How Not to Build a CubeSat – Lessons Learned from Developing and Launching NMSU's First CubeSat

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ABSTRACT

Ionospheric Neutron Content Analyzer (INCA), a student led CubeSat project at New Mexico State University (NMSU). INCA is launching on NASA's ELaNa 20 mission carrying a neutron detector designed and built by NASA's Goddard Space Flight Center. The INCA mission is the first spacecraft built by New Mexico State University in many years, as such, the program was essentially started from scratch with minimal pre-existing resources. While eventually successful, INCA took many missteps along the way, starting out as a 6U, eventually being completely redesigned to a 3U, before launching after around six years of development. This paper documents INCA's design, build, and early operations, along the way the team learned many lessons about designing and building a small satellite in the context of a university program. This paper is targeted at new university teams considering starting a mission, documenting best practices learned by the INCA team, and some pitfalls to avoid.

INTRODUCTION

The Ionospheric Neutron Content Analyzer (INCA) is a 3U student mission led by New Mexico State University (NMSU). While this is not the first SmallSat built by NMSU, the previous efforts occurred several years prior to the INCA mission, with everyone including the faculty who worked on previous missions have left NMSU. As such the INCA mission is being conducted by an all-new team which had essentially no prior experience with SmallSats.

Figure 1: INCA undergoing final testing

This paper is intended to document the mistakes and lessons learned by the INCA team with the hope that future missions will be able to learn from NMSU's mistakes. While the INCA mission has had significant challenges, the mission is now essentially complete and is manifested on the upcoming ELaNa 20 launch. The INCA mission is a partnership with NASA Goddard, where NMSU built the spacecraft, and Goddard provided the science instrument.

INCA MISSION

Science Mission

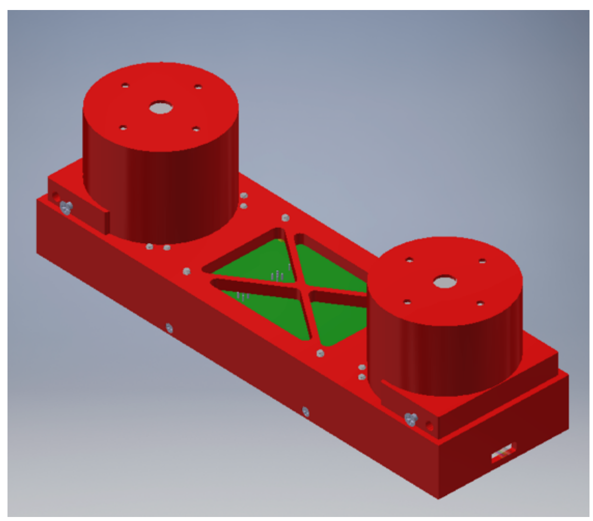

Figure 2: Interior of the Neutron Detector including the mount for the two scintillators

The INCA CubeSat is flying a Silicon Photomultiplier (SiPM) based Neutron Detector. This Neutron detector will for the first time measure the time and latitude dependence of the Neutron Spectrum in Low Earth Orbit (LEO). The Neutron detector, which was built by NASA's Goddard Space Flight Center, and is based around two cylindrical P-Terphenyl Scintillators. These scintillators generate photons when hit by energetic particles such as neutrons. The photons are then read out by an array of SiPMs, which convert the them into an electronic signal. The two main scintillators are enclosed in a box of veto panels, which only react to charged particles and not neutral particles, therefore making it possible to reject charged particles. This is necessary, as the main detector cannot distinguish between charged and neutral particles. The Neutron detector determines the energy of a particle by measuring the time of flight between when a neutron strikes each of the two scintillators.

INCA's science objective is to measure the neutron flux in LEO, which feeds into models of the formation of Earth's magnetic field. Additionally, these measurements contribute to understanding the radiation environment that satellites encounter, and to the understanding of neutron air showers, which pose a radiation hazard to occupants of high-altitude aircraft such as airliners.

Software Design

INCA utilizes a multi-processor architecture, with the main system board being controlled by a low-power ARM processor, and the neutron detector controlled by a BeagleBone Black. This architecture allows the payload to communicate with the BeagleBone Black via a USB network protocol, utilizing the processing power of the high-power consumption BeagleBone Black only during science collection. Off-board INCA, the ground station computer is used to communicate with the satellite. The communication between these computers is a master-minion tree, where the ground station computer is the master of the system board on the satellite. Onboard the satellite, the system board is the master of the BeagleBone Black. The master controls the communication link, with the minion only responding when requested by the master. This is critical for the half-duplex communication link between the ground and the satellite in order to ensure commands can always be sent to the satellite.

The main-system board software uses a single executable structure to reduce complexities of inter-process communication. This is effective in reducing complexity but increases the risk of changing onboard software during flight, as the entire flight code must be re-uploaded to perform this procedure.

Hardware Design

The hardware for INCA is based on an off the shelf CubeSat system, which includes a 3U hard anodized aluminum structure, flight computer, battery, and a -Z panel with integrated antennas for a GPS and radio. Additionally, the system included side panels that cover the first 1U of the 3U structure. These panels contain 3-axis open core magnetorquers. The INCA team purchased a GPS, which integrates into the COTS flight computer and the included antenna on the -Z panel. Sensors integrated with the commercial system include sun sensors, temperature sensors, and magnetometers on the outer panels. The rest of the hardware consists of a BeagleBone Black and a Globalstar radio. The rest of the components were custom manufactured by the INCA team and not COTS parts.

Thermal analysis showed that some of the materials in the neutron detector would get too hot and lose their useful properties, so a copper heat sink with a mylar sheet facing the front of the satellite was included between the sun sensor on the front face and the front of the detector. NMSU made a custom PCB to mount the BeagleBone Black and Globalstar radio to the structure. Additionally, this board contained the circuitry required to connecting the detector to the BeagleBone and the flight computer. Providing power to the satellite, are a set of custom deployable and side solar panels. These panels included temperature sensors for a better understanding of the spacecrafts thermal state, and the circuitry for the deployment mechanism. Due to the accuracy required to achieve some of the mission objectives, a custom directionally sensitive sun sensor was required on the front face to accurately determine the attitude of the satellite with respect to the sun, as such a custom sensor was designed and fabricated to achieve this sensitivity.

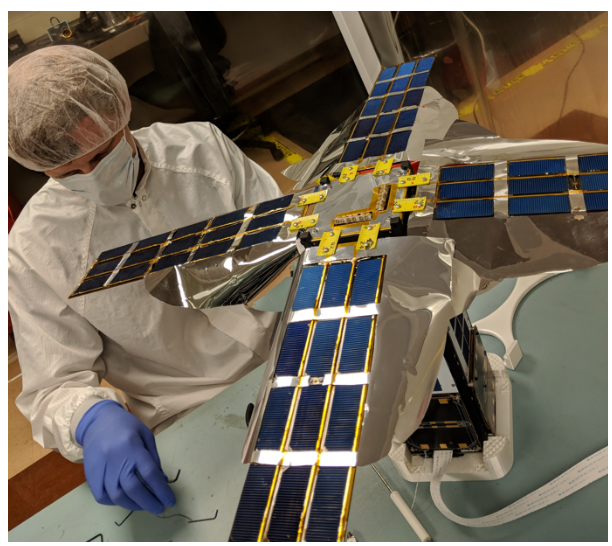

Figure 3: INCA with the solar panels deployed

INCA DEVELOPMENT CYCLE

UNP days

The INCA mission started as a 6U CubeSat in 2012 as part of the University Nanosat Program (UNP) in their NS-8 competition. INCA remained in the UNP program until the end of phase A, at which point the UNP program down selected from ten missions to five. INCA was down selected from the UNP program, primarily due to lack of design maturity at the time. The UNP project provided the INCA team with a strong foundation in developing the initial mission.

Converting to 3U

As the mission was fundamentally sound, merely behind schedule, and much of the UNP funding was still available, it was decided to continue development, even after the INCA mission was down selected from the UNP process. However, without the UNP programs support, obtaining a launch became significantly more challenging. It was quickly identified that launch opportunities for 6U's where few and far between. After careful analysis of INCA's design, it was determined by sacrificing a small amount of resolution in the neutron detector, it would be possible to shorten the detector, and shrink INCA into a 3U CubeSat. This decision substantially opened up launch opportunities, and eventually resulted in a launch slot through NASA's CubeSat Launch Initiative (CSLI).

Launch Selection

Due to a low budget once INCA lost continued UNP funding, it was necessary to find a low-cost launch option. As such, INCA applied to NASA's CSLI program. This competitive program launches CubeSat payloads from any US educational institution with a no transfer of funds agreement. The INCA program proposed to the CSLI program for the first time in November 2014, as a 6U CubeSat. This proposal was not selected, so the INCA team converted the mission into a 3U and reapplied in November 2015. In February 2016 the INCA team was notified that it had been selected for the CSLI program and a few weeks later it was announced that INCA was manifested for launch on the ELaNa 20 mission onboard Virgin Galactic's LauncherOne. This was a unique launch opportunity in that there was no primary payload, and the only other payloads where other ELaNa CubeSats.

3U Development

The COTS CubeSat system purchased by the INCA team included most of the major systems. These components fit together relatively well with minimal modifications. A CAD model of the satellite with all of the components included was used to determine how the spacecraft would fit together. The external components were fabricated first because the design of these would not be altered by any changes in the design of the detector. These external components included the front sun sensor, the deployable solar panels, and the side panels for the 2U of the structure not covered by the COTS side panels.

The detector took multiple iterations to finalize the design; though the external dimensions did not vary too greatly between iterations because the team had already identified how much space the rest of the avionics stack would take. Once the detector design was finalized, the structural parts were manufactured at NMSU in the on-campus machine shop. The completed detector structural components were then sent to NASA Goddard where the rest of the components were assembled into the detector structure. Upon receiving the completed detector at NMSU, a test fit into the spacecraft structure revealed that the detector was 0.5 mm too large in every dimension, which prevented the spacecraft from being assembled around the detector. The detector was too big as a result to the thickness of a Teflon wrap around the veto panels, which were not properly accounted for in the detector design. To deal with this issue, the detector was sent back to Goddard for modification. This is a good example of why prototypes of all components should be made as early as possible to prevent these issues from occurring at the last minute. Once the detector was integrated into the structure and the final position and dimensions determined, the custom board to mount the BeagleBone Black and the Globalstar radio were designed. This board needed to include a hole to clear part of the wiring harness for the detector. The CAD model was used to figure out the final position the BeagleBone would be mounted in and the mounting PCBs were ordered. After fully assembling one of these boards and installing it into the structure, everything appeared to fit correctly until the coax connector was installed on the radio. The connector stuck out roughly 8 mm beyond the side of the radio and was found to interfere with the side panel, which would have resulted in the external dimensions exceeding the size of the deployment canister. A redesign of the board was required which shifted the Beagleone and radio over enough to allow for the length of the stack from one side of the BeagleBone to the coax connector on the other side to fit within the side panels. Even with this change, a USB connector that would not be used on the BeagleBone had to be removed because it protruded too far past the edge of the board and the end of the coax connector had to be filed down to avoid contacting the side panel.

A challenge the INCA team faced was a poor decision made early on to try to make a UNP deadline, this resulted in hardware being selected that was not designed for the purpose. A system suite was selected, that was designed for a 1U satellite, and the INCA team added various boards to the encompassing suite to make it work with the additional solar panels, and the neutron detector. This solution worked but resulted in undesired issues. One of the issues required completely replacing the COTS interface board with a custom board to permit integration between CubeSat kit, and the rest of the system. This board design was complex and would not have been needed with better early system engineering.

LESSONS LEARNED

Program Management

The INCA mission learned a great deal of tips and tricks to improve the mission programmatically. The first major issue encountered was schedule delays. The mission ran significantly behind for most of the design and manufacturing process. Some of this was due to issues beyond the team's control, such as the teams initial funding being delayed for several months due to an extended government shutdown. However, most of the delay was due to inadequate internal programmatic designs. One of the biggest problems encountered by the INCA team was an underestimate of how long these projects would take. When working to a deadline that is years away, it is very difficult to apply the appropriate pressure on students to make progress on systems, particularly when they also have class work. One of the techniques that the INCA team found worked well was to create intermediate deadlines with real penalties if they were not met. What the INCA team recommends is creating a regular review schedule, with reviews at least twice a year. These reviews should have clearly defined expectations of where the systems should be at that point. This provides team members with clear and imminent deadlines along with the consequence of having to present to reviewers why they are not on schedule.

Another important aspect of program management that the INCA team recommends, is too create a series of tests which sub teams are expected to perform on a specific schedule. On the INCA mission, the test program was developed around doing the final system level tests once the mission was nearly complete and the systems where all integrated. This resulted in problems with individual systems not being identified until very late in the design process. This included determining that the team needed to re-spin a couple of custom electronic boards after they had already been integrated. The second problem this caused is that the team didn't do much work with the flight hardware until the system tests. This resulted in the team being generally unfamiliar with how to use the systems until late in the testing process, significantly slowing final development. To fix these, the recommended solution is to develop a series of simple tests, to be completed early on. These are steps like demonstrating power on, demonstrating two components can communicate with each other, or charging a battery. The important part is that these tests are measurable and can be performed progressively throughout the development cycle. These tests should be done with both prototype, and flight hardware.

Personnel

The biggest challenges encountered on the INCA project was the high turnover rate of undergraduate students. The INCA mission took over six years between inception, and launch. With the exception of the faculty PI, no one involved with the beginning of the project is currently involved. The long timeframes involved relative to the duration of a single student involvement necessitates that any university CubeSat project have a well-defined recruitment plan. The strategy the INCA team eventually came up with is to establish a team lead, and a co-team lead for each sub system. The co-team lead should be at least a year behind the team lead, so as to take over once the team lead graduates.

It is important to regularly recruit new students so as to ensure that there is always a pool of students to pull from as people graduate off the team. The INCA team found that the best recruiting method was to target students at approximately the sophomore or second semester freshmen level, this gave the team time for older students to train these students before they graduated. Additionally, it was found to be crucial to recruit the students before they became involved with other projects. It is also important to not overlook the value of graduate students, particularly if it can be arranged for the SmallSat project to be part of their graduate research. What the INCA team found is that in several important areas, namely communication systems, attitude determination and control, vibration analysis embedded systems, and thermal analysis. Undergraduates don't learn what they need to know to perform the work in these fields until the very end of their program. As such, the INCA team repeatedly found that students would learn enough to start these analyses in their final semesters and would not leave them with sufficient time to complete the work before they left. In order to perform analysis in these area's it is recommended to either have graduate students available to perform the work, or to arrange for an expert like a professor to be available to guide lower level undergraduates through these tasks. If all else fails, it is useful to arrange for funds to be available to hire an outside consultant to aid with these crucial tasks. This was not done on the INCA project, but probably should have been.

One final aspect to personnel that NMSU found very important to recruiting useful students was to pay them. It is not necessarily crucial to pay all of the students, however the INCA team found that volunteer students usually had to get a job in order to pay for school, which significantly impacted the hours they could put into INCA. The simple fact of the matter is that the amount of time that is required to be put into developing a SmallSat is more than most students can put in while also working and attending school full time.

Software

The largest pitfall for INCA's software development was manpower. As INCA is a student project, most of the workers were volunteers with only a few paid research assistants. This led to a shortage of workers at times and caused the main flight software team to merge with the Communication sub-team. Although these teams needed to work closely to get the communication software to work with the rest of the satellite flight software, this decision put strain on the small workforce of one to three students working on the software at the time. Additionally, the software developers wound up spending precious man-hours on the design, of an interface board. Future missions should ensure there is adequate manpower being devoted to both hardware design and software design.

COMMERCIAL OFF THE SHELF

INCA was developed with predominantly Commercial Off the Shelf (COTS) components. This was a sound decision for an inexperienced spacecraft team. However, the team did learn several important lessons about working with these types of components which should be considered. The first is that SmallSat COTS parts are not off the shelf in the sense that consumer electronics are off the shelf. SmallSat COTS parts are produced in small lots, and they should be tested nearly as rigorously as with custom components. However, the difference is that COTS parts will tend to pass their testing on the first attempt, something that is often not the case with custom components.

A second major recommendation the INCA team has for working with COTS components is to thoroughly vet the manufactures before purchasing components from them. When you develop a spacecraft, your component manufactures essentially become a partner on the mission and needs to act as such. The INCA team found several manufactures that were excellent to work with, producing high quality components that where extremely well documented, and included excellent customer support. INCA did purchase one major component from a company with a very good sales department. However, once the component was purchased, the company failed to provide useful documentation, or the required software libraries. This company then proceeded to provide poor support for their product for a few years until they finally told the INCA team that the support contract had expired. At this point the manufacture had still failed to provide all of the software that was supposed to be part of the original product. It was later discovered that this was a common problem with this particular manufacturer. The moral of this story is that like most industries, the SmallSat community has many suppliers who are very good; there are also several that are not; use caution when choosing who to work with.

WORKING WITH A PARTNER

Since NASA Goddard developed the payload for the INCA mission, the INCA team was able to experience both the challenges and the rewards of working with a partner on a space mission. The layout of the INCA partnership was that Goddard developed and supplied the instrument, which was then delivered to NMSU to integrate into the spacecraft. This arrangement worked well, with Goddard providing an instrument that NMSU could never have developed by itself. However, there were several mistakes made in this partnership. Such as it was never clearly delineated what parts where Goddard's responsibility, and which parts where NMSU's. This resulted in a few problems, one example was that late in the process, it was discovered that both groups had believed that the cable, which connected the neutron detector to the spacecraft bus, was being built and had been purchased by the other group. This cable included a high cost long lead-time connector which nearly resulted in INCA missing its vibe test. Fortunately, Goddard found a connector that had been purchased as a spare for another mission.

A second but closely related problem in the development was the lack of a clear Interface Control Document (ICD) between the detector and the spacecraft bus. The INCA team strongly recommends creating and maintaining an ICD with the partner. This document needs to clearly define the mechanical connection between systems, including both the structural connection and electrical connections. Additionally, the ICD needs to contain protocol information about how the software communicates. The INCA team did not have this document, and it resulted in a significant delay in the design as each time anyone wanted to work on those parts, it become necessary to schedule a meeting to determine the interface. This process also resulted in a good deal of redesign, as without a clear document more than once the two teams misunderstood the other, and the two groups designed conflicting parts. One particularly notable incident involved Goddard placing a wiring harness on the outside of the neutron detector which occupied the same location as one of INCA's avionics boards. This necessitated a redesign of the avionics board with a hole in the middle to accommodate the neutron detectors wiring harness.

One final comment on partnerships, is to ensure that both parties understand the others financial situation. Goddard built INCA's Neutron Detector as a spare time project with parts scavenged from other projects. In the end this worked out, but required NMSU to purchase parts, and to manufacture the neutron detectors structure. This arrangement worked but could have turned into a significant problem if both sides had not understood the arrangement. Overall the key to working with Goddard successfully boiled down to communication. It helped significantly to have a couple of in person meetings between the two teams which helped establish a rapport to enable future communications to go more smoothly. However, the most important element which significantly improved the two teams progress was the establishment of a weekly meeting between the key people on both teams. This meeting includes the engineers and scientists doing the work, and not just management.

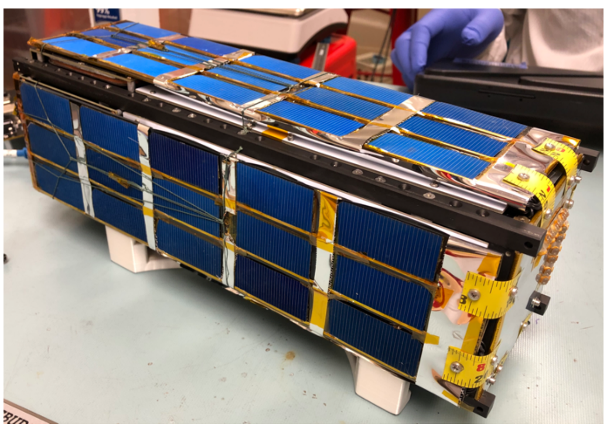

Figure 4: The Completed INCA CubeSat

CONCLUSION

In conclusion, the INCA mission has been very successful with over one hundred students working on it over its six-year design life. There have been numerous lessons learned, however they fundamentally boil down to three main points, first test early and often, second communication is key, and third create well documented processes early, keep them updated and follow them.