Software Development and Hardware Commissioning for Applications in the High Contrast Imaging Testbed Facility

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May – July, 2018

I. Abstract

The High Contrast Imaging Testbed facility (HCIT) of the Jet Propulsion Laboratory (JPL) currently houses four coronagraph testbeds, each designed and built to research and advance specific technologies that will further our ability to study exoplanets. These new technologies will be used in the development of the coronagraph instrument that will be placed in the Wide Field Infrared Survey Telescope (WFIRST), as well instruments to be used in other future missions.

The objective of my project was to update testbed and vacuum chamber hardware controlling routines, as well as assist in the installation and calibration of the Decadal Survey Testbed (DST) and its instruments. This objective was worked towards in the form of several small projects, including developing a vacuum pump gate valve controller and calibrating optical mounts for use in the DST. Moving forward, we will continue to develop and update software routines as needed to aid our research into new coronagraph technologies.

II. Introduction

During my internship at JPL in the summer of 2018, I was given the opportunity to work on my internship project with high contrast imaging group 383A in the HCIT. My project consisted of five major tasks:

1. Designing and Installing a Vacuum Pump Safety System for Chamber HCIT1
2. Assisting in Installation of the DST
3. Tuning the DST's Thermal Heater Proportional-Integral-Derivative (PID) controllers
4. Characterizing a Deformable Mirror (DM) Mount
5. Mounting and Installing DM 48.3 onto DST

These tasks are listed in the general chronological order that they were given to me. Many of these tasks were completed alongside or with the help of members of the HCIT team, including my mentors and fellow interns. The wide variety of tasks allowed each one to be interesting and exciting to work on. Although some of the tasks were not fully completed at the end of my internship, I am satisfied knowing that they will be completed by my fellow 383 interns whose internship periods extend past my own. Several other minor tasks not discussed in detail include reorganizing the Hi-Bay, writing Python methods for Dr. Pin Chen, and day-to-day intern duties such as brining tools around and wiping surfaces clean with isopropyl alcohol.

III. Background

All of the tasks that I completed during my internship have helped further our ability to develop and test new advances in coronagraph technologies. A coronagraph is an instrument used to block out direct starlight, originally developed to study the corona of the Sun. Although the idea behind the coronagraph remains the same today, we are now interested in studying the exo-planets orbiting the stars outside of our solar system. Currently, we are capable of viewing contrasts of 10^-9 between stars and their surroundings, but technology is in development and testing that has proven to reach contrasts of 10^-10. To put that in perspective, the Sun is about 3x10^9, or 3 billion, times brighter than Mars. In order to image an exo-earth, we would need a contrast of at least 10^-10. The journey to reach higher levels of contrast than ever before is one part of our search to find habitable planets or extraterrestrial life beyond Earth.

Figure 1: HCIT2 in 318 HiBay

Much of my work was on coronagraph testbeds, the instruments placed upon them, and the vacuum chambers that house them. Coronagraph testbeds are large optical tables with a regular grid of threaded holes, used to test new coronagraph designs and technology. Optics can be screwed onto the table in various configurations that vary based on the coronagraph design. These include mirrors, lenses, cameras, lasers, and in our case deformable mirrors (DMs) that are used to manipulate the wave front of the light. The table is then placed into a vacuum chamber to mimic space-like conditions and tested. In the HCIT there are two vacuum chambers, HCIT1 and HCIT2. HCIT1 can fit one testbed and is the chamber involved in my first task. HCIT2 (**Figure 1**) can house three testbeds and is the new home of DST. The results we get from testing these testbeds are then analyzed and the knowledge and data we gain are used to drive further innovation into new technologies and flight instruments.

IV. Task 1: Safety System for Turbo Vacuum Pump

My first and main task involved the design and installation of a safety system for the turbo vacuum pump of HCIT1. The turbo pump is connected to the chamber via a gate valve that can be opened or closed to seal the chamber. This gate valve is designed to automatically close when power is lost. The problem that we were trying to solve was that in the original configuration of HCIT1, if the turbo pump were to fail all power to HCIT1 would be cut in order to close the gate valve and seal the chamber. This loss of power could potentially damage equipment in use and prevent measurements or data from being collected while the problem persisted. The solution that Camilo and I came up with was to create a new safety system using a Python controlled power strip that could remotely turn off power to the gate valve only, sealing the chamber without cutting power to the whole chamber. **Figure 2** shows the vacuum chamber and the turbo pump, while **Figure 3** shows the turbo pump gate valve, and the pressure transducer in the turbo pump.

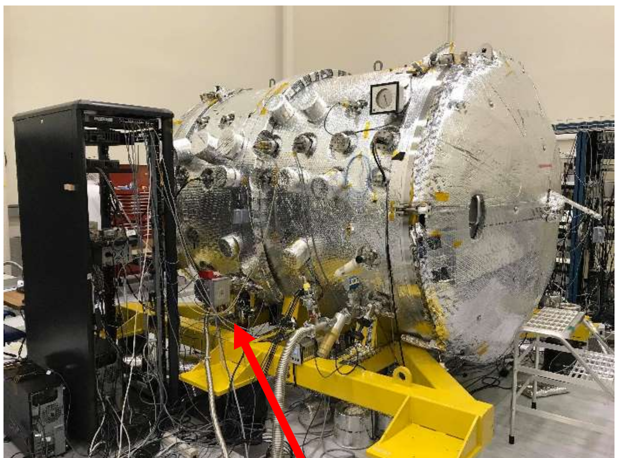


Figure 2: HCIT1 *Turbo Pump*

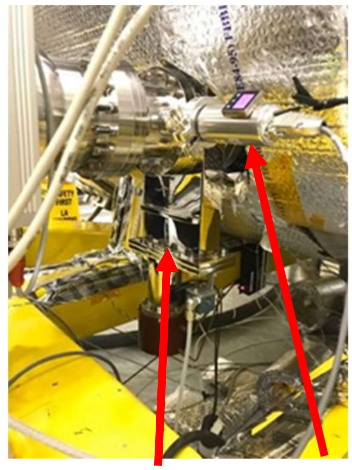


Figure 3: Gate Valve and Pressure Transducer

After coming up with the system design, I set about trying to find a programmable power strip. I was able to find a suitable power strip within the Hi-Bay, but it was being used elsewhere so I took down the make and model. After searching online, I found the power strip on Amazon and was able to get the power strip ordered and delivered. While waiting for the delivery, I wrote a first draft of the Python script used to control the outlet, which I named the Turbo Vacuum Pump Outlet Control (TVPOC). The power strip can be seen in **Figure 4** on the following page.

In order to write TVPOC I had to figure out how to communicate with the pressure transducer and the power strip. I searched online for manuals for the pressure transducer and power strip and was able to find the commands and syntax necessary to communicate with them. I had no experience with communication via serial ports or remote connections using Python scripts, so I had to learn them on the spot. After lots of trial and error trying to debug issues with the remote connections, I was able to get data from the pressure transducer and command the power strip remotely.

After I had finished testing the communications, my next step was to install the system. **Figure 2** shows the computer rack that I originally bolted the power strip to, but we later moved it down into the trenches on the floor to reduce the chance of someone accidently pulling out the wires we later connected to the power strip. Multiple wires had to be switched out and many devices such as pumps and control boxes were moved to reduce the trip hazard around HCIT1. In the end, the HCIT1 pumping system has ended up much cleaner and safer than before.

Figure 4: Programmable Power Strip

I presented my new system to the HCIT team and received unfortunate but useful feedback. The first issue with my system was that the gate valve required air pressure in the pump lines in order to close, even if the power was shut off. Because of this, the system had to be redesigned to also include a pressure sensor within the pump lines. The second issue with my system was that a better system could be achieved using vacuum interlocks, which would not require a loop running at all times. This was overlooked because we do not currently have the hardware in order to implement the interlock system but should be implemented later on if the parts are acquired.

In order to finish the system, the new pressure sensor for the pump lines still has to be ordered and installed. My fellow intern Masato Nakano will finish installing the new sensor when it arrives and implement it into the TVPOC code. After that is done, TVPOC can be implemented fully into the current Watchdog system to improve the safety of HCIT1 operation.

V. Task 2: Installing DST

The second main task of my internship was to aid in the installation of the Decadal Survey Testbed, or DST. The installation of DST started around the third or fourth week of my internship and took around five days to complete. DST was lifted by crane from its original location across the HiBay and moved into the west end of HCIT2, which is depicted in **Figure 1**. DST already had most of the optics installed on top of it, so we did not have to worry about placing and aligning any instruments. Once inside, we began the tedious process of connecting all of the D-SUB connectors, installing the heaters and thermal sensors, untangling and rerouting optical fibers, taping up loose wires, balancing the Minus K isolators beneath the bench, and hooking up the coolant lines. After several days of hard work, we made sure all the motors were working properly and everything was communicating fine. The nearly fully installed DST, without the two DMs, is shown in **Figure 5**. Finally, we sealed and pumped down the chamber so that we could start running tests on DST. During this task I learned a lot about patience and the importance of taking things slowly when working with fragile or expensive equipment to make sure nothing breaks.

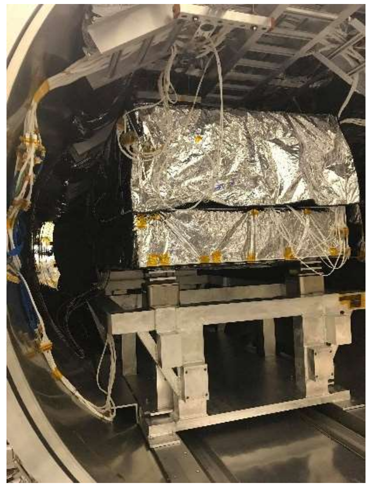


Figure 5: DST Fully Installed With Insulating Blankets

VI. Task 3: Tuning DST's Thermal PID Controllers

The third task I worked on was tuning DST's thermal PID controllers after the DST was installed and placed in vacuum. PID controllers are continuous control systems used to keep some measured variable, in this case temperature, as close to a set value as possible. The four parameters that PID control systems use include a set-point value, a proportional value K_p, an integral value K_i, and a derivative value K_d. At some combination of the four values, the PID control will result in a smooth curve up to the set-point with minimal overshoot and oscillation.

After setting the set-point to some arbitrary safe temperature, the first step I took was to blindly guess K_p values until the system was able to reach the set-point temperature. If the K_p value is too low, the set-point would not be reached. I discovered that the K_p value that produced the behavior we wanted was ten times greater than what we expected, which was strange but we continued on anyway. Using the K_p values I calculated K_i and K_d values and tried using the three values together. This setup caused the temperatures to jump wildly and perform unexpected behavior so I stopped the process and tried to find the issue. After a few days while debugging a completely different issue, we discovered a bug in the code calculating the power being sent to the heaters. After we fixed this bug I recalculated the values and the behavior we got from the PID controllers was close to what we expected. Dr. Keith Patterson fine-tuned the controller even further after I finished and we were able to achieve control within a few milli-Kelvins as shown in **Figure 6**.

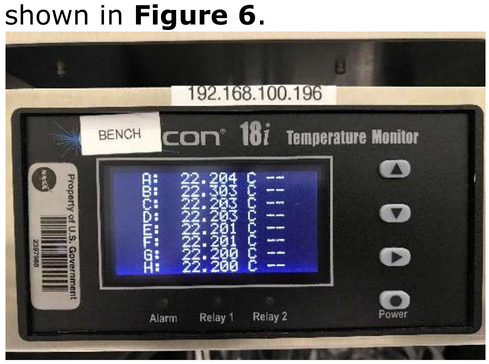


Figure 6: DST Thermal Sensor Readings

VII. Task 4: Characterizing a DM Mount

The fourth major task I worked on was characterizing a DM Mount's voltage-controlled crystal piston motors. These motors (**Figure 7**) control the tilt of the mirror carriage that is attached to the mirror (**Figure 8**). The plan was to apply varying amounts of voltage to the motors and use an interferometer (**Figure 9**) to measure the tilt of the mirror and plot the delta tilt per volt. An interferometer is a device that shines a laser through a half one-way mirror. Some of the laser light is reflected by this mirror back into the interferometer and is used as a reference. The rest of the laser passes through the mirror and is reflected off of whatever is in front of the interferometer and also returns into the interferometer as the measurement light. The interferometer compares the reference light and the measurement light and we are able to analyze this comparison in order to determine characteristics of the surface of the object that reflected the measurement light, including the tilt.

In order to characterize the mount, I used a surrogate mirror instead of the DM because of the high risk of working with such expensive equipment. We originally planned to use a polished stainless-steel plate as the surrogate mirror. Unfortunately, we found that the light reflected off the mirror was not clear enough for the interferometer to analyze. We were able to find a highly polished aluminum coated glass mirror about the same size and weight as the stainless-steel plate and used that as a surrogate mirror instead. Using the new mirror, we were able to get good readings from the interferometer and the process of characterizing the motors started.

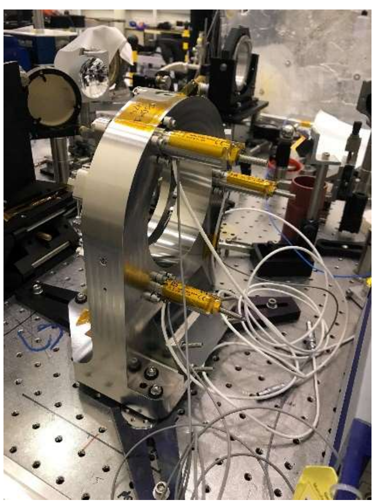


Figure 7: Three Crystal Piston Motors

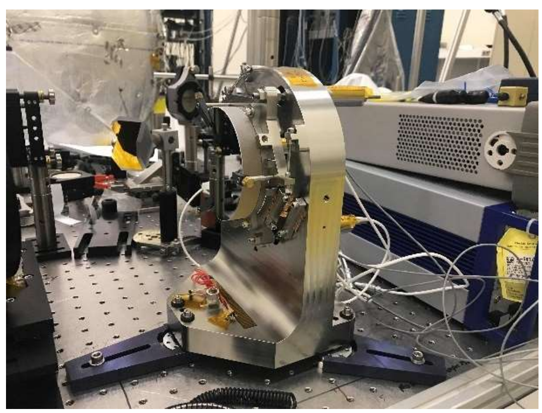


Figure 8: Surrogate Mirror

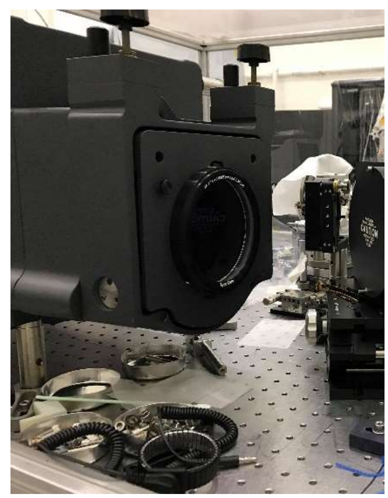
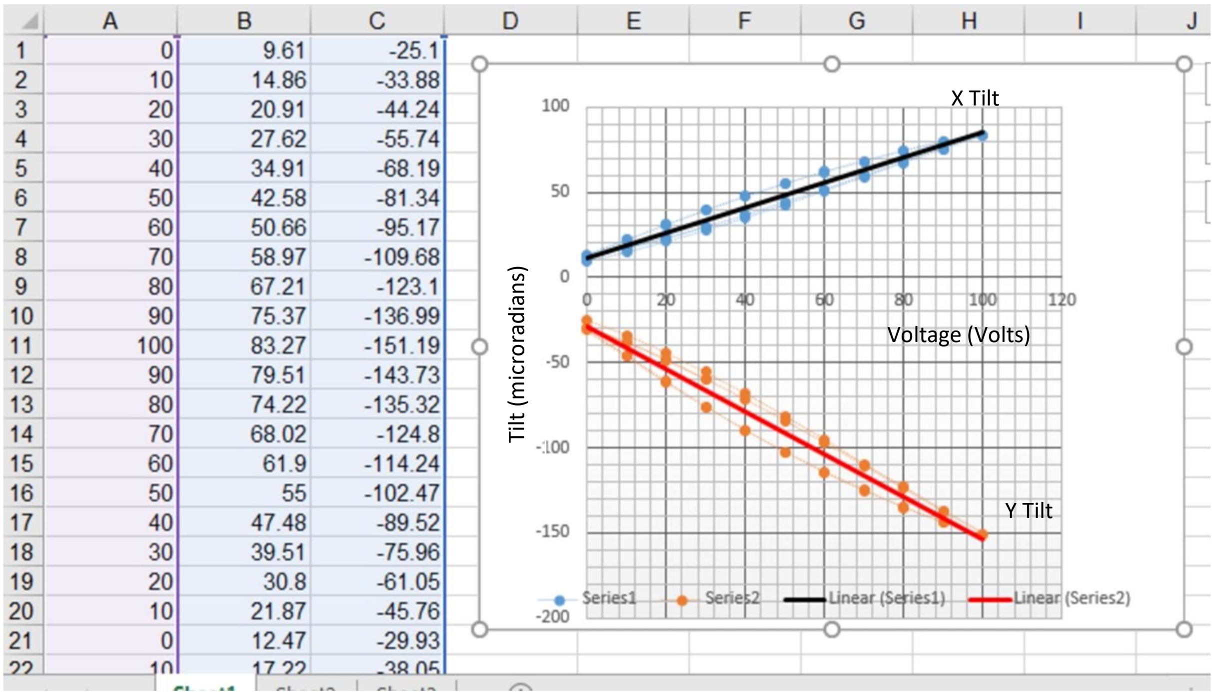


Figure 9: Front of Interferometer

I cycled through each of the three motors from 0-100 volts several times at intervals of 10 volts each, recording the data onto a spreadsheet. After each motor went through several cycles, I plotted the data using an x-y scatter plot to show the delta tilt per volt, shown in **Figure 10**. The change in tilt of the mirror caused by the motors is extremely fine, measured in microradians. To put these tiny adjustments in perspective, it takes a little under 5 microradians to equal an arcsecond, which is 1/60th of an arcminute, which is 1/60th of a degree. One arcminute is about the angle from the ground to the top of a soccer ball 775 meters away! After plotting the data, I sent it out to Dr. Keith Patterson and other members of the HCIT team so that they could use the information to plan future tests.



	A	B	C
1	0	9.61	-25.1
2	10	14.86	-33.88
3	20	20.91	-44.24
4	30	27.62	-55.74
5	40	34.91	-68.19
6	50	42.58	-81.34
7	60	50.66	-95.17
8	70	58.97	-109.68
9	80	67.21	-123.1
10	90	75.37	-136.99
11	100	83.27	-151.19
12	90	79.51	-143.73
13	80	74.22	-135.32
14	70	68.02	-124.8
15	60	61.9	-114.24
16	50	55	-102.47
17	40	47.48	-89.52
18	30	39.51	-75.96
19	20	30.8	-61.05
20	10	21.87	-45.76
21	0	12.47	-29.93
22	10	17.22	-38.05

Figure 10: Data From Motor 2 of DM Mount

VIII. Task 5: Mounting and Installing DM 48.3

The final major task of my project was mounting and installing DM 48.3 (**Figure 11**), the first DM that was installed onto DST. A DM is a mirror with a square grid of actuators, in this case 48x48, located behind the surface of the mirror. These actuators are controlled by electronics that come out of the back of the mirror. When voltage is applied to these actuators, they can move forward or backwards in order to change the shape of the mirror surface. By applying a certain configuration of voltages, one can manipulate the wave front of the light being reflected by the mirror. This technology is used in coronagraphs in order to further change the starlight and reach deeper contrast levels. One more DM, using the mount that I helped characterize in Task 4, will be installed onto DST in a few more weeks. This task was not so much difficult as it was tedious and stressful. We ran into many unforeseen problems that caused delays in the process, but because of this we learned a lot that will help the next DM installation go much smoother.

The first task of mounting the DM was to prepare a strain reliever for the electronic cables coming out of the DM. The strain reliever was basically a metal comb with 48 spaces, one for every two cables coming out of the DM. Unfortunately, the machine shop was unable to cut the spaces small enough, and the spaces ended up being 20 microns larger than we wanted. Our solution was to place four pieces of tape 10 microns thick between each comb in the areas where the cables would be in order to make up for the extra space. We ran out of the 10 microns thick tape after a few combs and had to resort to using tape that was 5 microns thick and was extremely sticky. This meant we had to put eight pieces of tape between every comb, which became extremely tedious when the pieces kept sticking to our gloves and other surfaces. After a couple of days working on this, we cut the excess tape. However, the tape did not cut cleanly and left adhesive all over the strain reliever which caused more problems for us down the line.

We placed the strain reliever at first about a foot up from the deformable mirror, and our plan was to slide it down the cables to the bottom. The stickiness of the tape that we used made it extremely difficult to do so, and so we spent several long hours slowly pushing and pulling the strain reliever towards the mirror. This painfully slow process was exacerbated by the fact that the DM costs several hundreds of thousands of dollars, which if we broke would be a huge embarrassment for ourselves and JPL as a whole. It took us several days to bring the strain reliever as close to the mirror as we were comfortable with, and we bolted it down to keep it in place.

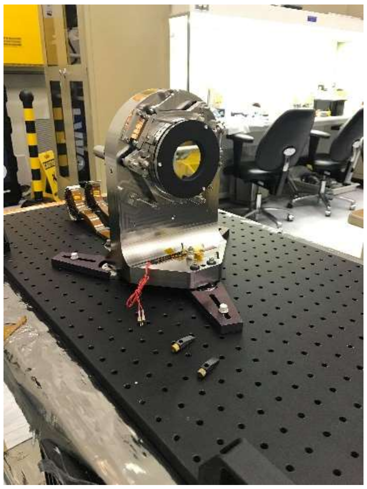


Figure 11: DM 48.3 Uncovered

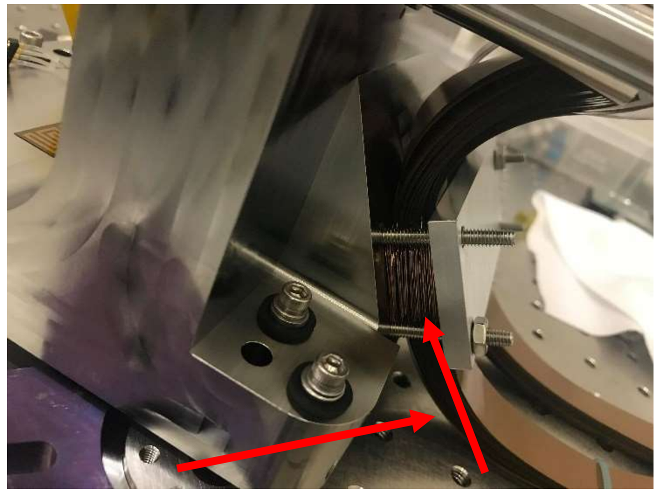


Figure 12: DM Cables Bolted Alongside Copper Strips

After the strain reliever was in place we cut pieces of copper into strips and threaded these strips in between all of the cables (**Figure 12**). The goal was to clamp down the cables along with the copper strips in order to create a path for thermal conductivity. This process only took about a day and went much more smoothly than the strain reliever, although we still had to be careful not to cut the DM electronics with the copper or the clamps. Then we made a cover for the DM using a hard-plastic sheet and prepared the DM and its electronics for installation. We carefully moved the DM across the Hi-Bay to the DST and spent around two days getting the mirror in, removing the surrogate mirror, plugging in all of the electronics, and aligning the mirror and its circuit boards. After a few problems arose that were quickly solved, DM 48.3 was fully installed and ready for use in DST.

IX. Conclusion

During my internship here at JPL, not only did I learn a lot about space, optics, coronagraphy, programming, and engineering, but I learned a lot about working with other people in a laboratory environment and collaborating with others to achieve things that I could never hope to accomplish on our own. I am glad that I was exposed to such a wide variety of tasks so that I could truly experience what it is like to be an engineer at JPL, or at least one that works in the HCIT lab. This internship has opened my eyes to just how important and widely used the skills that I have been learning and will continue to learn in computer science classes at the University of California, Berkeley are. It was exciting to be able to see a project that I had worked on be used in something useful for the first time, especially since projects at school tend to be work for the sake of work. Outside of pure academics, I learned a lot about tools, hardware, machines, and engineering methods that will definitely come in handy when I have to start fixing things on my own later on in life. I am humbled to have had the opportunity to contribute, however small the amount, towards our mission to discover habitable planets and life out in the universe beyond our current capabilities of sight. Looking back at the ten weeks of my internship, I regret not signing up for and getting involved with more activities earlier on in my internship. Two of my favorite experiences were in the last week of my internship, when I went on tours of the Space Simulator and the Mission Control Center. However, I am very happy with how my first internship went overall and am very excited to see what the future holds for space exploration and travel.

X. Acknowledgements

I would first like to thank my mentors Dr. Hong Tang and Dr. Camilo Mejia Prada for guiding me through my first internship. I had an amazing time at JPL and they were the ones constantly helping me out, giving me things to do, and organizing events to help my internship be both fun and productive. I would also like to thank Dr. Keith Patterson and Dr. Pin Chen for giving me work to do when I had downtime during various tasks while waiting for parts to arrive and such. Another thanks to my fellow interns Masato Nakano and Jordan Rupp for keeping me company during the last few weeks of my internship and for their future efforts in finishing the tasks that I was unable to complete during my internship period. Additionally, I would like to thank the rest of the HCIT team for putting up with me throughout the ten weeks of my internship and for all their help and friendliness during my stay. Finally, I extend my gratitude to Caltech and JPL for enabling me to have this experience of a lifetime, and to the University of California, Berkeley for teaching me most of the skills I needed prior to working here at JPL.

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by JPL Summer Internship Program and the National Aeronautics and Space Administration.