COMPUTER SIMULATION OF THE ATTITUDE OF LUNAR ICECUBE DURING EARLY OPERATIONS AND DEPLOYMENT

A Thesis

Presented to

the Faculty of the College of Science

Morehead State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

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April 21, 2017

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Lunar Ice Cube is a six unit cubesat designed to insert itself into lunar orbit after ejection on the EM-1 NASA mission. Deployment from the rocket body the satellite will result in transference of angular momentum on the satellite body. The tumbling as a result will need to be counteracted and control of the satellite body established. This will be accomplished with an attitude control system (ACS) developed by Blue Canyon Technologies (BCT). The system makes use of 3 reaction wheels to counteract the angular momentum on the tumbling satellite body. A primary limitation of reaction wheels as an ACS system is the spin rate limit of each wheel which when achieved is called saturation and prevents further storing of angular momentum in the wheel. The goal of this project is to model the deployment, de-tumble operations, and solar vector alignment. The modeling of these operations will be done through computer simulation software. The attitude control system will be modeled as a proportional-integral-derivative controller or

PID controller which is how Blue Canyon operates attitude control systems. If not properly modeled before delivery the mission risks failure within a few short hours of deployment due to complications from uncontrolled tumbling.

Accepted by: ________________________________, Chair
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Chapter I

Introduction

1.1 Lunar IceCube

Lunar IceCube is a six unit cubesat designed to achieve lunar orbit after ejection from the Space Launch System Interim Cryogenic Propulsion State (ICPS) on the NASA EM-1 mission. EM-1 is an upcoming NASA mission with the primary objective of testing the new Space Launch System (SLS) the most powerful rocket yet developed. Lunar IceCube is one of several secondary payloads onboard the SLS. The secondary payloads are contained inside the ICPS. Each payload is mounted along the rocket body wall inside its dedicated deployment system.

1.2 Deployment

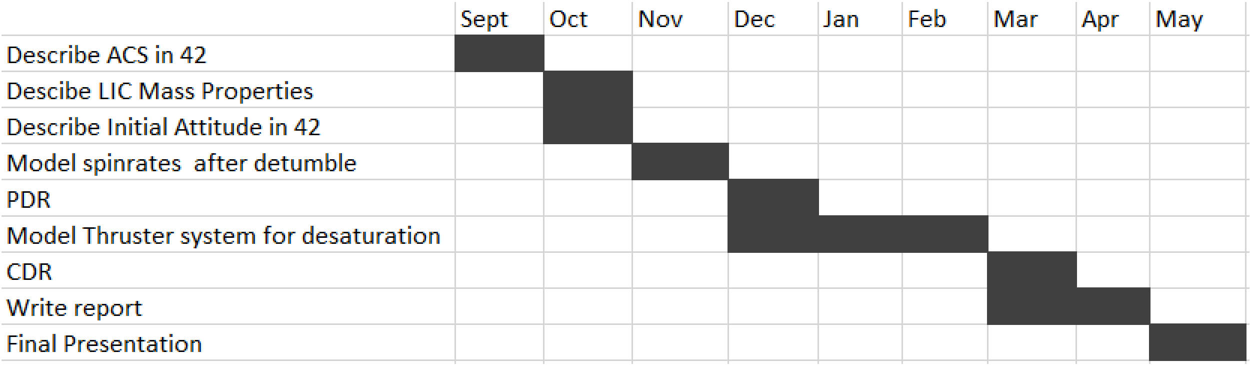
Deploying from the ICPS the satellite will result in transference of angular momentum from the ICPS to the satellite body. The deployment system will eject Lunar IceCube at a 45 degree angle from the rocket body. The two vectors along separate angles will impart a roll upon the satellite body or a tumble. In addition to the rocket inertia vector and the deployment vector the rocket body will have a roll rate of 1rpm during deployment. The roll of the rocket body is for thermal management of the rocket body to prevent a temperature differential that could hinder operations during flight. Standard procedure for satellite deployment from a rocket body is to stabilize the attitude of the rocket body during satellite deployment in order to minimize the initial tumbling rates of ejected payloads. As this is the maiden voyage of the SLS the priority of the primary payload has been increased and has added additional challenges to the secondary payloads. The rocket body roll will add three additional vectors to the initial tumble of the satellite body. The tumbling that results will need to be counteracted and stabilized control of the satellite body established. This will be accomplished with an attitude control system (ACS) developed by Blue Canyon Technologies (BCT), and the control algorithms implemented on the ACS. The system makes use of 3 reaction wheels to counteract the angular momentum on the tumbling satellite body. A primary limitation of reaction wheels as the primary element of an ACS system is the spin rate limit of each wheel which when achieved is called saturation and prevents further storing of angular momentum in the wheel. The goal of this project is to model the deployment, de-tumble operations, solar pointing, and wheel desaturation that will occur using the propulsion system. Modeling of these operations will be accomplished through computer simulation software. The attitude control system will be modeled as a proportional-integral-derivative controller or PID controller which is how Blue Canyon operates attitude control systems. If not properly modeled before delivery the mission risks failure within a few short hours of deployment due to complications from uncontrolled tumbling.

The simulation software employed is controlled with the C programming language by editing text files manually. Software development is not a skill that I have proficiency in. This is expected to be the primary obstacle to the completion of this project. The plan to deal with this issue is to confer with experts from both the Space Science Center and NASA Goddard Space Flight Facility in overcoming this obstacle.

1.3 Work Breakdown Structure & Timeline

The first semester is focused on the development of the detumble simulation code. This simulation is focused on the immediate attitude actions taken by the satellite after deployment. The basic commands to carry out the maneuver shall be completed with the assistance of NASA Goddard. What needs to be completed is to describe the mass and inertia properties of the satellite. This must be done so that the general effectiveness of the ACS on the body of the satellite can be determined. The initial attitude of the satellite must be described in the simulation so that the detumbling capabilities can be tested against the predicted worst case scenario for post deployment tumbling. The simulation must also be set up that the appropriate numerical data is outputted in an easily usable format.

Below is the timeline for the project milestones. While the issue of describing the ACS led to the command issue with the first simulation, the other steps are mostly unaffected and still required for the completion of the project.



	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Describe ACS in 42	■								
Descibe LIC Mass Properties		■							
Describe Initial Attitude in 42		■							
Model spinrates after detumble			■						
PDR				■					
Model Thruster system for desaturation				■	■	■			
CDR							■		
Write report							■	■	
Final Presentation									■

1.4 Cost Estimates

While most equipment and personnel required for the completion of this project are currently on hand at the time of writing and start of the project a budget will be presented with the valuation of all required elements. The simulation will require a computer so that the software can be run. The computer cannot be a simple low powered workstation since the program’s real time calculation are more intensive than a basic workstation can produce in a reasonable timeframe. The cost of the high power laptop that I am using for the project costs approximately $800. The labor was calculated at a relatively modest but workable salary of $15 per hour. Estimating that the project will take 30 weeks to complete and that the project will considered a full time job at 40 hours per week the total cost of labor comes to $18,000. The assistance from NASA Goddard comes from the 0.4 assistance of a NASA employee. While the employee will work in an assortment of roles the total cost of the 0.4 will be recorded at $100,000. In case of unforeseen costs or delays a layer of budgetary “fat” of 20% will be applied to the total cost. Overhead at Morehead State University is 25% and will be reflected in cost estimate. The total cost estimate of the project comes to $178,200.

1.5 Risk Areas

The primary risk to this project are further delays to acquiring assistance from NASA Goddard. If additional delays occur then the project delivery will likely slip back depending in the severity of the situation. Other risks are concerned with the ability of myself to write the software commands of the second simulation. It is possible that the code may be much more difficult and complex in 42’s software. The time estimated allots for additional time that may be needed but depending on the level assistance and complexity of the task there is a possibility that the second simulation could take longer than expected.

1.6 Deliverables

The completion of this project will result in a set of key deliverables. The computer simulation itself will be delivered to The Lunar Ice Cube SharePoint. The results of the simulation will determine whether or not the attitude control system will be capable of detumbling the satellite body during the worst case tumble scenario. This information will be delivered immediately upon its determination to the project manager. By the completion of the project copies of all source code of the completed simulation will be delivered to the Morehead Space Science Center in whatever way the project PI determines.

Chapter II

Review of Literature

2.1 Attitude Control Systems

There are several methods of maintaining attitude control of a satellite body. Reaction wheels, also known as momentum wheels, are a popular form of active attitude control. Passive attitude control methods do not rely on energy input from the satellite and rely on naturally occurring forces in nature to control the attitude profile of a satellite (Eterno, 1999). Active methods are powered through the electrical system of the satellite or through the expenditure of a fuel reserve and some type of thrust system (Eterno). The goal of any attitude control system is to stabilize the satellite by managing the angular momentum stored in the satellite using free body physics (Eterno).

2.2 Thrusters

Thrusters consume fuel to create a thrust vector 180 degrees out of phase to the angular momentum of the satellite to render a net energy of zero along the tumbling axis (Eterno, 1999). This method allows the total energy of the satellite to be directly controlled. The drawbacks of this method are potential unwanted changes to the orbital trajectory of the satellite and the lack of fine precision for body mounted sensors. Thrusters are also problematic on missions that are constrained by mass and volume limitations due to fuel storage requirements (Reeves, 1999). The use of fuel also means that attitude control is no longer possible when the fuel cells are depleted.

2.3 Reaction Wheels

Reaction wheels are a set of rotating wheels typically in a set of three one wheel for each axis. When the wheels spin they will by the laws of physics have angular momentum (Eterno, 1999). By spinning the wheels 180 degrees out of phase with the direction of the tumbling of the satellite body the angular momentum of the body is conserved into the spinning reaction wheels stabilizing the attitude of the satellite body (Eterno). Reaction wheels are powered by the satellites electrical system negating the need for fuel reserves and can rely on power generated by the satellite's solar panels. The electrical nature of the system allows reaction wheels a very high level of precision (Eterno). This allows fine sensor pointing for the gathering of data for the payload and a near net zero attitude for the satellite body. Reaction wheels do have some drawbacks. Unlike the thruster where a new force is placed upon the satellite body to negate the current rotation, reaction wheels simply store the angular momentum through their constant rotation (Eterno). If the wheels ever cease to turn or their rotation rate were to fall then the angular momentum is conserved back onto the satellite body (Eterno). This drawback can be useful however if the spacecraft needs to be turned towards a target for sensor pointing, antennas, and solar panels. The need to constantly rotate to store the angular momentum requires that the attitude system will constantly draw power from the satellite's electronic power system at all times including during eclipse when power generation through the solar panels is not possible. Reaction wheels are however limited by the motors that drive the rotation of the wheels themselves. Motors have limits as to how fast they can rotate. This means that the reaction wheels have a maximum spin rate and therefore a maximum amount of angular momentum that they are capable of handling(Eterno). When this maximum spin rate has been achieved it is known as saturation. When saturation occurs there is nothing else that the reaction wheels are capable of doing to control the attitude of the satellite other than releasing what energy they have stored.

2.4 Lunar IceCube ACS

Lunar IceCube will have two forms of attitude control available, a reaction wheel system and a thruster system. The reaction wheel system along with a star tracker for attitude determination will be provided by Blue Canyon Technologies (BCT). BCT is the only current provider of cubesat attitude control systems and was therefore the selected vendor. The thruster is developed by Busek and is a cutting edge low thrust ion propulsion system. The thruster's primary role is translational force for trajectory adjustment, station-keeping during the science orbit, and disposal after the primary mission is complete either by deorbit and lunar collision or transferring to a new trajectory for a new scientific target. The thruster is capable of a 10 degree gimbal which can allow for desaturation of two of the 3 reaction wheels. If we make use of a somewhat unusual thrusting method called spiral thrusting we can slowly desaturate the third wheel through gyroscopic forces while nominally maintaining the original thrust vector which will keep unwanted adjustments to the trajectory to a minimum. The Busek BIT-3 thruster is unfortunately a massive power draw on the satellite. Making use of the BIT-3 when the satellite is not attitude stabilized and collecting solar power is a risky method of attitude control especially given its low thrust output. This means that we cannot rely on using the BIT-3 thruster during early post deployment attitude control for fear of draining the satellite battery before alignment with the sun vector is achieved and recharging of the batteries begins. The early attitude operations will be placed entirely on the operational capabilities of the BCT XACT reaction wheels system.

Chapter III

Methodology

3.1 Software Package

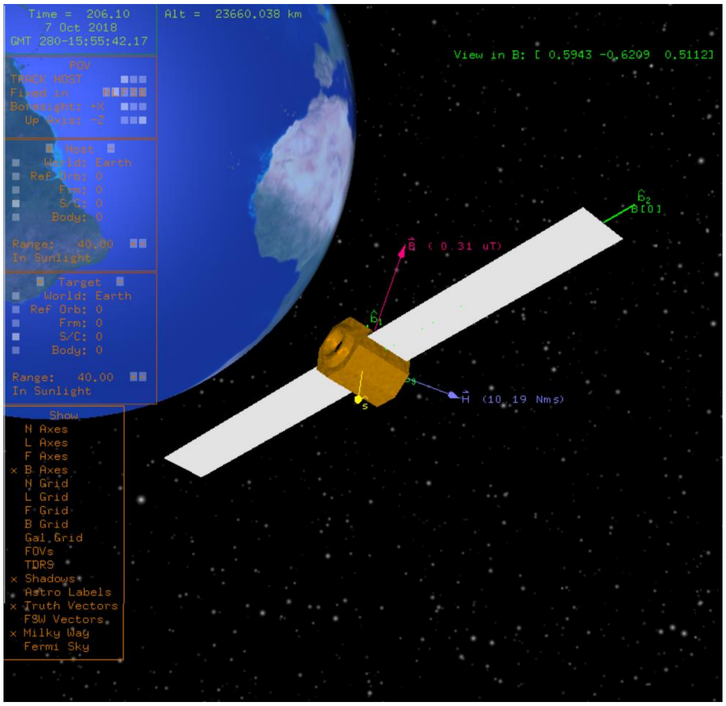
Attitude modeling is mathematically intensive due to the numerous variables that must be maintained and accounted for. Having the attitude be calculated through software simulation is the obvious choice. It was decided to use a recognized attitude software package rather than a fully custom solution for reliability of the simulation's fundamentals. What we were looking for in a software package was the capability to accurately simulate the detumbling operations of the reaction wheels, a low enough cost to fit within the constrained budget of Lunar IceCube, and preferably a well-designed graphical user interface (GUI) to assist with general operation of the software.

We first looked at using Systems Tool Kit (STK) by Analytical Graphics Incorporated due to our preexisting licensing agreements which provides continuous access to STK at the Space Science Center. The software is a high end industry standard simulation software that we are familiar with operating. Unfortunately the attitude control tools within STK that we have access to are not sufficient for this project. Additional plugin tools such as SOLIS were available for purchase from AGI recognized companies but were too expensive to fit in with the existing Lunar IceCube budget.

The software package we did decide to use was called 42. This package was recommended to us by NASA Goddard personnel as a potential good fit for our needs. 42 is an open source six degrees of freedom (6DOF) software package developed by Eric Stoneking of NASA Goddard. It is operated and controlled in C rather than a GUI which gives the package great flexibility, but at the cost of ease of use for general users. The version of 42 we would be able to use is not While a software package with a GUI was greatly preferred, 42 was capable of simulating the attitude needs of Lunar IceCube and being free it would have no impact on the budget.

42 is a highly customizable open source 6DOF software package that allows attitude and trajectory modeling. It is controlled with the C programming language through manual modification of the software files through a text editor such as notepad or as we recommend and ended up using notepad++. Most variables in the simulation are controlled by the files in the InOut folder in 42. The InOut folder is also where quantifiable results will be recorded for analysis after the simulation is completed. The command inputs do not stop here however. The heart of the simulation is found in the flight software under the source folder. The flight software file contains several prewritten commands to use as examples or starting points for advanced attitude simulation. There is also a dedicated section for rapid prototyping custom flight software which is what we used. The rapid prototyping section is selected by default though the other examples can be selected if desired. After all parameters are entered and flight software completed an executable must be created using a make command from a command line. For command line control on windows minGW was used as the default windows command line is not compatible with 42. When the executable is run 42 will open several windows and will begin to calculate in real time the attitude adjustment of the satellite body. One window is a 2D orbital tracking map of the satellite over Earth which is not particularly useful to us in this specific simulation. The second window is a 3D representation of the attitude of the satellite. This allows us to see the animated simulated performance of the attitude system in real time. This window also can be customized to display key vectors such as the net vector exerted by the reaction

wheels on the body and how this vector changes as it tries to stabilize and align along the sun vector.



```
 Time =  206.10      Alt =  23660.038 km
  7 Oct 2018
GMT 280-15:55:42.17
```

```
View in B: [ 0.5943 -0.6209  0.5112]
```

```
      POV
TRACK HOST
Fixed in        NLFSB
Boresight: +X
  Up Axis: -Z
```

```
     Host
   World: Earth
 Ref Orb: 0
     Frm: 0
     S/C: 0
    Body: 0

Range:   40.00
In Sunlight
```

```
     Target
   World: Earth
 Ref Orb: 0
     Frm: 0
     S/C: 0
    Body: 0

Range:   40.00
In Sunlight
```

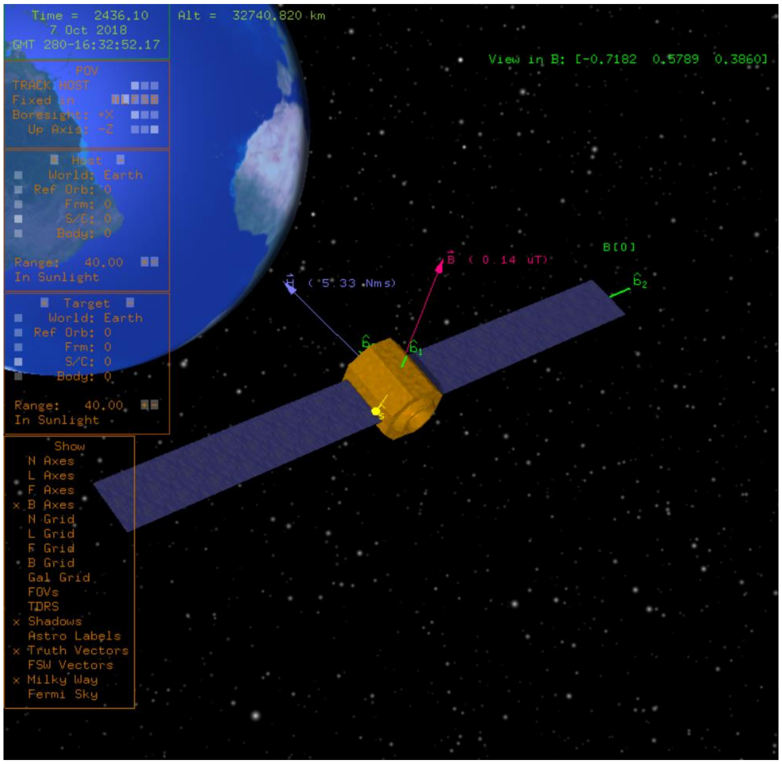
```
     Show
  N Axes
  L Axes
  F Axes
× B Axes
  N Grid
  L Grid
  F Grid
  B Grid
  Gal Grid
  FOVs
  TDRS
× Shadows
  Astro Labels
× Truth Vectors
  FSW Vectors
× Milky Way
  Fermi Sky
```

3.2 Flight Software

The flight software needed to fulfill three criteria. The satellite must begin in a tumbling state to simulate the attitude of the newly ejected Lunar IceCube from the ICPS. The satellite would then start to detumble in a manner similar to the use of reaction wheels. The satellite would target an assigned face towards the sun vector for power generation by the solar cells. If these attitude operations were completed successfully after ejection then the mission could proceed as planned and the Busek BIT-3 thrusting system could be used to desaturate the reaction wheels if necessary.

For the simulation we considered two different methods of how to approach the detumbling operations. One option would be to simulate the physics of the ejection and the angular momentum created by the reaction wheels to counteract the initial tumble. The issue with this method is keeping track of the multitude of variables that effect the freebody of the satellite. The ejection itself contains at least five vectors created by the deployment system and the movement and attitude profile of the rocket body itself. In addition to this we would have to simulate the effects of the space environment on the attitude of Lunar IceCube such as the effect of the solar radiative pressure which would have a different vector if the launch of Lunar IceCube was delayed. This method would also not be easily combined with other simulations to be created by our collaborators at NASA Goddard who were developing the attitude plan for the coasting, spiral down, and science orbit phases of the mission.

The method we decided to use was a stability theory method of attitude control. This method looks at the capability of the attitude system over the mass and inertia properties of the satellite body and represent these capabilities as PID gain values. This method would work well with our collaborators at NASA Goddard and would simultaneously keep the complexity of the flight software in 42 relatively simple compared to the physics simulation method. From this method we could also implement an estimated ten degrees per second initial tumbling rate provided to us by the launch provider as a worst case scenario. The flight software code that we used in 42 was developed by myself and Paul Mason of NASA Goddard who provided invaluable assistance. When the code was completed we were able to input basic estimated values for the gains and satellite mass properties and successfully run the simulation.



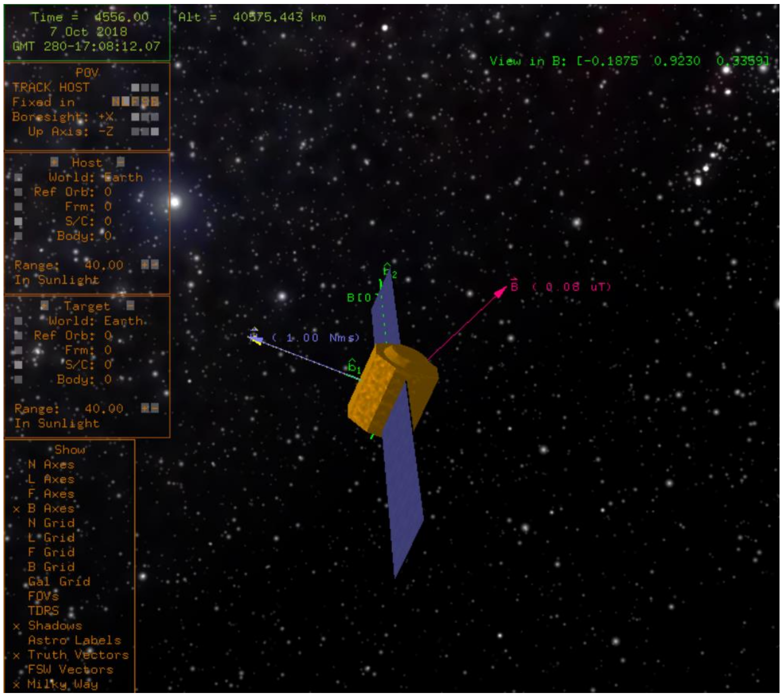
```
Time =  2436.10
 7 Oct 2018
GMT 280-16:32:52.17
```

```
Alt =  32740.820 km
```

```
View in B: [-0.7182  0.5789  0.3860]
```

```
POV
TRACK HOST
Fixed in
Boresight: +X
 Up Axis: -Z

Host
 World: Earth
 Ref Orb: 0
 Frm: 0
 S/C: 0
 Body: 0

Range:   40.00
In Sunlight

Target
 World: Earth
 Ref Orb: 0
 Frm: 0
 S/C: 0
 Body: 0

Range:   40.00
In Sunlight

Show
 N Axes
 L Axes
 F Axes
x B Axes
 N Grid
 L Grid
 F Grid
 B Grid
 Gal Grid
 FOVs
 TDRS
x Shadows
 Astro Labels
x Truth Vectors
 FSW Vectors
x Milky Way
 Fermi Sky
```

Lunar IceCube detumbling



```
Time =  4556.00
 7 Oct 2018
GMT 280-17:08:12.07
```

```
Alt =  40575.443 km
```

```
View in B: [-0.1875  0.9230  0.3359]
```

```
POV
TRACK HOST
Fixed in
Boresight: +X
 Up Axis: -Z

Host
 World: Earth
 Ref Orb: 0
 Frm: 0
 S/C: 0
 Body: 0

Range:   40.00
In Sunlight

Target
 World: Earth
 Ref Orb: 0
 Frm: 0
 S/C: 0
 Body: 0

Range:   40.00
In Sunlight

Show
 N Axes
 L Axes
 F Axes
x B Axes
 N Grid
 L Grid
 F Grid
 B Grid
 Gal Grid
 FOVs
 TDRS
x Shadows
 Astro Labels
x Truth Vectors
 FSW Vectors
x Milky Way
```

Lunar IceCube stabilized and aligned with the sun vector

3.3 PID Gains

With the simulation software properly running and the flight software written and successfully performing garbage in garbage out tests the next step was obtaining the PID Gains of the XACT system. We contacted BCT and requested the PID gains. We were told to respond with the inertia matrix of Lunar IceCube. The inertia matrix was calculated using the then current model of Lunar IceCube and developed by myself and Kevin Brown of Morehead State University.

Chapter IV

Products

4.1 Delivered Products

Without the PID gain values or estimates provided by BCT an accurate simulation of the post deployment operations of Lunar IceCube cannot be completed. Despite this roadblock several products of use can still be delivered. The 42 software has been correctly setup at several nodes inside the Space Science Center. This includes installations across Linux and Windows operating systems which have several difficulties in correctly installing. The custom flight software code used in 42 is working as intended and can easily be used in the future for post deployment analysis. Should the PID gains ever be disclosed by Blue Canyon Technologies or at least obtain viable estimates we can apply the simulation's flight software code as a comparison to the BCT simulation. Contacts at NASA Goddard have been made, specifically in the attitude control department. These contacts will be invaluable for future missions where we need more advanced attitude control solutions.

4.2 Flight Software Code

```
void PrototypeFSW(struct SCType *S)
{
    struct FSWType *FSW;
    double alpha[3],Iapp[3];
    long Ig,i,j;

    FSW = &S->FSW;
```

```
  if (FSW->Init) {
   FSW->Init = 0;
   FSW->DT = DTSIM;
   for(Ig=0;Ig<FSW->Ngim;Ig++) {
    FindAppendageInertia(Ig,S,Iapp);
    for(j=0;j<3;j++) {
                if (SimTime <1200) {
                    FindPDGains(Iapp[j],0.05,1.0,
      &FSW->Gim[Ig].RateGain[j],
      &FSW->Gim[Ig].AngGain[j]);
                 FSW->Gim[Ig].MaxRate[j] = 0.5*D2R;
                 FSW->Gim[Ig].MaxTrq[j] = 0.001;
                }
                else{
                FindPDGains(Iapp[j],0.05,1.0,
      &FSW->Gim[Ig].RateGain[j],
      &FSW->Gim[Ig].AngGain[j]);
     FSW->Gim[Ig].MaxRate[j] = 0.5*D2R;
            FSW->Gim[Ig].MaxTrq[j] = 0.001;}
    }
   }
  }

/* .. Find qrn, wrn and joint angle commands */
  ThreeAxisAttitudeCommand(S);


/* .. Form attitude error signals */
```

```
    QxQT(FSW->qbn,FSW->Cmd.qrn,FSW->qbr);
    Q2AngleVec(FSW->qbr,FSW->therr);
    for(i=0;i<3;i++) FSW->werr[i] = FSW->wbn[i] - FSW->Cmd.wrn[i];

/* .. Closed-loop attitude control */

                        if (SimTime <1200) {
                                VectorRampCoastGlide(FSW->therr,FSW->werr,10.0,1.0E-1,0.5*D2R,alpha);
                        }
                        else{
                            VectorRampCoastGlide(FSW->therr,FSW->werr,20.0,1.0E-2,0.5*D2R,alpha);
                        }

    for(i=0;i<3;i++) {
                FSW->IdealTrq[i] = FSW->MOI[i]*alpha[i];
                if(FSW->IdealTrq[i]>=0.01){
                  FSW->IdealTrq[i]=0.01;}
                else if (FSW->IdealTrq[i]<-0.01){
                FSW->IdealTrq[i]=-0.01;}
                else {
                        /* do nothering */
                }
        }



}
```

Chapter V

Conclusions, Actions, and Implications

5.1 Conclusions

The project as of now has not achieved the final goal of the project. However the Space Science center now has several more tools that we can apply in the future for attitude control simulation. With our new contacts at NASA Goddard, the obtaining of the 6DOF 42, and the creation of the detumble to solar alignment code the Space Science Center is now in a measurably better position now than when the project began.

5.2 Actions

To solve the issues regarding the capabilities of the BCT XACT system in early operations it has been suggested that we should purchase a simulation from BCT itself for $65,000. We were originally offered this simulation when we purchased the XACT system from BCT. It is possible that by reverse engineering this simulation we can obtain the PID gain values indirectly and apply them to the original simulation in 42 to run as a check on the simulation purchased from BCT.

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Eterno, J. (1999). Attitude Determination and Control, In: J. Wertz, and W. Larson, ed., Space Mission Analysis and Design, 3rd ed. Hawthorne: Microcosm Press, New York: Springer, pp. 354-380.