg, Chuck. The ZMODEM Inter Application File Transfer Protocol. Portland Oregon: Omen Technology Incorporated. Print.