As the job market continuously becomes more competitive, college engineering and science students are being pushed to gain ‘real world’ experience to remain attractive candidates to potential employers. Real world experience can be gained through multiple avenues and one of the best is through on-campus laboratories that promote student built projects. While student built projects are a fantastic way for young scientists and engineers to partake in a group design, build and fly environment, one of the most over-looked aspects of these projects is testing. The testing methodology used on three major projects in the Boulder Space Grant: RocketSat, Hermes CubeSat and DANDE NanoSatellite are explored. The tests conducted on the different projects have helped to improve the engineering in many ways and the results have yielded improvements to each system. These tests not only help to validate and verify the design’s performance but they occasionally provide an interface between the team and industry professionals who have given great feedback on the projects. It is through a good test plan that a project can truly excel and perform to expectations.
1 Background: The Projects

The Drag and Atmospheric Neutral Density Explorer (DANDE), Figure 1.1, is a 50 kg, spherical spacecraft being developed by students at the University of Colorado at Boulder by the Colorado Space Grant Consortium (COSGC) in partnership with the Aerospace Engineering Science Department (ASEN). The goal of the DANDE (http://spacegrant.colorado.edu/dande) mission is to provide an improved understanding of the satellite drag environment in the lower-thermosphere at low-cost.

DANDE is a part of the Air Force Research Laboratory’s (AFRL) University NanoSat Program (UNP) which has as its goal the development of satellite-design and research capability at universities as well as the education of the future space-engineering workforce. DANDE was selected as the winning satellite from a national competition with 10 other universities to build, test, and fly a working satellite.

DANDE has been hugely successful for the University of Colorado and has promoted many scientific and industry collaborations for the student team and the Boulder Space Grant.

RocketSat, Figure 1.2, is another very successful start up program from the Boulder Space Grant. RocketSat enables lower classmen, and some upper classmen to gain their first experience with the engineering process while working on a project that they will be able to see launch within a calendar year. RocketSat payloads consistently have environmental sensing hardware which specifically target the 40 mile to about 90 mile altitude ranges. The program is on its sixth iteration and has had multiple successful missions while training more inexperienced students in engineering.

Hermes CubeSat, Figure 1., is another long duration satellite project that has been in development since the summer of 2006. Hermes’ mission is a technical demonstration of an S-band high data rate communication system. If the S-band system is shown to work, it will increase the average 1-unit CubeSat’s data rate by about 50 times. Hermes has also had recent success with its manifest on the NASA Glory launch scheduled for November 2010. It will be the first satellite the Boulder Space Grant has had prepared for orbit since 3-CornerSat launched in 2004.

These three projects represent different complexity levels, design challenges and testing methodologies. Systems of this complexity take significant amounts of design and analysis. As with any satellite or other product constructed in industry, testing is used to not only verify analyses, but to ensure that assumptions and estimates are valid. Hermes and RocketSat have had to relay extensively on internal resources and testing while DANDE has been able to utilize many facilities, and advisors external to Space Grant to achieve its testing goals. The successes and benefits of these styles of testing are discussed and conclusions are drawn concerning what makes a good test methodology for a student project to create success.

1 http://www.vs.afrl.af.mil/UNP/
2 Purpose behind testing plans

Each of the projects takes a different approach to testing. DANDE frequently keeps records of tests and uses written test plans that are reviewed by multiple people to conduct tests. Hermes and RocketSat follow a more informal process and most often do not use test plans and instead rely on one or two students’ judgment to ensure that tests have been properly conducted. Even with this diversity, the basic purpose of all conducted tests is the same: understand what the system can do while achieving a new level of capability on the system. Each new level of capability is a milestone that allows the student engineers to know what progress has been made and that the system should be able to perform at or better than that test for the rest of the lifetime of the project. This philosophy that each round of testing brings about a permanent level of development is similar to a lot of agile software development practices, which have gained favor due to their efficiency. Hermes, RocketSat and DANDE have all used this practice in some aspect of the project, most often with electronics boards and their iterations.

A testing plan however, should be more than a process to develop hardware. A testing plan should be derived directly from a project’s requirements. As requirements are created, their verification method should also be defined, one of which is testing. Therefore, a good test plan comes from having good requirements and understanding what the system must be engineered to do. This has been seen throughout all of the projects. DANDE has produced well-defined requirements for most of its mechanical systems and some of its electrical systems. An example of this is the mass spectrometer (NMS) which requires that ‘The NMS shall measure wind magnitude with a 1-sigma precision of ± 100m/s. GOAL: NMS should measure the wind magnitude to within 20 m/s.’ As seen by (Figure 2.1), NMS is able to measure wind between 5m/s and 13m/s. This test was clearly necessary as defined by the requirement and the instrument’s performance is now characterized! Hermes has had rather poorly described requirements and due to this, has consistently had issues with its tests. The lacking requirements have caused components like the wiring harness to not be robust which has caused numerous issues throughout the other subsystems during testing.

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Another important reason to have a good test plan and methodology is to identify where students may be making assumptions and then use that knowledge to test those assumptions when possible. The initial designs for Hermes had the S-band system being able to communicate with the Boulder ground station using only a small, 2 meter dish. Testing however showed that the link budget was a little optimistic and attenuation testing demonstrated the real capabilities of the S-band system. It was found that a 3 meter dish was more sufficient. Background noise was also measured during a test at the Boulder ground station and it was found that the wireless internet created too much noise around the communication frequencies and so a remote S-band ground station has been created simply to combat all of those issues. This is but one of many examples where tests have properly adjusted plans so that a system can actually function as designed.

Finally, tests have been used to verify and validate models and analyses on the projects. On RocketSat, finite element models were used to analyze the internal structure. The models gave reasonable factors of safety however destructive tensile and compression tests were conducted on engineering units of the structure to ensure that the models were yielding believable results. It was found that the models were slightly underestimating the static strength of the RocketSat structure and that the overall structure was slightly stronger than the models predicted. The factor of safety was around 2.5 for the RocketSat II structure and the expected loading was only estimated to be around 240 lb, while tensile testing showed a yield of the structure around 600 lb (Figure 2.2). This helped the team gain confidence that the finite element models were giving reasonable estimates and that they could be trusted for further design decisions.

While there are often more models created than tests conducted, it is desirable to understand when it is good to test a model or a design. The ability to decide what requires a test versus another form of verification can be decided in multiple ways. The following sections discuss it in more detail.

3 The philosophy of DANDE testing

Testing on student projects often take two primary forms: formal and informal testing. As with many student projects, there is a lot of testing done simply to ensure basic functionality or provide ‘sanity checks’ for the student. Many of these informal tests are easily performed on any project, such as board conductivity testing on printed circuit boards (PCBs). Formal tests however, are much more infrequent and their execution depends drastically on the project. DANDE has been highly successful in obtaining several formal tests in industry and other laboratory facilities. Obtaining and conducting formal tests is a time consuming endeavor however, when done properly, it yields fantastic results. The following discussion explores how formal tests have been chosen, how often they the team decides tests should be conducted as well as some other considerations made before testing occurs.
3.1 When to test

Ideally there would be infinite time and resources to test all of the systems of a student project to ensure that it was properly designed and constructed. This however is too costly in both time and money to be the reality. Student projects often experience these limitations acutely and it therefore becomes imperative to understand what needs to be tested and why, so that the proper test can be performed. Requirements can aid this process significantly however, many of the student leaders have found several key reasons to create official tests.

The DANDE team has utilized external industry advisors extensively to aid the design process. While not every student project can have industry advisors, an experienced professor or instructor is also a good aid to students who are still learning the engineering process. Project advisors, when possible, should be picked so that they can bring years of experience with them concerning a specific topic. Their expertise in specific areas should aid the team with identifying questionable assumptions or things that can only really be verified through testing. On DANDE, there have been numerous tests and demonstrations of their separation system which has led to a successful design of that system. However, the separation system has never been flown in space and therefore requires significant amounts of testing. Through the advise of one of DANDE’s structural mentors the team learned that both the mechanisms and the electronics should be tested in a thermal vacuum chamber (Figure 3.1). At vacuum, and over a wide range of temperatures the mechanism’s components can shift causing misalignments while electronics can exhibit odd behavior due to the extreme environment. This complete end to end test was considered excessive by the student team but was shown to be necessary by the industry advisor to ensure that the system truly was shown to work in a flight-like condition. Considerations like this are often overlooked by students due to lack of experience, however they are clear to more experienced industry advisors. This type of aid has been pivotal to many of the successes on DANDE, Hermes and RocketSat.

Aside from advisor input, it has been found that another great reason to conduct a test is to set a milestone for the team. Programmatically, it is often very useful to have solid goals and timeframes for the team to complete tasks. Hermes recently has been using this method to great success in preparation for their final environmental testing and delivery. The team, in order to reach Day in the Life (DITL) testing for the satellite has been pushing to verify all subsystem functionality and performance requirements. Through this testing, the team did not reach DITL testing as quickly as desired however they were able to learn about their system and uncover issues that were not anticipated. The team encountered several issues including several electrical shorts of their hardware to the structure (Figure 3.2) which were fixed and allowed Hermes to reach a new level of development. The team has made tremendous progress, even on issues it did not know Hermes had, and has benefited from a demanding testing schedule.
Tests are also used when information or data is required by the team but it is not available or analysis would be extremely difficult. Examples of this are vibrational modes in structures. RocketSat, CubeSat and DANDE have or will all experience dynamic loading due to rocket propulsion. Each of these projects employs FEM analysis and basic hand calculations however these can often only give ballpark estimates of the modes of vibration in a structure. Similarly, it is possible to create a finite element model (outside of commercial packages) for each individual project, however this takes an engineer experienced in FEM and significant time, neither of which are often present in a student project. ‘Paralysis by analysis’ is something that student projects must avoid especially since tests can be just as educational as a drawn out calculation. It has been found that testing, in these cases is also extremely useful and informative. The advantages of testing versus complex analysis can be seen with DANDE’s structural analysis. To ensure that DANDE would survive launch, the structure was designed to have a high natural frequency. The models had an estimated 120Hz first fundamental mode however the measured value was 84Hz. This test led to a redesign and stiffening of the structure which has improved the overall design of the system. Thus, testing has also been used to help understand the system when analysis is not good enough or there is insufficient information to properly predict what the system will do.

Tests can also be very informative for new students on a project and they can learn significant amounts during testing. Testing allows hands-on activity with the system which new students must quickly learn. Using new students to help test also gives them a feeling that they have contributed to the project very quickly. They often become more invested in the project because of this and it is a practice employed, when possible, on all of the projects.

3.2 How often to test

On student projects, it seems like testing is often an overlooked aspect of the project; something to be done at the end. This however is a dangerous philosophy and can stunt the project’s ability to succeed. The problem often arises from the fact that it is difficult to understand what and how a piece of hardware or the system should be tested. Good requirements are key to understanding what the most pivotal parts of a project are which allows for focused testing of those objectives or subsystems. Still, there are often other components of a project that need frequent testing and demonstrations of levels of maturity are a must. Electronics and software are two key examples. DANDE, CubeSat, and RocketSat through its multiple project iterations, have all been able to develop their electrical and software systems using many test phases. Most of the initial development was done on bread and development boards. This is pivotal for validating design choices and ensuring that the concept of the design actually works as desired. From there, basic PCBs are created with a first level approximation for what is necessary on a subsystem (adding in the ability to easily test the boards in early revisions is also desirable). In the first stages of development, all three projects have found it
extremely useful to have electronic boards that are non-flight and that are very easy to probe. This allows for debugging of the electronics and software. Funds permitting, multiple other revisions of electronics can be made, each with increased software functionality when necessary. DANDE has progressed through five or more PCB iterations on some subsystems and CubeSat has a similar number of iterations. Iterating electronics and software functionality have been shown by these projects to be very important for achieving desired performance from a system. Each iteration promotes further testing on the system which increases the team’s knowledge and confidence in the system. Thus, electrical and software systems have been found to benefit from relatively frequent testing.

Most mechanical systems have not needed nearly as much testing. Static loading tests are relatively easy to conduct and simple stress analysis can sufficiently analyze static cases. Dynamic loading is often the most important testing for structures and should only require one or two tests to verify the overall performance.

On Hermes and DANDE it has been found that the mechanisms, deployment systems and any moving structural member are the real candidates for multiple revisions and tests like the electronics and software. Mechanisms are generally very difficult to design and analyze and testing is the best way to ensure the proper performance is attained. Hermes has gone through several iterations in their antenna deployment design due to testing, settling on a very simple burn-wire technique. DANDE, has changed their mechanism design very little but has undergone many tests on the mechanisms including repeated activations of the system, microgravity testing, and thermal vacuum testing.

While the Boulder Space Grant is only recently adopting some agile development methods, the frequency of testing can be thought of as an agile process. The agile process of creating goals and development stages with test periods at the end of each stage is very similar to the electrical and mechanism development processes conducted by DANDE and Hermes. Both DANDE and Hermes have been design review and major test milestone driven but an agile process could help designers create more distinct phases of development and will likely become the more common development technique within the Boulder Space Grant on future projects.

3.3 External vs. internal tests

Throughout all of the testing done, the majority of the testing on all three projects has been conducted within the Boulder Space Grant facility or in one of the near-by laboratories. Testing internally makes the entire testing effort much easier. Internal testing can often be done when needed and done more frequently making hardware development time much less dependent on external influences. Internal testing pacers the test process at the team’s leisure, something that can significantly reduce stress on the team. Another advantage about internal testing is that it allows for less formal testing to occur so that students can take and analyze data without the external pressures of a timetable. Adjustments to equipment during an internal test is significantly easier because of all of the amenities of the team’s lab space is within reach.

Conversely, external tests take much more preparation and time to complete. When testing externally, the team must conform to the other facility’s schedule, work day, and possible fees. It has been learned by all three teams that external tests should only take place when it is simply not possible to properly conduct a test without outside equipment or facilities. There have been multiple instances where a test was slightly descoped to be conducted internally which allowed for all of the conveniences of an internal test while only losing small amounts of data that were only desired, not required. On DANDE, it was originally desired to place the solar panels into a
sun simulation chamber. Obtaining access to this type of facility was both difficult and expensive. The team instead decided to take the solar panels outside into direct sunlight. This only required a small electronic board modification and some algorithms to be written. While the team lost the ability to characterize the solar panels in a vacuum chamber, it gained the ability to test the panels more than just once with the test equipment that was created. This has proven to be more useful than any single test could have been.

Another issue with external testing is simply obtaining the test facilities. Most companies have their test equipment frequently in use and giving free or significantly reduced cost tests is a secondary priority. The use of the facilities is an expense due to the fact that engineers and technicians that conduct the test are being paid. However, DANDE and Hermes have received and utilized several offers by different companies. It usually only takes a contact within the company and a simple request by a student for engineering firms to try and aid students. If a reasonable need is shown to an engineering firm, they are often willing to aid students, and that has led to very rewarding tests and relationships for the students and the companies.

One part of external testing that is rarely considered concerns apparatuses. For small projects, this is generally not an issue but for larger, more massive equipment several apparatuses may be needed to properly conduct a test. During transportation, lifting, and attaching to test equipment, apparatuses are necessary. This increases the workload for any student team because the apparatuses need to be designed, built, and tested before they are ever actually used for their intended purpose.

Finally, during an external test, the student team needs to behave in a professional manner at all times. The engineers and scientists helping the students conduct the test will recognize and applaud a polite, well organized team. Being well organized is incredibly important, not only to be professional but to remain on schedule during testing. Procedures should be written and worked through early as possible before arriving at the test site. If available, external advisors and the test conductors themselves should have a chance to review and understand the procedures before the team arrives so that everyone is on the same page and agrees that what the students propose is actually possible. Another piece of advice given to DANDE was to treat every piece of equipment with respect and use it only as it is intended i.e. don’t lean on your own transportation equipment when it is not in use because it is not intended for human support and it gives the impression that the students do not take good care of their equipment. Finally, the procedures should be very clear what data should be taken and when it should be taken.

3.4 When not to test

One part of a good testing methodology is to know when not to test. There are many times when a simple analysis can take the place of a test. Tests are time consuming and may not provide all of the insight into the behavior of a system that an analysis can. This is often the case for static load analysis and simple dynamic systems. Systems like RocketSat often do not conduct much testing on their heritage components because they have successfully flown numerous times. Re-inventing the wheel is something to be avoided so that progress can be made in other areas. Destructive tests are also considered carefully before any testing actually occurs because this can be costly and often do not reveal as many results as expected. Also, analysis is usually cheaper and more simple than testing. Radiation analyses have been done for Hermes and DANDE using CREME96\(^3\) and yields good ballpark estimates on the amount of

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radiation the satellites will see on orbit. This analysis coupled with research into robustness of components in the environment allows for an understanding of how long equipment will survive on orbit. If instead radiation testing were conducted on hardware to find their total ionizing dose, the cost would be tens of thousands of dollars and take significant time. Cases like this are extreme but show when tests should be avoided.

4 Industry

While most testing takes place within the laboratory facilities available to the students, external tests do occur and are often very important for the progress of a student project that would otherwise not have the resources to properly test their system. Industry facilities and mentors are key to student project development. They have been tremendously helpful on RocketSat, Hermes, and especially DANDE. None of these projects would be the success stories they are today without external experience and aid. On DANDE and Hermes, their communication systems benefitted greatly from industry mentorship and anechoic chamber facilities used for testing. DANDE could not have completed its mass properties or vibrational testing without industry support. As mentioned earlier, the vibration test helped DANDE identify structural issues early and a stiffer structure has since been created. DANDE was in a competition with nine other universities and DANDE was the only project with an actual vibration test. This undoubtedly aided DANDE’s score since the project had actual data to support their models and the redesigned structure had more validity as an improvement. Vacuum chamber testing of both the mass spectrometer and separation systems were conducted externally to the Boulder facilities and has increased the technical readiness level (TRL) of both systems.

Engaging industry has been incredibly rewarding for both the mentors and the students. Mentor input into a design has allowed all projects a better design review process while reducing the amount of wasted student effort. Utilizing industry test facilities has provided many students with unique opportunities, even among their peers, to engage in complex and professional testing environments. Mentors have also appreciated student’s interest in their fields and they generally like to help young scientists and engineers succeed in their studies. DANDE has continued to utilize their industry contacts due to the very successful mentor/mentee relationship that has been built and Boulder Space Grant itself has promoted every project to have external mentors to aid the students and their projects.

5 Conclusion

Developing a good testing methodology is very important to creating a successful project. RocketSat, Hermes CubeSat and DANDE have all conducted many tests and have done so with both formal and informal testing schemes. Conducting the majority of tests internally allow for quick and frequent testing of electrical, software, and occasionally mechanical systems. External tests are conducted sparingly but help to advance the project and gain data that could otherwise not be collected. Tests are done to not only verify assumptions and models but to validate the system in both the students’, and others’ eyes. In the long run, no one believes that a design can do what it is supposed to do until it is tested and a good test methodology allows for everyone to know how well a system can perform.