An Analysis of SkySat-1 Attitude Determination and Control

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AA 279C - Spacecraft Attitude Determination and Control
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Revision History

Table 1: Report Changelog

Rev	Changes
PS1	- Created document - Added problem set 1 material

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1 Background

SkySat-1 and SkySat-2 are microsatellites built and operated by Skybox Imaging that acquire high resolution panchromatic and multispectral images of Earth. The spacecraft are three-axis stabilized by using an on-board closed-loop control system without any propulsion. Each satellite has a mass of 83 kg and features body-mounted solar panels. The microsatellites also feature an aperture cover that protects the imaging payload during launch and initial orbital operations. The cover also hosts the high-data rate antenna of the satellite.[30]

By April 2012, Skybox Imaging (Mountain View, CA) had raised a total of $91 million of private capital from Khosla Ventures, Bessemer Venture Partners, Canaan Partners and Norwest Venture Partners to develop the SkySat constellation.[5]

On November 21, 2013, the first satellite, SkySat-1, was launched on a Dnepr rocket from Yasny, Russia.[13]

On June 10, 2014, Skybox Imaging announced that it had entered into an agreement to be acquired by Google for $500 million.[23][24] Skybox Imaging changed its name to "Terra Bella" on March 8, 2016, to indicate its focus on image analytics.[25] The new name was partially based on the Terra Bella Ave. in Mountain View, California, where the company's headquarters are located.[26]

In 2017, Google sold Terra Bella and its SkySat satellite constellation to Planet Labs for an undisclosed price and entered into a multi-year agreement to purchase SkySat imaging data.[28]

2 Mission Description and Requirements

2.1 Mission Objectives

The resolution of the SkySat satellite imagery and videos is high enough to observe objects that impact the global economy such as terrain, cars and shipping containers. The satellites can capture video clips lasting up to 90 seconds at 30 frames per second.[5] The high-definition satellite video from SkySat satellites is aimed to help understand the world better by analyzing movement of goods and people, providing visual data about supply chains, shipping, industrial plant activity, and even humanitarian relief efforts. [4]

The constellation's goal is to be able to provide high-resolution satellite imagery of any place on Earth multiple times a day. [5] When Skybox originally developed the satellites, they planned to change the nature of the satellite industry by building satellites with off-the-shelf electronics that cost under $50 million. [5]

2.2 Spacecraft Orbit

Orbit Parameters[30]	
Reference system	Geocentric
Regime	Low Earth, Sun-Synchronous
Launch Date	21 November 2013, 07:11:29 UTC
Perigee	563.8 km
Apogee	592.6 km
Semi-major Axis	6949 km
Inclination	97.7°
Period	96.1 minutes

Table 2: SkySat-1 Orbit Parameters

2.3 Sensors and Actuators

Attitude determination primarily relies on Star Trackers and Inertial Measurement Units with an internal closed-loop control system in charge of running the Attitude Determination and Control scheme. Reaction wheels and magnetic torque rods are the primary actuators of the spacecraft.

SkySat-1 is equipped with two ST-16RT2 star trackers (Sinclair Interplanetary), three TQ-15 magnetic torque rods (built under license by SpaceFlight Industries), and four RW3-1.0 reaction wheels (built under license by Millennium Space Systems).

Star Tracker Parameters[31]	
Accuracy	<7 arcsec RMS cross-boresight, <70 arcsec RMS around boresight
Availability	>99.9%
Size, Mass	59mm x 56mm x 31.5mm, 90g
FOV (Field of View)	7:5° (half axis)
Exposure Time	100 ms
Catalog	3746 stars

Table 3: ST-16 Star Tracker Parameters

Torque Rod Parameters [32]	
Nominal Dipole	15 Am^2 @ 28V
Max Dipole	19 Am^2 @ 34V
Length	228mm
Mass	400g
Resistance	250 Ω nominal each coil

Table 4: TQ-15 Magnetic Torque Rod Parameters

Reaction Wheel Parameters [33]	
Momentum	1.0 Nm-sec @ 6000 rpm
Torque	100 mNm
Power	24V to 34 V

Table 5: RW3-1.0 Reaction Wheel Parameters

2.4 ADCS Requirements

Pointing Accuracy: $\pm 0.1°$ [30]
Slew Rate: 10 deg/s (Estimated from Reaction Wheel Parameters [33])

3 Spacecraft Model

3.1 Model Parameters

The following vehicle parameters were used to create the subsequent vehicle model proposed in this section.

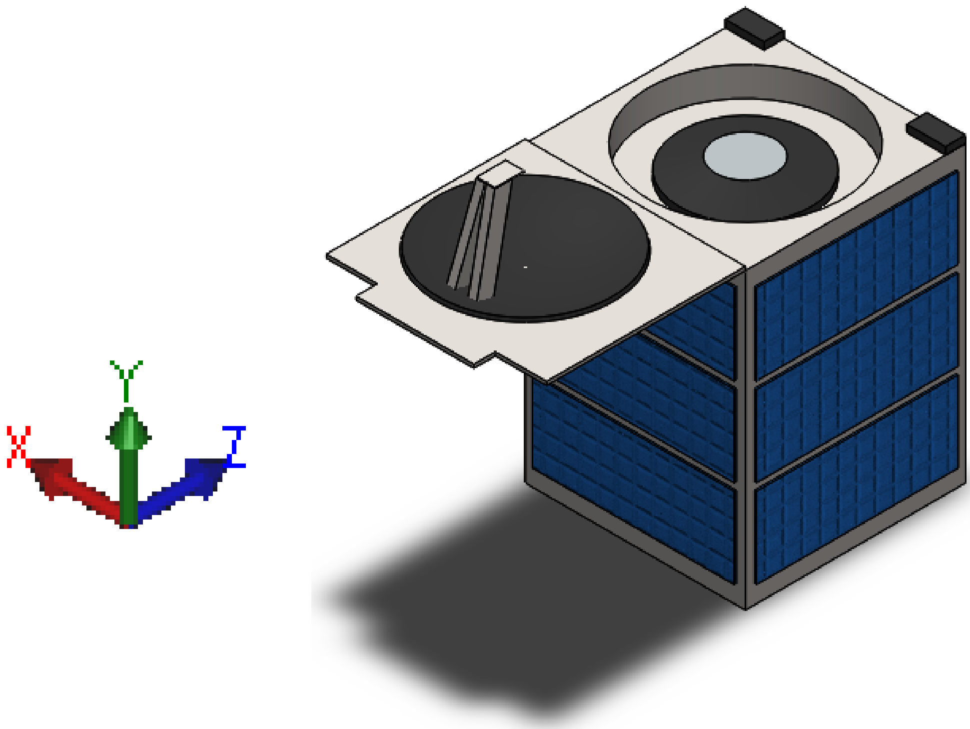
Spacecraft Parameters [30]	
Mass	83 kg
Bus Size	60cm x 60cm x 80cm
Power	120 W OAP (Orbit Average Power)
Attitude Control Accuracy	$\pm 0.1°$
RF Communications	X-band downlink of payload data: 470 Mbit/s S-band uplink: 16 kbit/s Onboard data storage capacity: 768 GB
Design Life	4 years

Table 6: SkySat-1 Spacecraft Parameters

In order to make a CAD model of this vehicle, emphasis is placed on guaranteeing the model matches SkySat-1's mass and bus size dimensions. The other parameters will be used primarily in ACDS calculations.

3.2 Vehicle CAD Model

The following model was created in SolidWorks 2017 with an arbitrary body axis as shown below:

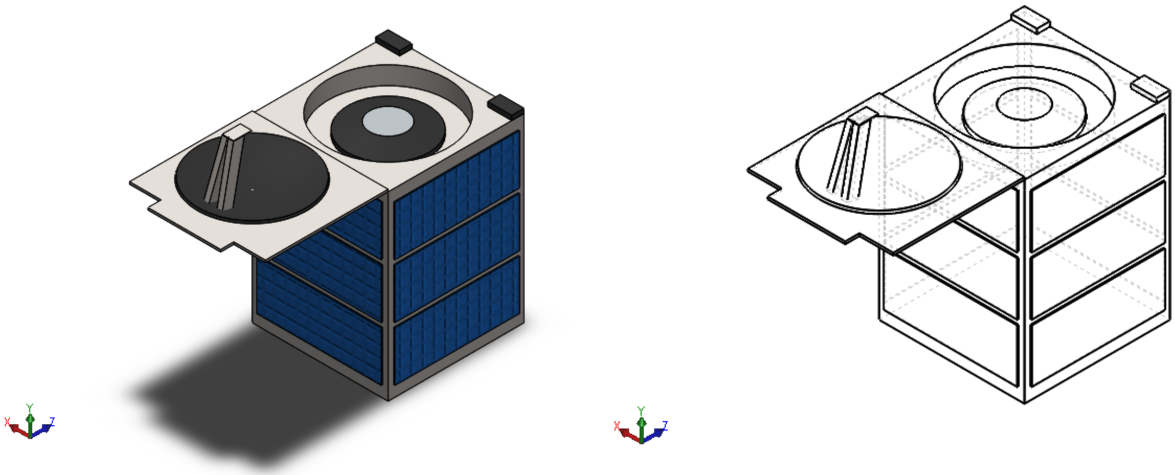


(a) Body Frame Axes (b) Vehicle Model

Figure 1: Vehicle Model With Body Axes

To simplify the model, the vehicle was broken down into simple shapes like rectangular prisms, cylinders, and spheres, and held to an assumption that each piece has a uniform density. This simplified model is then used to calculate the vehicle's center of mass and body-frame inertia matrix.

It can be seen from the following figure that the internal components of the satellite were ignored and the internal structure was replaced by a solid body. This assumption was made for two reasons: (1) since the internal structure of the satellite is unknown to the public, and (2) the rectangular prism design of the bus allows its center of mass to only have small asymmetric deviations in center of mass from the true vehicle design (the shape provides a constraint on where the mass-center of the vehicle must be).



(a) Vehicle External Model (b) Vehicle Internal Model

Figure 2: Vehicle Model Used for Mass Property Analysis

3.3 Model Inertia Matrix

From an analysis of the CAD model in SolidWorks 2017, the following mass properties were generated:

Model Parameters	
Mass	83.00 kg
Volume	0.29 m^3
Surface area	4.11 m^2
Center of mass (wrt origin)	X = 0.00 (m) Y = 0.39 Z = -0.01
Principal axes of inertia	I_x = (0.00, 0.95, -0.33) I_y = (0.00, 0.33, 0.95) I_z = (1.00, 0.00, 0.00)
Principal moments of inertia	$P_x = 5.61$ (kg-m^2) $P_y = 7.03$ $P_z = 7.49$
Moments of inertia (wrt c.m.)	$L_{xx} = 7.49$, $L_{xy} = 0.00$, $L_{xz} = 0.00$ (kg-m^2) $L_{yx} = 0.00$, $L_{yy} = 5.76$, $L_{yz} = -0.44$ $L_{zx} = 0.00$, $L_{zy} = -0.44$, $L_{zz} = 6.88$
Moments of inertia (wrt origin)	$I_{xx} = 20.22$, $I_{xy} = 0.00$, $I_{xz} = 0.00$ (kg-m^2) $I_{yx} = 0.00$, $I_{yy} = 5.77$, $I_{yz} = -0.83$ $I_{zx} = 0.00$, $I_{zy} = -0.83$, $I_{zz} = 19.60$

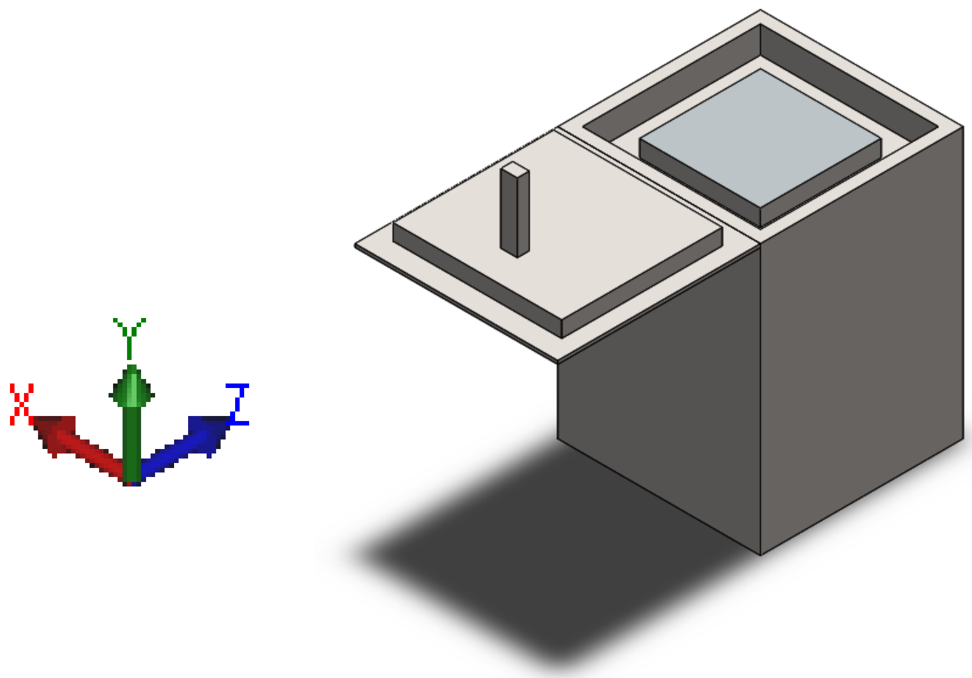
Table 7: CAD Model Parameters

From the information found in the previous table, it can be seen that the rotation matrix corresponding to a transformation from the body frame to the principal frame can be written as:

$$ {}_bR_P = \begin{bmatrix} I_x \\ I_y \\ I_z \end{bmatrix} = \begin{bmatrix} 0.00 & 0.95 & -0.33 \\ 0.00 & -0.33 & 0.95 \\ 1.00 & 0.00 & 0.00 \end{bmatrix} $$

3.4 Model Normals

With a discretization of the outer surfaces of the model into simpler planar sections, the following model was generated:



(a) Body Frame Axes (b) Simplified Vehicle Model

Figure 3: Simplified Vehicle Model With Body Axes

Since this model is entirely composed of rectangular prisms, it is a suitable model to specify the centroid, normal vector, and area of each piece. This will eventually be used to calculate environmental torques such as those due to atmospheric drag.

From a Section Properties analysis of the simplified CAD model, geometric properties were calculated and collected by shared normal vectors. The following information summarizes the simplified model normals analysis:

Model Section Parameters		
Normal Vector	Area	Centroid (wrt c.m.)
$\hat{x}$	0.58m^2	X = -0.25 (m) Y = 0.07 Z = -0.03
$-\hat{x}$	0.58m^2	X = -0.25 (m) Y = 0.07 Z = -0.03
$\hat{y}$	0.96m^2	X = 0.00 (m) Y = 0.41 Z = -0.36
$-\hat{y}$	0.72m^2	X = 0.00 (m) Y = 0.01 Z = -0.29
$\hat{z}$	0.57m^2	X = 0.00 (m) Y = 0.07 Z = 0.22
$-\hat{z}$	0.58m^2	X = 0.00 (m) Y = 0.08 Z = -0.28

Table 8: Simplified Model Normal Vector Section Parameters

4 Dynamics

The following orbit simulations were conducted on Skybox Imaging's SkySat-1 with analysis conducted both with and without Earth Oblateness effects as a function of J_2. All initial conditions were derived from the Two Line Element set (TLE) in Appendix A.

4.1 Keplerian Initial Conditions

The initial conditions of the simulation are provided as a set of Keplerian orbital elements and an initial epoch date and time. Since a TLE for this mission is available, initial launch time is replaced with an active epoch time.

Therefore, although the mission has a launch date of 21 November 2013, 07:11:29 UTC, all initial conditions are taken from the TLE at Epoch: 23 April 2018, 18:27:02 UTC.

$a = 6949.20$ km
$e = 0.0021$
$i = 97.6738°$
$\Omega = 197.6475°$
$\omega = 323.6251°$
$M_0 = 36.3572°$

4.2 Inertial Position and Velocity I.C.'s

By treating these initial Keplerian elements as osculating quantities, computing the corresponding initial position and velocity in the appropriate inertial frame (Earth-Centered Inertial for an Earth-orbiting mission), leads to the following vectors:

${r_0}^{ECI} = [-6611.700,\ -2101.292,\ 14.831]'$ [km]
${v_0}^{ECI} = [-0.300,\ 0.967,\ 7.518]'$ [km/s]

4.3 Unperturbed Orbit Propagation

For an unperturbed system, vehicle dynamics follow a simple second-order non-linear ODE with zero disturbance forces present. This ODE represents the gravitational acceleration felt on the vehicle in ideal conditions. Using the initial inertial states as provided in section 3.2, the following equation can be numerically integrated [34]:

$$\ddot{\mathbf{r}} + \frac{\mu \mathbf{r}}{r^3} = \mathbf{0}$$

By neglecting any perturbations beyond the two-body spherical gravity force acting on the orbit, the following orbit path was produced over a span of 500 complete orbits with a numerical integration step size of 10 seconds.

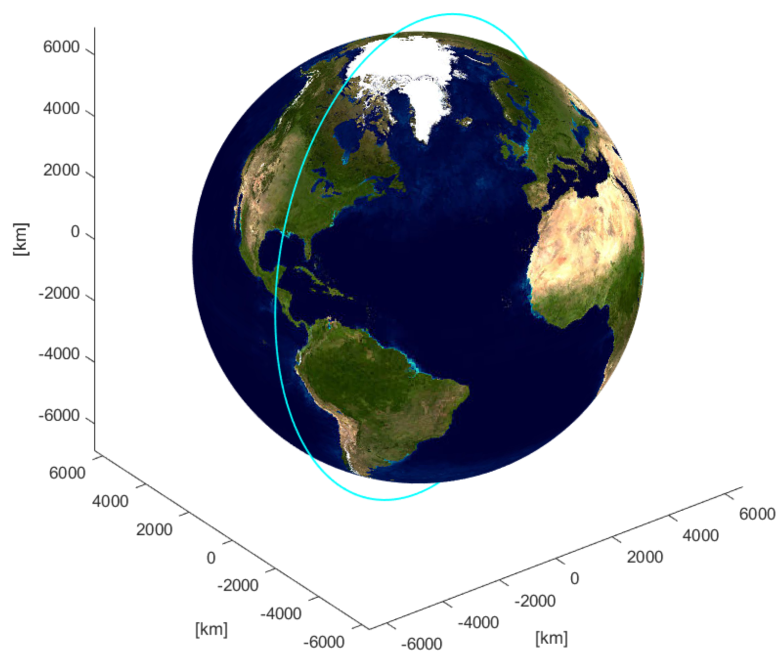


Figure 4: Unperturbed Orbit Path

4.4 Orbit Propagation with J_2 Effects

By considering J_2 effects from Earth oblateness, small disturbances can be introduced into the numerical integration to produce a non-constant orbit path. The governing dynamics then introduce non-zero forces proportional to J_2 as prescribed below [34]:

$$\ddot{X} = -\frac{\mu X}{r^3}\left[1 - \frac{3}{2}J_2\left(\frac{R_e}{r}\right)^2\left(5\frac{Z^2}{r^2} - 1\right)\right]$$
$$\ddot{Y} = -\frac{\mu Y}{r^3}\left[1 - \frac{3}{2}J_2\left(\frac{R_e}{r}\right)^2\left(5\frac{Z^2}{r^2} - 1\right)\right]$$
$$\ddot{Z} = -\frac{\mu Z}{r^3}\left[1 - \frac{3}{2}J_2\left(\frac{R_e}{r}\right)^2\left(5\frac{Z^2}{r^2} - 3\right)\right]$$

The following orbit path was run over the same parameters as Figure 1 with the addition of J_2 effects.

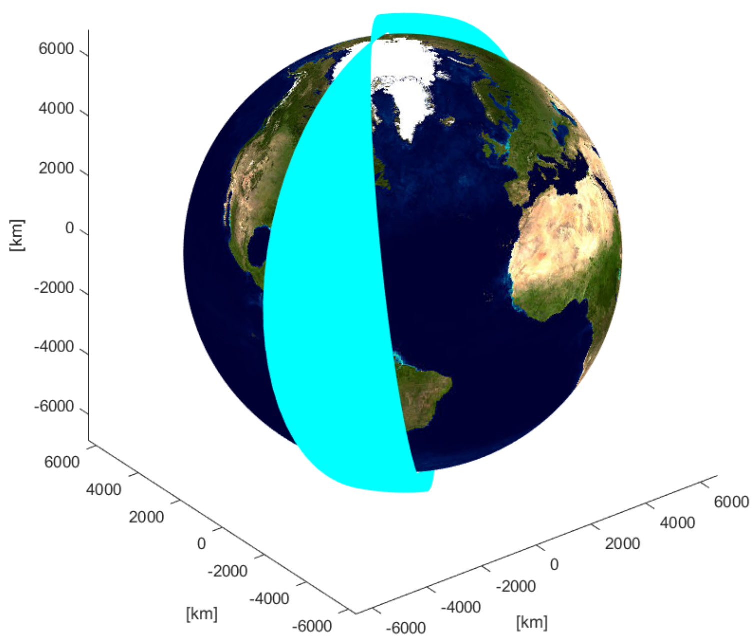


Figure 5: Orbit Path with J_2 Perturbation

Appendices

A Two Line Element Sets (TLE)

```
SKYSAT-1
1 39418U 13066C   18113.76877470  .00000289  00000-0  28950-4 0  9998
2 39418  97.6738 197.6475 0020756 323.6251  36.3572 14.98649985241598
```

B GitHub Repository URL

https://github.com/cwc5613/SkySat-1-ADCS.git

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