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CUBESAT ATTITUDE DETERMINATION

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Abstract

When satellites are placed in orbit, often times a specific orientation is required to achieve mission purposes. Different factors (such as atmospheric drag, magnetic fields, solar winds) or tumbling upon deployment from the launch vehicle, may result in an undesirable satellite orientation. To address these challenges, the ability to control the orientation, termed as attitude determination, becomes critical to any mission. This thesis will focus on developing an earth-pointing and sun-pointing mode in order to meet the objectives of the ESSENCE CubeSat. The earth-pointing mode orients the vehicle to point towards a desired target on the earth surface, and the sun-pointing mode orients the vehicle such that the maximum solar array surface area is exposed to the sun when the vehicle is out of eclipse.

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Nomenclature

Acronyms

BOF	Body frame
CoM	Center of Mass
ECEF	Earth centered Earth fixed frame
ECI	Earth Centered Inertial Frame
ESSENCE	Educational Space Science and Engineering CubeSat Experiment
GDC	Guidance
LEO	Low Earth Orbit
ORB	Orbital frame
SC	Spacecraft
TER	Terrestrial Frame
WGS	World Geodetic System
wrt	with respect to

Greek Symbols

λ	Latitude
ϕ	Longitude

Roman Symbols

$\underline{C}_o^I$	Rotation matrix (ORB to ECI)
$\underline{r}_S^E$	Spacecraft position vector in ECEF frame
$\underline{r}_T^E$	Target position vector in ECEF frame
$\underline{r}_{ST}^I$	Position vector (target to SC) in ECI frame
$\underline{r}_s^I$	SC position vector in ECI frame
$\underline{r}_{ST}^o$	Position vector (target to SC) in ORB frame
$\vec{F}_E^T$	Frame rotation (ECEF to target)
$\vec{F}_E^T$	Frame rotation (earth to target)
$\vec{F}_I^T$	Frame rotation (ECI to target)
$\vec{h}_s$	SC angular momentum
$\vec{r}_S$	Spacecraft position vector
$\vec{r}_T$	Target position vector
$\vec{V}_s$	SC velocity vector
h	Altitude

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Chapter 1

Introduction

The focus of this thesis is to develop an attitude pointing mode for a CubeSat. The compact size of a CubeSat drives the mission to be more cost efficient than building, operating and launching larger satellites. However, the drawbacks of the compactness are mass and volume restrictions. The lack of redundancy of components such as sensors, batteries or solar arrays is limited, and thereby fewer alternatives exist if degraded over time.

The ESSENCE (Educational Space Science and Engineering CubeSat Experiment) will test different attitude modes to determine if vehicle recoverability is achievable with underactuated controls [11]. This CubeSat is in a 3U (3-unit) vertical configuration, with each cube having a dimension of (10x10x10)cm. ESSENCE will be launched into low earth orbit (LEO) to conduct the on-orbit attitude experiments.

This report focuses on an earth-pointing and a sun-pointing mode. The earth-pointing mode utilizes the camera, located on the bottom face, to track a desired earth target. As ESSENCE will have a polar orbit, it will track the environmental changes occurring in the polar region. The sun-pointing mode shall orient the long axis of ESSENCE to face the sun at an optimal angle to produce the maximum solar array charge.

Chapter 2

Attitude Dynamics

The attitude of a spacecraft (SC) is the measure of its orientation in 3D space. Attitude is controlled through rotation of the SC about its center of mass (CoM) in one or all of its axes. Sensors provide SC position measurements in a given reference frame. Torque commands are applied to reaction wheels to orient the SC to the desired position.

2.1 Theory of Kinematics

2.1.1 Definitions

Vector A three-dimensional representation of a point, expressed with a magnitude and direction ($\vec{r}$)

Reference Frame Standardized coordinate system used to determine motion of bodies with respect to one another (F)

Euler Angles A three-dimensional angle rotation about each axis

Quaternions A three-dimensional rotation expressed as a four element vector

2.1.2 Coordinate Frames

Relative motion between different bodies is obtained with respect to the same reference frame; otherwise a frame transformation is required. The frames relevant to this report are defined in Table 2.1.1 [11].

Table 2.1.1: Frame Definitions

Frame	**Parameters**
BOF	Origin: SC CoM
	X-axis points towards zenith direction
	Z-axis points in the direction of SC angular momentum
	Y-axis completes right-hand frame
ECI	Origin: Earth CoM
	X-axis points to vernal equinox (J2000)
	Y-axis completes right-hand frame
	Z-axis points to polar axis
TER(ECEF)	Origin: Earth CoM
	Noni-inertial: fixed to the earth as it rotates
	X-axis points to 0° latitude and 0° longitude
	Y-axis completes right-hand frame
	Z-axis points to geographic north pole
WGS	Same origin and axes orientation as ECEF
	Coordinates are measured in terms of latitude and longitude

2.2 Earth-Pointing Mode

> *Note*: *Equations for this mode were obtained from [10] [8] [7] [1]. With the guidance of my advisor, the theoretical procedure was summarized to produce Section 2.2.*

The frame transformations required to move from the earth target frame to the SC frame are described as:

$$\boxed{\text{TER} \rightarrow \text{WGS} \rightarrow \text{ECI} \rightarrow \text{BOF}}$$

A preselected target location on the earth's surface is transformed to the SC position vector using the geometry in Figure 2.2.1.

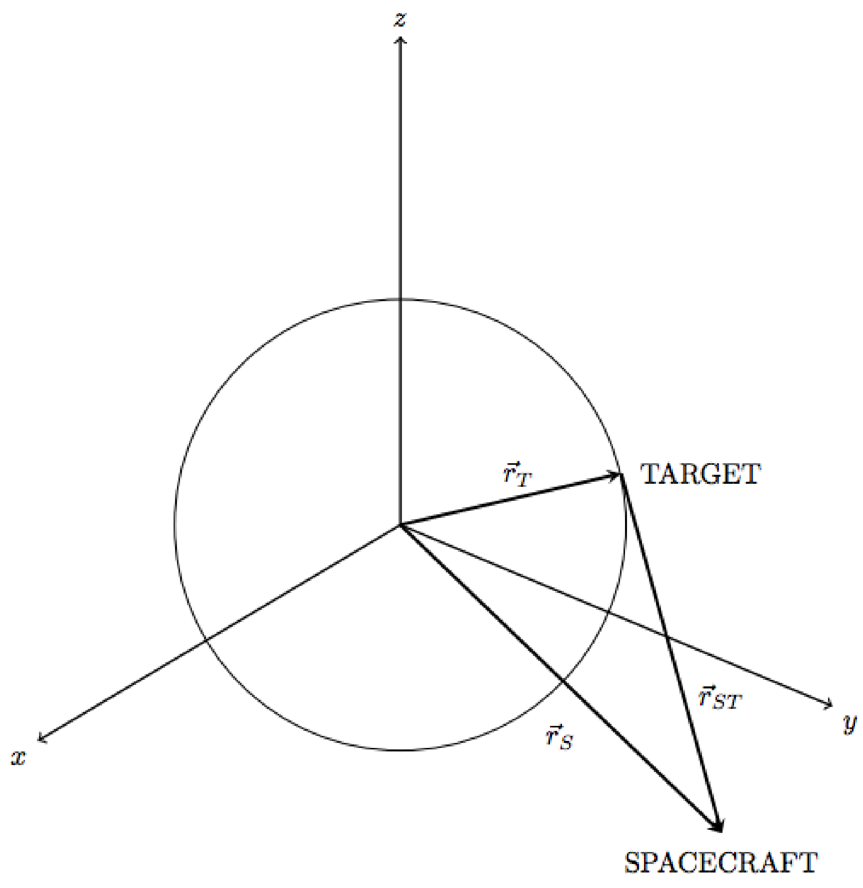

Figure 2.2.1: Position Vector Geometry

Target position vector ($\vec{r}_T$) is subtracted from spacecraft position vector ($\vec{r}_S$), resulting in the position vector target to SC ($\vec{r}_{ST}$).

$$\vec{r}_{ST} = \vec{r}_S - \vec{r}_T \tag{2.1}$$

Spacecraft position vector is the product of a frame rotation from earth to target ($\vec{F}_E^T$) with spacecraft position vector in ECEF frame ($\underline{r}_S^E$), obtained from GPS measurements.

$$\vec{r}_S = \vec{F}_E^T \cdot \underline{r}_S^E \tag{2.2}$$

Target position vector in ECEF frame is calculated using measured longitude(ϕ), latitude(λ) and altitude values (h).

$$\underline{r}_T^E = \begin{bmatrix} \left(\frac{R_E}{(1-e^2 \cdot sin^2\phi)^{1/2}} + h\right) \cdot cos\phi \cdot cos\lambda \\ \left(\frac{R_E}{(1-e^2 \cdot sin^2\phi)^{1/2}} + h\right) \cdot cos\phi \cdot sin\lambda \\ \left(\frac{R_E}{(1-e^2 \cdot sin^2\phi)^{1/2}} + h\right) \cdot sin\phi \end{bmatrix} \tag{2.3}$$

Target position vector ($\vec{r}_T$) is obtained when the frame rotation of ECEF to target ($\vec{F}_E^T$) is dotted with position vector of target to ECEF frame ($\underline{r}_T^E$).

$$\vec{r}_T = \vec{F}_E^T \cdot \underline{r}_T^E \tag{2.4}$$

Position vector (target to SC) in ECI frame ($\underline{r}_{ST}^I$) is obtained by:

$$\underline{r}_{ST}^I = \underline{r}_S^I - \underline{C}_{IE} \cdot \underline{r}_T^E \tag{2.5}$$

Position vector (target to SC) in ORB frame ($\underline{r}_{ST}^o$) is obtained by:

$$\underline{r}_{ST}^o = \underline{C}_{IE}^T \cdot \underline{r}_{ST}^I \tag{2.6}$$

SC angular momentum ($\vec{h}_s$) is obtained when crossing SC position vector ($\vec{r}_s$) with SC orbit velocity($\vec{v}_s$).

$$\vec{h}_s = \vec{r}_s \times \underline{v}_s \tag{2.7}$$

SC position vector ($\vec{r}_s$) is the product of frame rotation from ECI to target ($\vec{F}_I^T$) dotted with SC position vector in ECI frame ($\underline{r}_s^I$).

$$\vec{r}_s = \vec{F}_I^T \cdot \underline{r}_s^I \tag{2.8}$$

SC velocity vector ($\vec{V}_s$) is obtained when frame rotation from ECI to target ($\vec{F}_I^T$) is dotted with SC velocity vector in ECI frame ($\underline{V}_s^I$).

$$\vec{V}_s = \underline{F}_I^T \cdot \underline{V}_s^I \tag{2.9}$$

The SC axis is unconventional such that the negative x-axis points towards nadir. The rotation about each axis is computed in ORB:

$$\vec{x}_o = \underline{F}_I^T \cdot \underline{x}_o^I \qquad \vec{y}_o = \underline{F}_I^T \cdot \underline{y}_o^I \qquad \vec{z}_o = \underline{F}_I^T \cdot \underline{y}_o^I \tag{2.10}$$

Each axis in ORB frame to ECI frame:

$$\underline{x}_o^I = \frac{\underline{r}_s^I}{\|\underline{r}_s^I\|} \qquad \underline{z}_o^I = \frac{\underline{r}_s^I \times \underline{v}_s^I}{\|\underline{r}_s^I \times \underline{v}_s^I\|} \qquad \underline{y}_o^I = \underline{z}_o^I \times \underline{x}_o^I \tag{2.11}$$

Rotation matrix from ORB frame to ECI frame ($\underline{C}_o^I$):

$$\underline{C}_o^I = \begin{bmatrix} \underline{x}_o^I & \underline{y}_o^I & \underline{z}_o^I \end{bmatrix} \tag{2.12}$$

ORB frame to BOF frame rotation ($\vec{C}_{BO}$):

$$\vec{C}_{BO} = \vec{C}_x(\phi) \cdot \vec{C}_y(\theta) \cdot \vec{C}_z(\varphi) \tag{2.13}$$

To prevent infinite rotations, the rotations about the y-axis and z-axis are set to zero, thereby the SC can only rotate about its x-axis and maintain target pointing (negative x-axis to nadir).

$$\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} = \vec{C}_x(\phi) \cdot \vec{C}_y(\theta) \cdot \left(\frac{\underline{r}_{ST}^o}{\|\underline{r}_{ST}^o\|} \right) \tag{2.14}$$

2.3 Software

ESSENCE is built on MATLAB and modelled on Simulink. The theory examined in Section 2.2 is implemented into the background of functions. Attitude adjustments occur to minimize the error between measured and desired values. System block logic is defined in Figure 2.3.1 below.

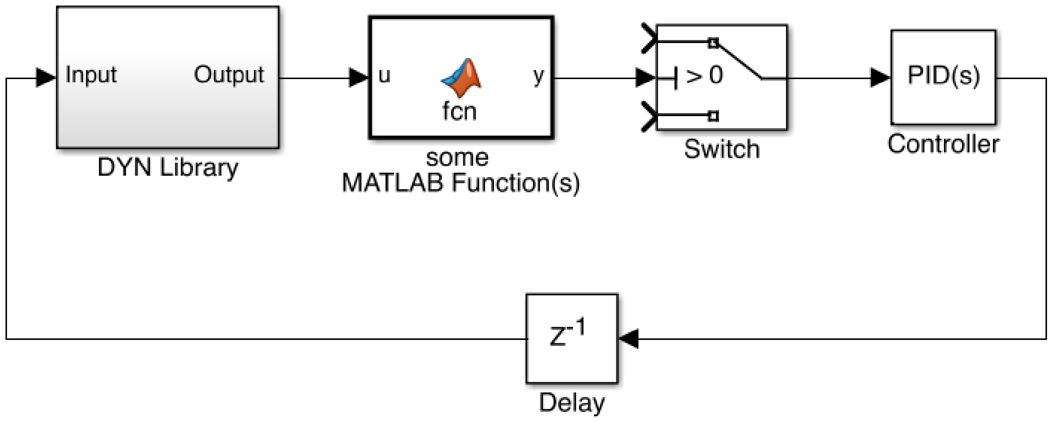

Figure 2.3.1: General Closed Loop Control

2.3.1 Errors

The equations outlined in Section 2.2 assume exact values for the three-dimensional quantities. Generally, measurements obtained by instruments cannot provide 100% accuracy, thereby the system must be in a state of continuous corrections. Each iteration provides updated measurements (such as SC position, orientation, velocity, etc.) which are compared with the desired quantities. The difference between the measured (estimated) values and desired (reference) values is the error of the system.

Chapter 3

Attitude Determination

3.1 Design Parameters

Using software to predict the ability of a satellite's attitude control serves as a major advantage for identifying problems prior to launching into orbit. To simulate the target pointing of ESSENCE, the following block model in Figure 3.2.4 was created by Mike Alger (MA) and Wil Travis (WT). Table 3.1.1, succeeding the figure, outlines the functions of each submodule.

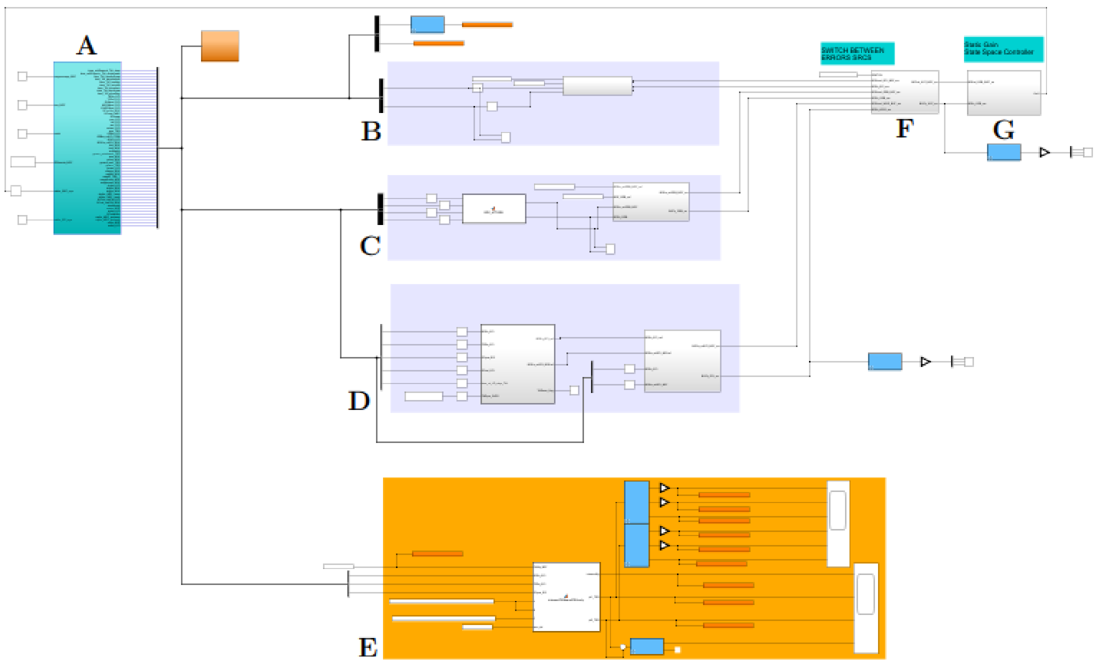

Figure 3.1.1: Simulink Block Model for WGS Positioning

Table 3.1.1: WGS Block Submodules

Block	**Function**
A	Block contains dynamics library with parameters such as time and motion of bodies (SC, earth, sun, moon) in different reference frames.
B	Block computes the difference between measured and desired (reference) values as quaternions or as the angular velocity in one frame wrt to another. The quaternion output and angular velocity output are the errors in the respective shared frames.
C	Left block computes frame transformation and the difference in angular velocity rates between two different frames expressed in the same frame. Error computation block (right) uses the same logic as block B, except errors are computed in different frames.

D	Left block has a nested model called Guidance Function (GDC) which transforms the target and SC positions wrt to different frames (ECI and BOF), computes the attitude error and checks for visibility between the target and SC. Within the GDC Function is a nested Orbital Propagator model which generates target and SC position, velocity and relative motion between the two, expressed in the same frame. Error computation block (right) uses the same logic as block B, except errors are computed in different frames.
Note:	*Simulink nested models are found on the following page.*
E	Block generates intersection points between SC camera to earth surface in latitude and longitude coordinates.
F	Switch block computes relative angular velocity and quaternion errors in one of the three frame sources.
G	Controller block multiplies quaternion and relative angular velocity (in the same frame) by a gain constant. Output returns result to the delay gain connected to an input in the DYN Library block.

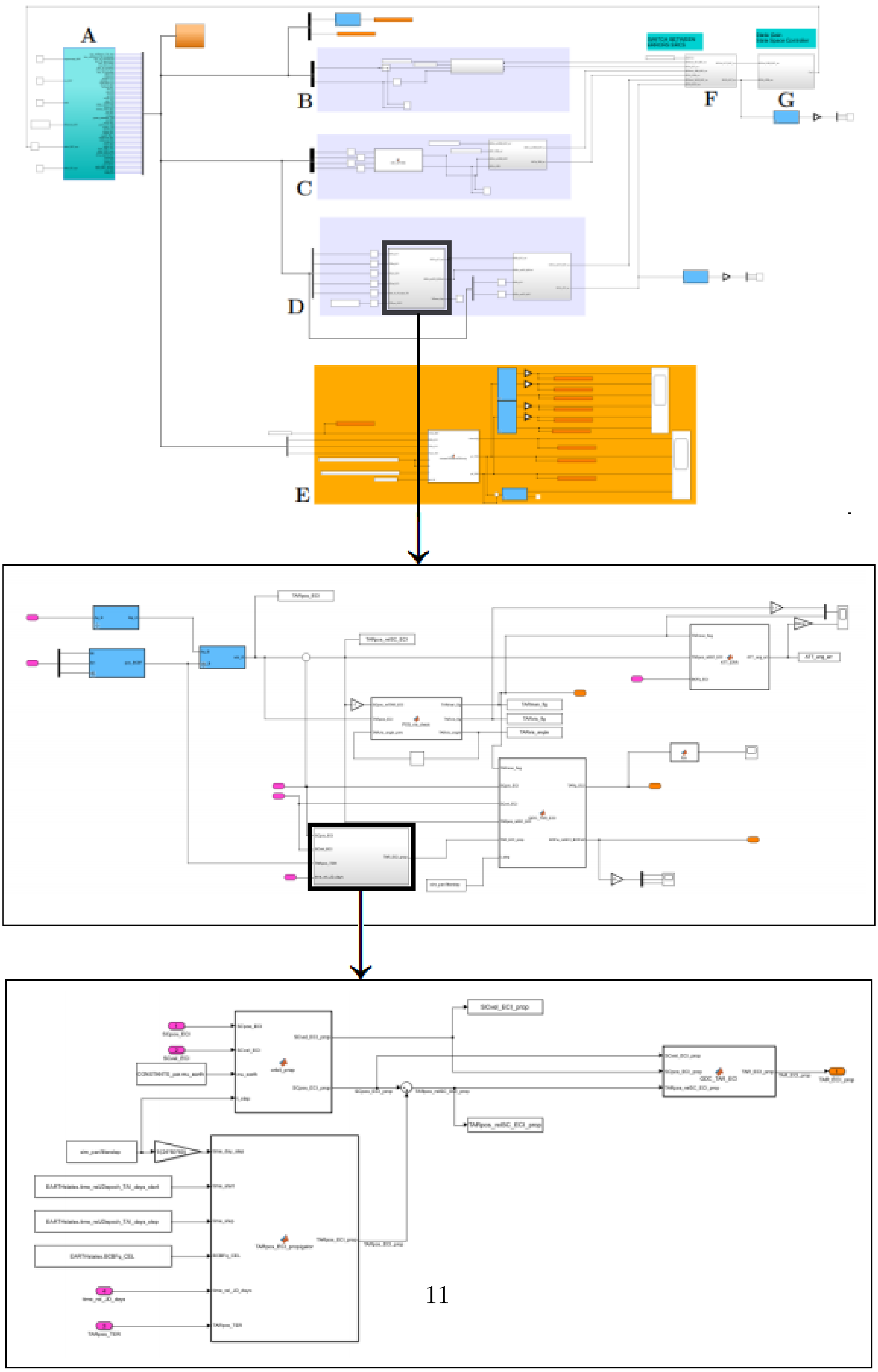

Figure 3.1.2: Nested Blocks (by WT & MA)

3.2 Analysis

3.2.1 Flags

The GDC function for WGS (Block D) contains a block (Figure 3.2.1) to identify when the target is visible to the SC. The dot product between SC position vector relative to target and position vector of target is computed.

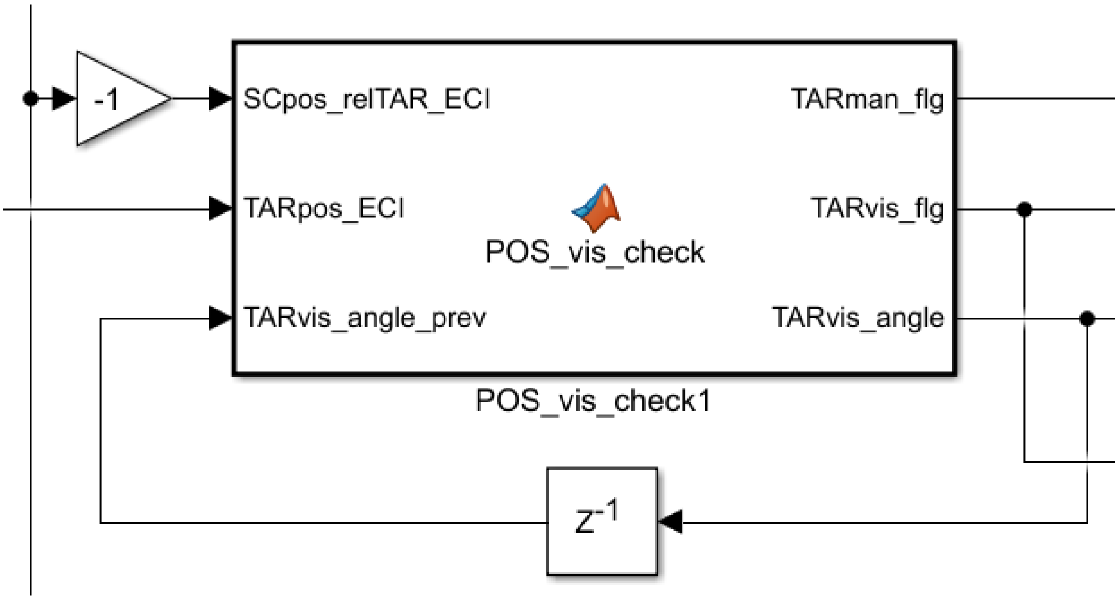

Figure 3.2.1: Target Visibility GDC

A target maneuver flag is generated if both conditions are met:
i) The target visibility angle is $0 < \theta \leq 112.5°$ (camera angle of view)
ii) The difference between the new and old visibility angle is less than zero

A visibility flag is generated if both conditions are met:
i) Target maneuver flag exists (equals to 1)
ii) Dot product between the position vectors of the target and SC relative to the target is greater than 0 (meaning there is a line of sight)

In Figure 3.2.2, instead of one expected flag per orbit, two flag instances occur (per orbit). This may be attributed to the false flag generated when the SC is on the exact opposite side of the sphere.

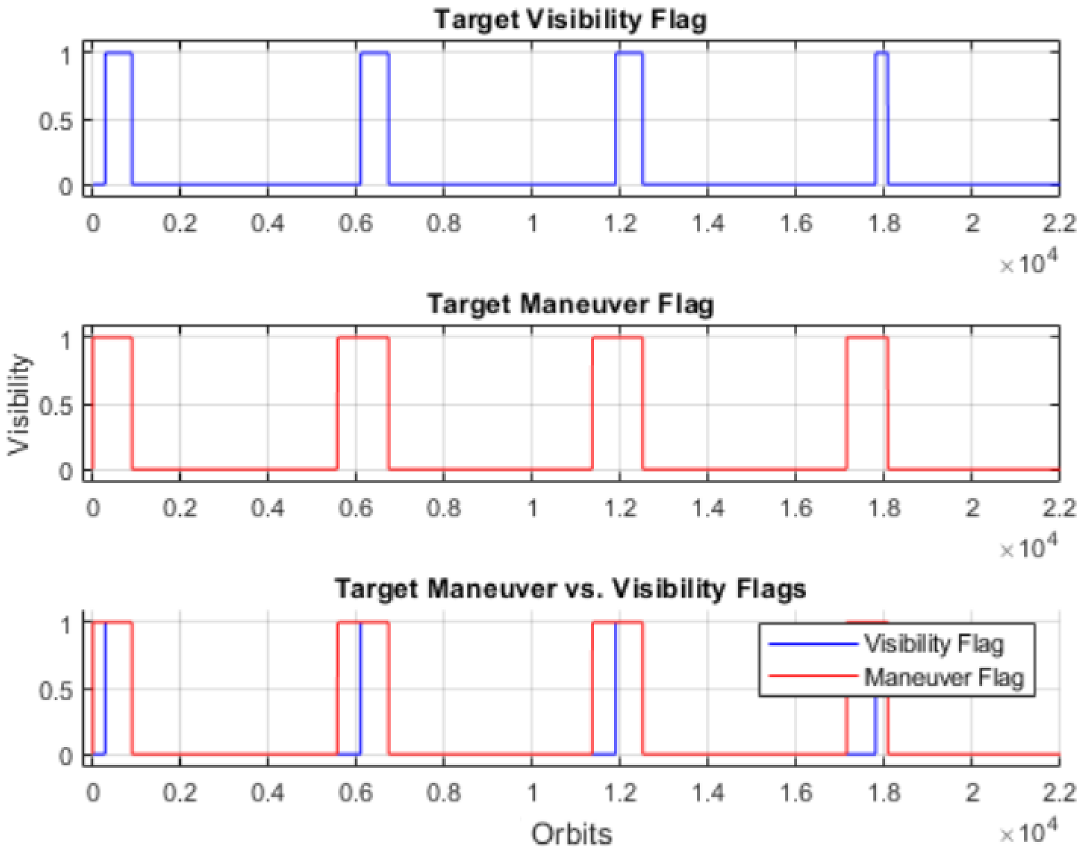

Figure 3.2.2: Visibility and Maneuver Flags

Similarly, the same idea is observed when considering the intersection points P1 and P2 in Figure 3.2.3 (from Block E). The target vector from the camera to the earth surface passes through the sphere, where two locations are intersected at the same point of time.

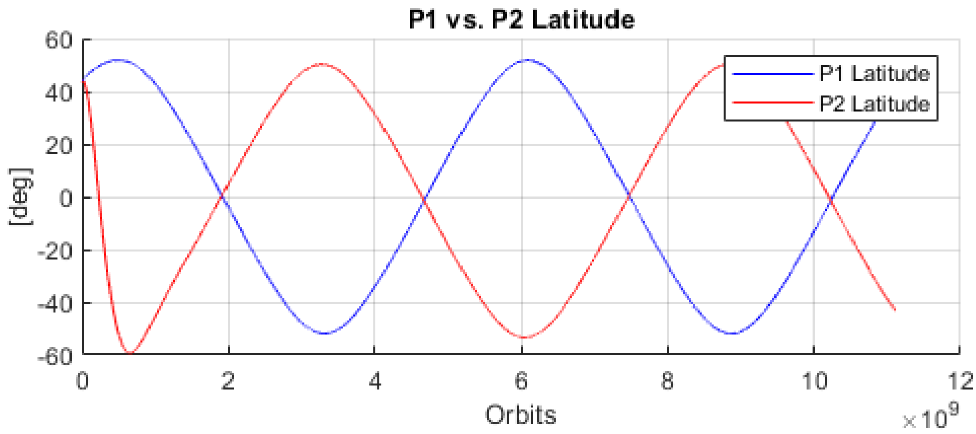

Figure 3.2.3: Latitude of Points 1 & 2 in ECI Frame

3.2.2 Bore Angle

An additional script (by WT), generated a Bore Angle Error animation to visualize the intersection vector from SC to target (Figure 3.2.4).

It was observed that each time the script ran, a slightly different bore angle error was calculated. Five trial runs were recorded in Table 3.2.1.

Table 3.2.1: Bore Angle Errors

Trial	Angle [deg]
1	131.39°
2	122.31°
3	114.77°
4	115.30°
5	126.80°

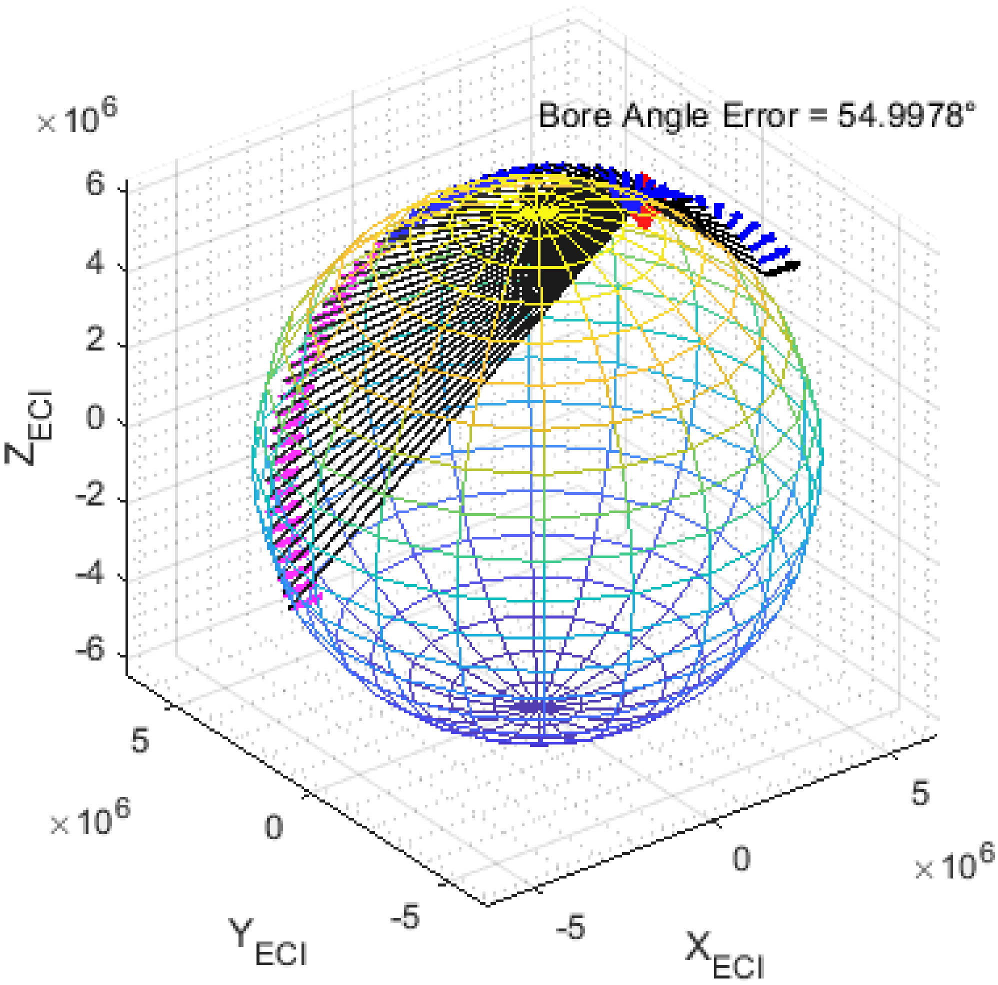

Figure 3.2.4: Bore Angle

These errors may be attributed to the following factors:
i) SC does not have the same starting reference position at the start of each run.
ii) A consequence of the Parallax Error: when the satellite is looking at a target, it is at an angle which is not perpendicular to the surface, thereby causing some distortion to occur.

3.2.3 Test Comparison

To better understand when the correct attitude control is achieved, a completed test "Test Pointing" (left) was compared to the work in progress test "WGS Test Pointing" (right).

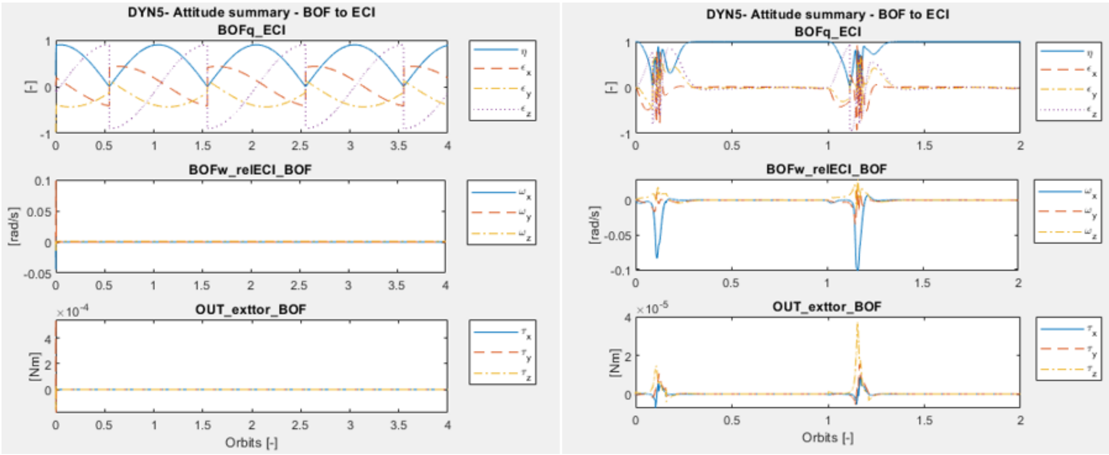

Figure 3.2.5: Complete vs. Incomplete BOF to ECI

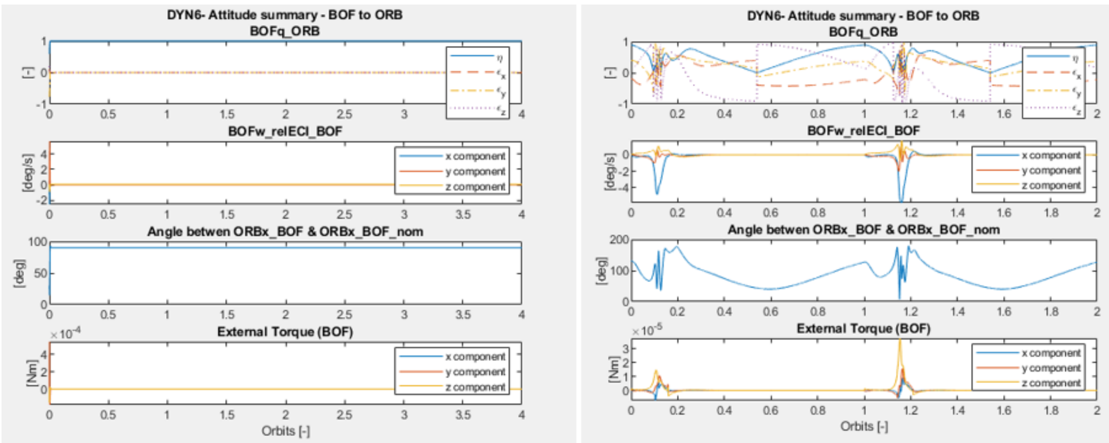

Figure 3.2.6: Complete vs. Incomplete BOF to ORB

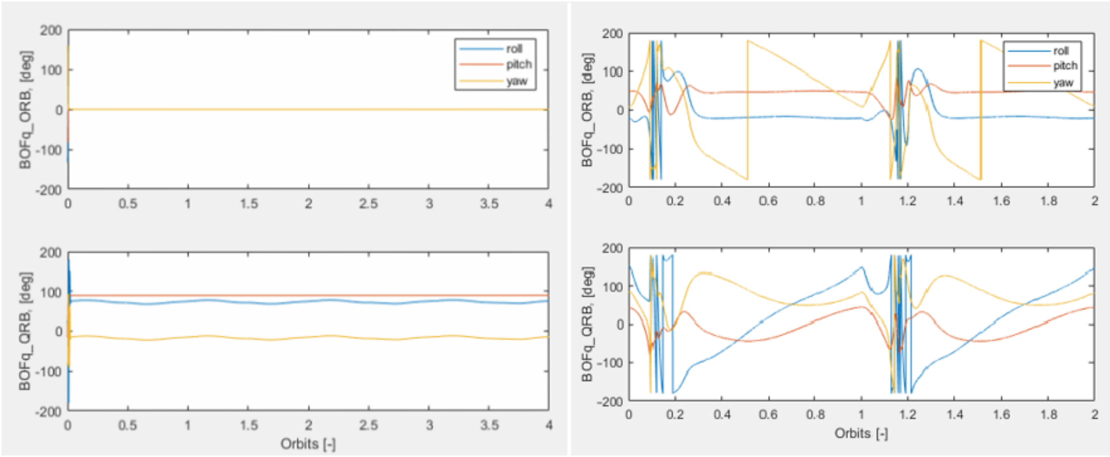

Figure 3.2.7: Complete vs. Incomplete RPY to ORB

The data from the incomplete test is clearly undesirable and would not be able to meet mission objectives until axis rotations are stabilized. The process of determining the way to control axis rotations in WGS Test Pointing was in-progress.

3.3 Future Work

The work that remains is the completion of the earth-pointing and sun-pointing modes. The theoretical understanding behind the required steps is clear (frame transformations), yet it's the application of the software which remains unclear.

3.3.1 Earth-Pointing

For earth-pointing mode, the visibility flags between the SC and target location provides an indication when attitude control should direct the SC to point at the target. When the SC exits the horizon, the camera face should continue pointing towards the earth surface to minimize orientation recovery when the target returns to view. A constant pointing location (when target is invisible) is the nadir, as it is independent of the SC orbital position.

3.3.2 Sun-Pointing

The sun-pointing mode will use a similar concept, where frames are transformed to be wrt one another. An eclipse flag would indicate when to begin the attitude control of maintaining a 45° angle to the sun along the long axis. To preserve power, the attitude control must be turned off when the eclipse flag is activated.

Chapter 4

Conclusion

The overall goal of this project was to develop an earth-pointing and a sun-pointing mode for the ESSENCE CubeSat. The earth-pointing mode allows for target tracking, specifically to monitor environmental changes in the northern regions. The sun-pointing mode allows for the SC to maximize its solar array recharging.

Most of the semester was spent learning the theory behind attitude determination. Albeit fascinating, this did not provide as much help as anticipated when working with the software. Gaining the knowledge in this topic was challenging, yet extremely rewarding to see the real life application of these concepts.

The idea of seeking help in a self-driven project such as a thesis did not make sense. However, when help was requested, it was extremely valuable as it streamlined broad topics and helped bring an understanding to the methods behind the theory. The time constraint was not realized during the course of self-study; perhaps asking for help throughout the entire process would have been acceptable.

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