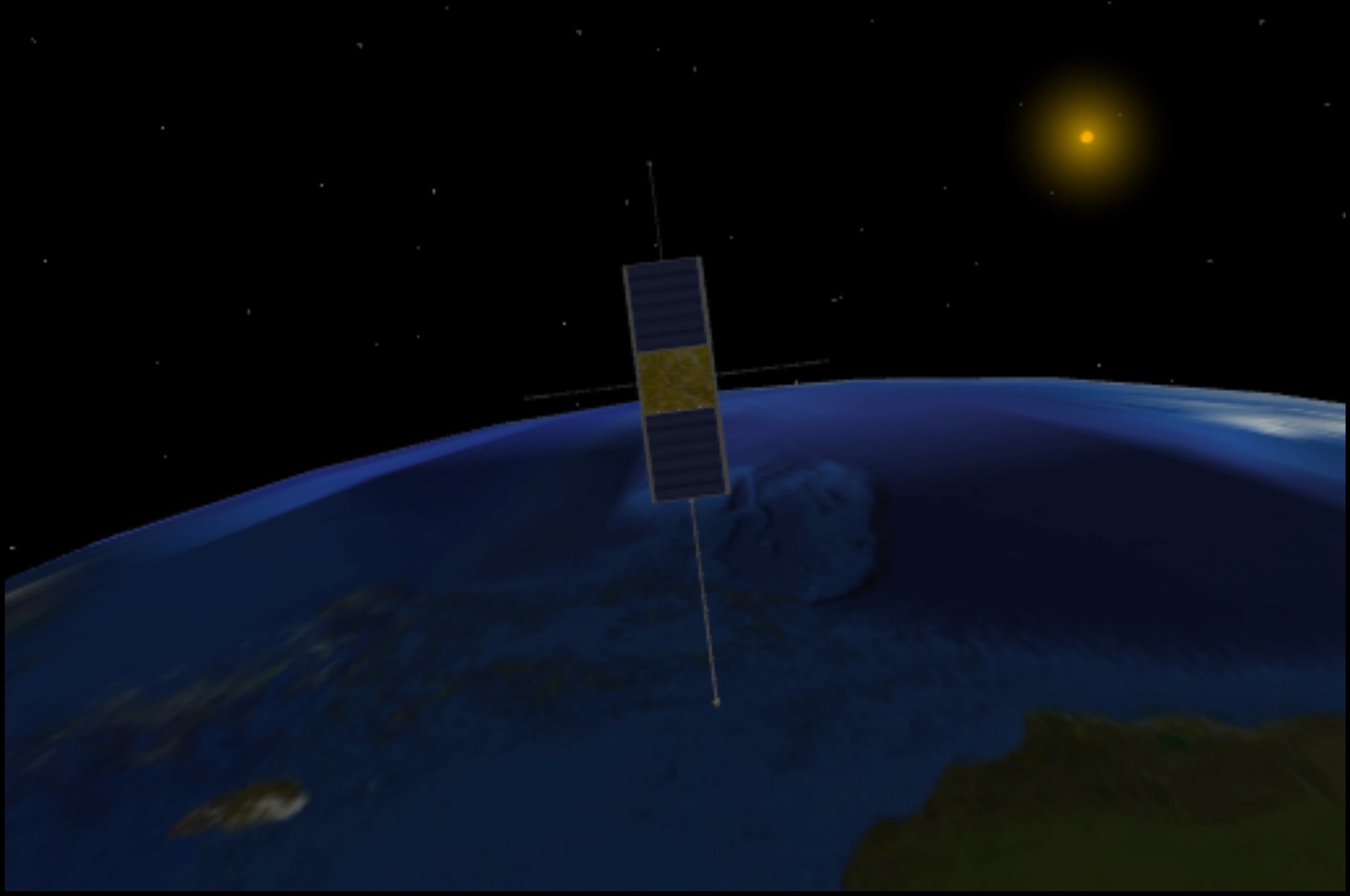
The CubeSat Book



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Princeton Satellite Systems, Inc.

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The CubeSat Book

1st Edition

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CHAPTER 1

INTRODUCTION

This book is written to allow students starting in the sixth grade to build a CubeSat. A CubeSat is a small satellite. The book provides all of the essential math and physics necessary This book is fully self-contained and no other references are needed.

The math topics covered in this book are

1. algebra
2. trigonometry
3. calculus
4. linear algebra

The physics topics are

1. mechanics
2. electromagnetism
3. optics
4. orbital mechanics

The engineering disciplines are

1. electrical
2. mechanical
3. astronautical
4. thermal
5. structural
6. software

The book does not try to give in-depth coverage of each, rather it gives just enough material for the student to be able to build a CubeSat. The book is broken into short chapters. Each chapter has problems at the end to help the student reinforce her or his knowledge. Each chapter ties together math, physics and engineering. In many cases the chapters involve building a component of a CubeSat and instruction are given for the needed lab work.

CHAPTER 2

OVERVIEW

A CubeSat is a miniature spacecraft with a volume of from 1 to 3 liters and a mass from 1 to 3 kg. California Polytechnic State University and Stanford University developed the CubeSat specifications to help universities worldwide to perform space science and exploration. CubeSats provide an opportunity for students to learn about satellites and engineering.

In this book we will design and build a specific CubeSat shown in Figure 2-1 on the following page.

We arrived at this design be first analyzing the requirements for the CubeSat, that is what the CubeSat is supposed to accomplish during its mission. Our mission is to study space weather. In particular we want to study the interaction of the earth's magnetic field with the ion and electron flows in the upper atmosphere. To accomplish this goal we need

1. Electric field sensors
2. Magnetic field sensors
3. Ion detectors
4. Electron detectors
5. Position (in the orbit) sensor.

We need a method for recording the outputs of these sensors and detectors and a way to send the information back to earth. For the sensors to work, and to send the information to earth, we need power. Since we also need to orient (or point) the satellite in the right direction we need a control system to point the satellite.

The spacecraft requirements are given in Table 2-1 on page 5. Requirements tell us the characteristics of a the spacecraft that are needed to accomplish the mission. The system employs three spacecraft although the science mission can be accomplished with two.

S-band is specified for communications since it allows standard S-band satellite ground stations to collect science data and provides more bandwidth than amateur radio bands (2.4 GHz versus 0.03 to 1 GHz for VHF and UHF). The spacecraft will be a 3U design. This provides sufficient area for body fixed solar panels of the required power output.

Figure 2-1. CubeSat layout

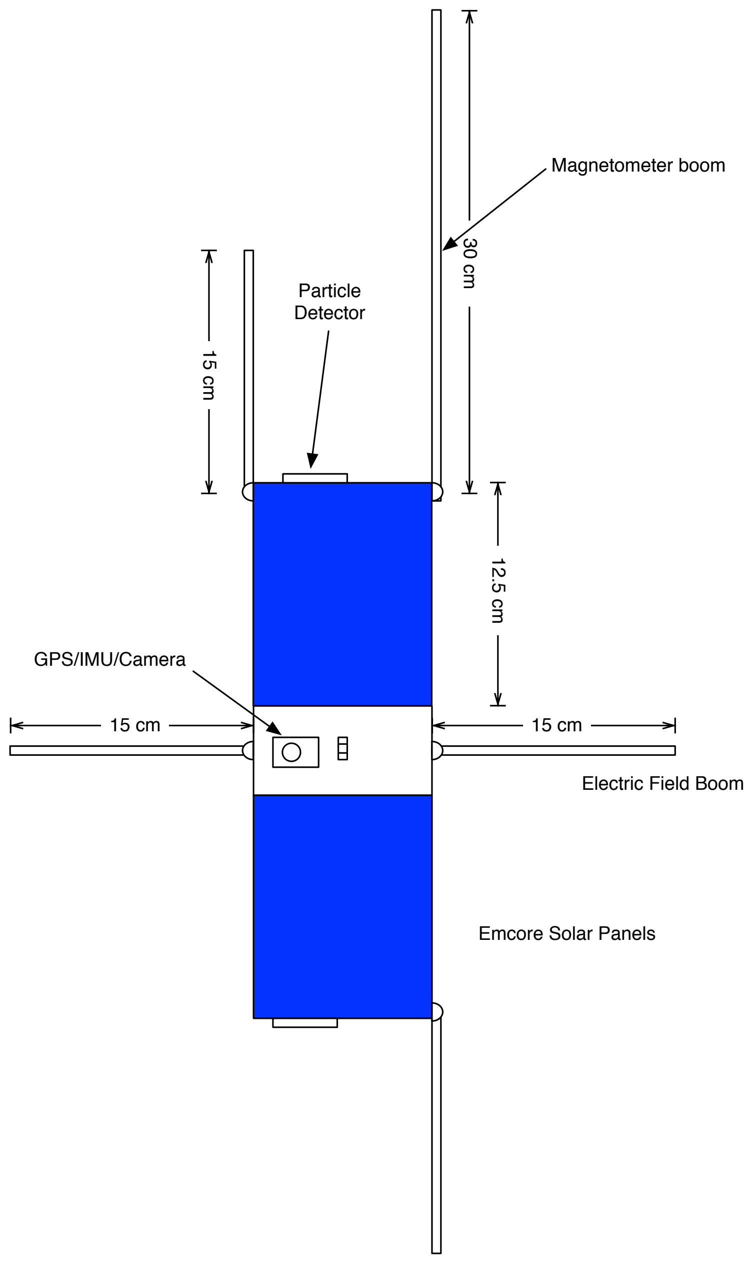


Table 2-1. CubeSat requirements

Requirement	Value	Units
Number of spacecraft	3	
Mass	3	kg/spacecraft
Orbit Altitude	600-1200	km
Orbit Inclination	Sun noon-midnight	km
Phasing between spacecraft	1 - 10	km
Power	4	W
Battery	30000	W-hr
Electric field wires	6	
Electric field wire length	15	cm
Attitude pointing accuracy	1	deg
Attitude Control	3-axis	
Onboard Data Storage	160	GB
Communications	S	Band
Position knowledge	1	km
Data transmission per orbit	TBS	Mb/orbit
Mission duration	3	months

CHAPTER 3

VECTORS

3.1 Introduction

In this chapter we are going to introduce you to vectors.

3.2 Newton's Law

Newtons Second Law of motion is

$$F = ma \tag{3-1}$$

where F is the force, m is the mass and a is the acceleration. In English this equation says, "force equals the product of mass and acceleration." Push something! It will move. That is because you are applying a force F. The bigger the mass the less acceleration you get. Do you see why?

Acceleration is the change in velocity. Using calculus notation we write

$$a = \frac{dv}{dt} \tag{3-2}$$

The d means change so $\frac{dv}{dt}$ means the change in velocity with respect to time. We always say "with respect to" the bottom quantity. In English we read this in shorthand as "d v d t". v is velocity and t is time. If you are in a car and the driver pushes the accelerator pedal the car accelerates. This means that the velocity changes. This happens every time your car moves away from a stop light or sign or when you are trying to get through a light that is changing.

If your acceleration is a constant a_c then

$$v(t) = a_c t + v(0) \tag{3-3}$$

which means your velocity increases linearly. This equation looks the standard equation for a straight line which is

$$y = mx + b \tag{3-4}$$

The slope, m is a_c, t the independent variable and $v(0)$ is the y intercept.

The velocity is the change in position with respect to time.

$$v = \frac{dx}{dt} \tag{3-5}$$

where x is position. Using our car example if your car is going at a steady speed of 60 mph your position, x will change by 60 miles every hour. If your velocity is a constant v_c then

$$x(t) = v_c t + x(0) \tag{3-6}$$

$x(t)$ means x at time t. $x(0)$ means x at time 0. If $x(0) = 0$ and v_c is 60 mph then when $t = 2$ hrs $x(2)$ = 120 miles. We could have derived this using calculus but it is not important to do so now.

Speed is always a length measurement divided by a time measurement.

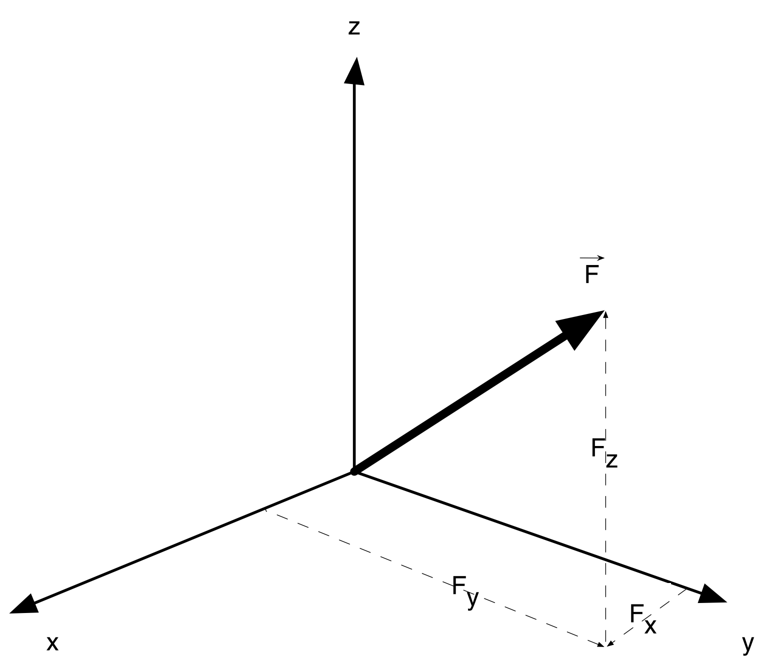
3.3 Vectors

Suppose that we are not driving along the x-axis. How do we write Newton's law? We do this by writing three equations

$$F_x = ma_x \tag{3-7}$$
$$F_y = ma_y \tag{3-8}$$
$$F_z = ma_z \tag{3-9}$$

one for each direction $\hat{x}$ $\hat{y}$ and $\hat{z}$. (The $\hat{}$ denotes direction). We use subscripts $_x$ to denote a component of F. For example, F_x is the x component of F or the component of F along the x axis. Figure 3-1 shows the three elements of the F.

Figure 3-1. Cartesian coordinates. The vector $\vec{F}$ has components along $\hat{x}$, $\hat{y}$ and $\hat{z}$



We can use shorthand notation

$$\begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = m \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} \tag{3-10}$$

This is vector notation. A vector is a container with the 3 components of F or a or anything else. The shorthand is

$$\vec{F} = m\vec{a} \tag{3-11}$$

(3-12)

where

$$\vec{F} = \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} \tag{3-13}$$

and

$$\vec{a} = \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} \tag{3-14}$$

For example, with numbers

$$\begin{bmatrix} 18 \\ 12 \\ 6 \end{bmatrix} = 6 \begin{bmatrix} 3 \\ 2 \\ 1 \end{bmatrix} \tag{3-15}$$

The number 6 multiplies each element of $\vec{a}$ to produce $\vec{F}$

The magnitude of a vector is

$$\vec{r} = \begin{bmatrix} r_x \\ r_y \\ r_z \end{bmatrix} \tag{3-16}$$

is

$$|\vec{r}| = \sqrt{r_x^2 + r_y^2 + r_z^2} \tag{3-17}$$

What is r_x^2?

$$r_x^2 = r_x \times r_x \tag{3-18}$$

and

$$r_x^3 = r_x \times r_x \times r_x \tag{3-19}$$

For example, if

$$\vec{r} = \begin{bmatrix} 2 \\ 3 \\ 1 \end{bmatrix} \tag{3-20}$$

$$|\vec{r}| = \sqrt{2^2 + 3^2 + 1^2} = \sqrt{4 + 9 + 1} \approx 3.60555127546399 \tag{3-21}$$

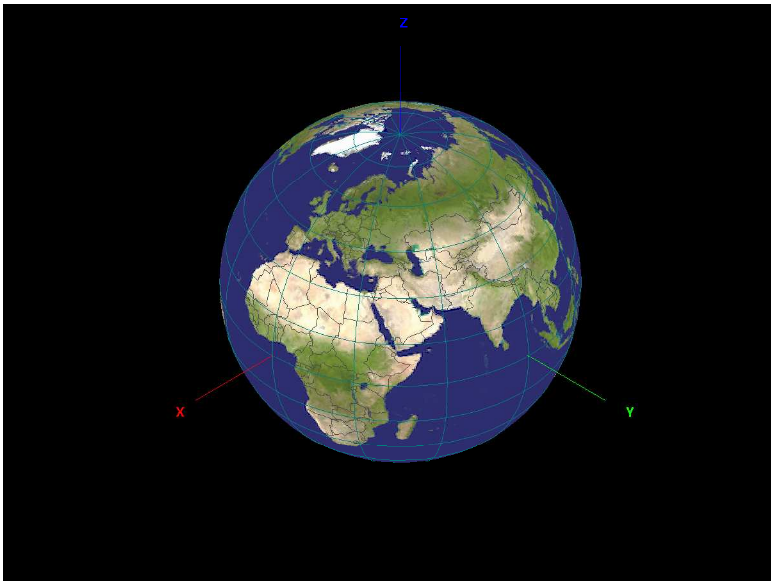
At John Witherspoon Middle School in Princeton, NJ, USA you are sitting at a position vector roughly

$$\vec{r} = \begin{bmatrix} 1286.527 \\ -4693.093 \\ 4109.407 \end{bmatrix} \tag{3-22}$$

in kilometers. Figure C-2 on page 24 shows the earth fixed coordinate system.

Can you find Princeton? Do you see why Princeton's y coordinate is negative?

Figure 3-2. Earth map. The x -axis is along the Greenwich Meridian and goes from the earth center through the equator. The z-axis goes through the north pole



3.4 Problems

1. If you have a force of 1 Newton (N) and a mass of 2 kg what is the acceleration? The units will be m/s^2.
2. What happens if you double the force?
3. Write an orbital position vector with x = 7000 km, y = 0 km an z = 0 km. Where is it over the earth using the picture in this chapter?
4. Write an orbital position vector with x = 0 km, y = 0 km an z = 7000 km. Where is it over the earth using the picture in this chapter?
5. What is the magnitude of each of the two vectors?

CHAPTER 4

ORBITS

4.1 Introduction

In this chapter we are going to introduce you to orbits.

4.2 Gravity

The gravitational acceleration is

$$\vec{a} = -\mu \frac{\vec{r}}{|\vec{r}|^3} \tag{4-1}$$

μ is the gravitational constant. For the earth is is 3.98600436$\times 10^5$ km^3/s^2. The denominator looks mysterious! It is

$$|\vec{r}|^3 = \left(\sqrt{r_x^2 + r_y^2 + r_z^2}\right)^3 \tag{4-2}$$

Check the units! Acceleration is in units of km/s^2. "s" means seconds.

$$\mathrm{km}/s^2 = \mathrm{km}^3/s^2 \frac{\mathrm{km}}{\mathrm{km}^3} \tag{4-3}$$

It works!

What does this mean? We have to learn to read equations! We read this as "The acceleration of gravity is the negative of the product of the gravitational constant and the position vector divided by the cube of the magnitude of the position vector." First we see that the gravity force is in the direction opposite the position vector, that is it pulls you to the center of the earth. Figure **??** on page ?? shows you a circular polar orbit.

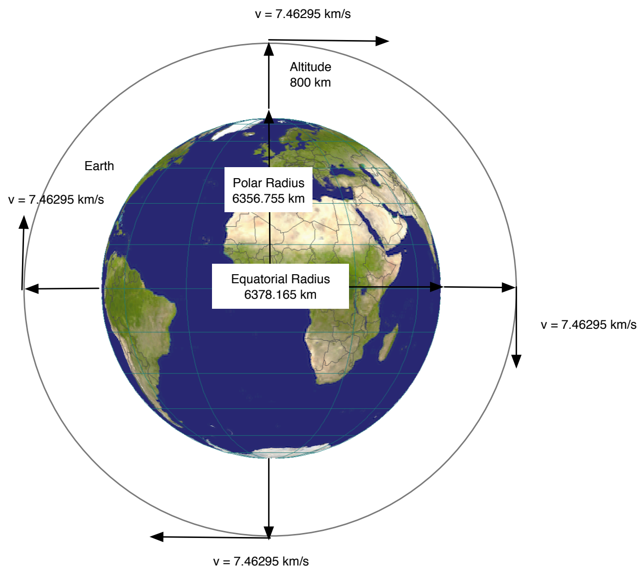
The easiest way to find the orbit rate is to balance the gravitational force and the centripetal force when the spacecraft is on the x-axis.

$$a = -\mu \frac{1}{r^2} \tag{4-4}$$

The centripetal acceleration, which is the acceleration felt on something that must move along a circular track (like a ball on a string that you swing) is

$$a = -\frac{v^2}{r} \tag{4-5}$$

Figure 4-1. A polar orbit



This is the acceleration towards the center needed to keep the object from flying outward. Set the two equal and simplify the equations

$$\frac{v^2}{r} = \mu \frac{1}{r^2} \tag{4-6}$$

$$v^2 = \mu \frac{1}{r} \tag{4-7}$$

$$v^2 = \frac{\mu}{r} \tag{4-8}$$

$$v = \sqrt{\frac{\mu}{r}} \tag{4-9}$$

Remember that $v^2 = v \times v$. v is the orbital velocity. What does the equation tell you? The bigger r is the smaller the velocity! μ is the gravitational constant which is bigger if the planet is more massive. That means that if you are orbiting a planet like Jupiter your orbital velocity, at a given r, is higher!

For our CubeSat our launch vehicle supplier will put us into the orbit we want. It is important to know the orbital velocity because that will tell us how long it takes for us to make one orbit! The orbital period is just the orbit circumference divided by the velocity.

$$P = \frac{2\pi r}{v} \tag{4-10}$$

If r is in km and v in km/s then P is in s.

4.3 Problems

1. Compute the velocity for the orbit in the diagram. Do you get 7.46295 km/s?
2. How fast are we going in miles per hour?
3. What happens if we change our orbit altitude to 400 km?
4. What happens to to the velocity if we change our altitude to 1200 km?
5. What happens if you park your spacecraft at a slightly higher orbit than your friend's spacecraft?
6. What is the period of the orbit in the diagram?

CHAPTER 5

ATTITUDE CONTROL

5.1 Introduction

The orientation of our CubeSat influences many aspects of operation. For example, the instruments in our payload need to be in the right orientation to take accurate measurements. This is why we need to control the CubeSat's attitude, or the direction in which it is pointing, throughout flight. CubeSats have a limited space in which we can fit instruments, so we will not be using propellants in attitude control. Rather, we are going to get the Earth's magnetic field to work for us. In order to understand how to do this, we must learn about electricity and magnetism.

5.2 Electricity

Electricity is the flow of electrons through a material. Electrons flow more easily through some materials than others. Materials that have a low resistance to electron flow are called conductors and materials with a high resistance to electron flow are called insulators. A material's resistance *R* to electric flow is determined by its length *L* and cross-sectional area A with respect to the direction of flow and a property of the material called resistivity ρ. The units of resistance is Ohms, and is written with the character [Ω].

$$R = \rho \frac{L}{A} \tag{5-1}$$

All this says is that electricity flows more easily when it is given more area of the material to flow through, and it flows less easily if it has to travel through a greater length. Figure 5-1 on the next page shows the wire wrapped around the core. The crosssectional area of the wire is A. The core has a radius of r so the circumference of the core is

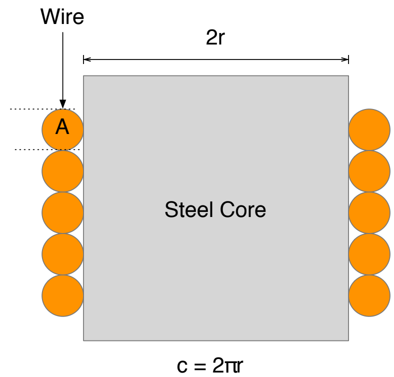
$$c = 2\pi r \tag{5-2}$$

If there are N loops of wire (5 are shown in the figure) then the total length of the wire is the number of loops times the length of each loop which is the circumference of the wire. Therefore the total length is

$$l = 2\pi r N \tag{5-3}$$

Units are important here. The area of the wire, the radius of the core an the resistivity must have the same units of measure. If the resisitivity is 1.678×10^-8 Ω-m, which is read as OHM meters, then the area must be in meters squared (m^2) and the radius must be in m. The amount of electricity that can flow from one object to another is its electric potential, which is measured in units of volts [V]. Electric potential is also called voltage. Current I is the

Figure 5-1. Wire wrapped around the core



the measure of flow of electric charge through a conductor. If we know the voltage V and the resistance R, we can calculate the current:

$$V = IR \tag{5-4}$$

Therefore,

$$I = \frac{V}{R} \tag{5-5}$$

Current is measured in Amperes, or for short, Amps [A]. If we know the electric potential (voltage V) and the rate at which this electricity flows (current I), we can calculate the power. The power, or rate at which energy is consumed or converted, is measured in Watts [W] and is given by the equation

$$P = IV \tag{5-6}$$

When computing current you need to think about what are reasonable numbers! Your household outlets are at 115 Volts and can deliver 15 Amps. That means we can plug a 1500 Watt hair dryer into the wall. Our CubeSat "socket" will be a 12 V and our total power will be 5 W. How many amps can we deliver? That would be

$$I = \frac{5}{12} \tag{5-7}$$

which is 5/12 or 0.42 Amp! Not a lot!

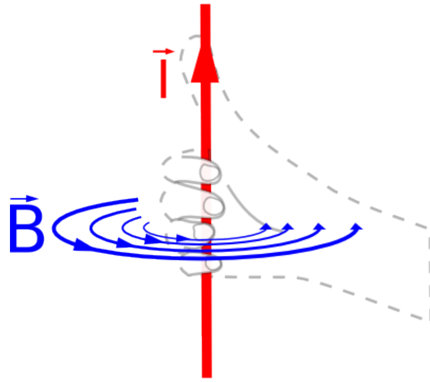
5.3 Magnetic Torquers

Flowing current through a wire induces a magnetic field B around the wire. Magnetic fields point from south to north. When induced by a current, its direction can be determined using the right-hand rule, as in Figure 5-2 on the facing page. If your thumb points in the direction of the current, the magnetic field points in the same direction as your fingers. Magnetic torquers are metal rods with wire coiled around them. The coiling produces a magnetic field whose strength is proportional to the number of times the wire is coiled. In a CubeSat, the magnetic torquer's field reacts with the Earth's magnetic field to produce a torque, or rotational force. The torque is dependent on the length *l* and radius *r* of the rod, as well as the number of times *N* that the wire is coiled around it. Torque is measured in Newton-meters [N-m].

$$\tau = \frac{\pi r^2 N I}{\frac{1}{\mu_r} + N_d} \tag{5-8}$$

τ is the torque, I is the current, r is the radius of the torque rod and l is the length of the torque rod. The variable μ_r is simply a measure of how magnetized the rod becomes in response to the created magnetic field. Its value depends on

Figure 5-2. Right-Hand Rule



the material used. For our CubeSat the relative permeability μ_r of the material is going to be about 2000 [N/A^2]. The value N_d is called the demagnetization factor, which is a term that depends on the geometry of a shape. For now, we will assume the value of N_d is approximately 0.15. The demagnetization factor can be no greater than 1.

5.4 Problem-Solving Tips

Converting Units

Suppose we want to find the resistance of a silver wire that is 10 [m] long and has a diameter of 0.6 [mm]. The resistivity of the material is 1.586 [$\mu\Omega$-cm].

The first thing we do is convert the units to standard SI units. We find that
resistivity $\rho = 1.586 \times 10^{-8}$ [Ω-m]
length $L = 10$ [m], and
diameter $D = 0.0006$ [m].

We are not done yet. Resistance is $R = \rho\frac{L}{A}$. We know ρ and L, but we do not have A, the *area* of the wire. However, we can find A from the diameter D. From the diameter we can calculate area $A = \pi\frac{D}{2}^2 = 2.827 \times 10^{-7}$ [m^2]

Now we can solve for resistance using $R = \rho\frac{L}{A}$ to get $R = 0.561$ [Ω]

Using Multiple Equations

Suppose now that our wire can carry a maximum current of 18 [A], and we want to know the minimum length of wire we can use if we are using a 9 [V] battery.

We don't have an equation relating current directly to the length, but we can find the length if we know the resistance $R = \rho\frac{L}{A}$, since we already have values for the area A and resistivity ρ of the wire. We also know that we can find R from I and V:
$V = IR$ so $R = V/I$ so $R = 0.5$ [Ω]
Using $R = \rho\frac{L}{A}$ we find that $L = \frac{RA}{\rho} = 8.912$ [m].

This is a two-equation problem, but the same idea applies to many equations.

Knowing Which Variables To Use

Suppose I wrap 10 [m] of silver wire around a rod that is 1 [cm] in radius and 6 [cm] in length. Assume the demagnetization factor is 0.5 for this shape. I want to know how much power I will use if my power source is a 9 [V] battery, as well as how much torque can be produced.

Sometimes there are separate parts of a system that work together to accomplish a goal. The magnetic rod and the current-carrying wire are two separate items and it is important to know which variables of the torque equation apply to each. In general, anything describing electricity refers to the wire, and anything describing magnetism refers to the rod.

To find power $P = IV$, we need to know voltage V, which is given, and current I. Current I flows through the wire, not the rod. We know that we can find current from $I = \frac{V}{R}$. All we need to find now is resistance R, which we can get from $R = \rho\frac{L}{A}$. It is important to remember to use length and area values for the wire, not the rod, when finding current. So $L = 10$ [m] and $A = 2.827 \times 10^{-7}$ [m^2]
as shown in the section on converting units. This gives us
$R = \rho\frac{L}{A}$ to get $R = 0.561$ [Ω] and
$I = \frac{V}{R} = 16.043$ [A]. This means that $P = IV = 144.4$ [W].

To find the torque, we want to use the equation $\tau = \frac{\pi r^2 NI}{\frac{1}{\mu_r}+N_d}$. We already know that
$I = 16.043$ [A],
$\mu_r = 2000$ [N/A^2] and
$N_d = 0.5$, but we do not know N, the number of times the wire is wrapped around the rod.

We know that the length of the wire is $L = 10$ [m], and that the radius of the rod $r = 1$ [cm], which, when converting units, turns out to be .01 [m]. When we wrap the wire around the rod once, the length of wire we use is equal to the rod's circumference. So we know from this that $N = \frac{L}{2\pi r} = 159.2$.

Using the torque equation, we find that we can produce 1.6 [N-m] of torque.

5.5 Problems

Today's problems will be based on experiment!

1. What are the rod's length and radius?
2. The resistivity of copper is 1.678×10^{-8} Ω-m. If a 0.03 mm^2 wire is wound around the rod 2000 times, what is the current that flows through the wire when attached to a 12 V battery?
3. In what direction do the current and magnetic fields flow?
4. How much power is consumed in this process?
5. How much torque is produced in Question 2?
6. If our maximum power output is 5 W, what is the maximum amount of times we can coil the wire around the rod? What is the voltage in this case?
7. How much torque is produced in Question 6?

CHAPTER 6

ANSWERS

6.1 Vectors

1. 0.5 m/s^2
2. 1.0 m/s^2
3. $[7000; 0; 0]$ km. Over the equator south of Greenwich England
4. $[0; 0; 7000]$ km. Over the north pole
5. 7000 km

6.2 Orbits

1. 7.46295 km/s
2. 16694.154 mph
3. 7.68068 km/s
4. 7.26275 km/s
5. Your friend's spacecraft will get ahead of you. Eventually you will be 1/2 orbit apart.
6. 6025.4 s or 1.67 hours

APPENDIX A

CONSTANTS

Table A-1. Useful Constants

Constant	Value	Units
Acceleration of gravity	9.80665	m/s^2
Earth black body radiation	429.4	W/m^2
Earth equatorial radius	6378.14	km
Earth gravitational constant	398600.436	km^3/s^2
Earth mean temperature	295	deg-K
Earth polar radius	6356.755	km
Solar flux at the earth	1367	w/m^2
Speed of Light	299793.458	km/s

APPENDIX B

GLOSSARY

Table B-1. Glossary

Term	Meaning
Acceleration	The change in velocity with respect to time.
Body	In the context of satellites may mean, spacecraft or any celestial body.
Coordinate Frame	Three orthogonal axes and an origin. Used to measure the location of something in 3 dimensions.
CubeSat	A satellite with dimensions 10 cm $\times$ 10 cm $\times$ 10U cm where U is from 0.5 to 3. (10U means 10 $\times$U).
Derivative	From calculus. The change in one quantity with respect to another. The derivative of x with respect to y is written as dx/dy which looks like division but isn't.
ECI	Earth-Centered Inertial reference frame.
EF	Earth-Fixed frame.
Electron	A negatively charged particle that orbits around the nucleus of an atom. Electrons also flow through wires as electricity.
Giga	One billion.
Gravity	A force that pulls one mass towards another. Einstein discovered that gravity is not really a force but due to the curvature of space-time.
Ground Station	A place on the ground with an antenna that talks with satellite.
Hertz	Cycles per second. A cycle is a repeating pattern.
Ion	An atom with one or more electrons removed so that it has a positive charge.
Jerk	The change in acceleration with respect to time.
Magnetic torquer	A coil of wire (which may be wrapped around an iron core). When a voltage is applied a current flows through the wire. The current produces a magnet field which interacts with the earth's magnetic field and produces a torque on the spacecraft.
Orbit	The path a satellite takes in space about another body. Orbits may be elliptical (close) or open (parabolic and hyperbolic).
Reaction wheel	A motor with a disk. The base of the motor is attached to the spacecraft. When the motor applies a torque the disk spins one way and the spacecraft spins in the opposite direction.
Position	The location of a point.
Satellite	A body that orbits another celestial body. Often shorthand for "artificial satellites".
Spacecraft	Any machine that goes into space.
S-band	A range of electromagnetic frequencies used by the radios in the satellite. S-band ranges from 2 to 4 Gigahertz.
Telemetry	Data sent wirelessly from a satellite to the ground.
Torque	The tendency of a force to rotate something about an axis if the force is transmitted to the object by means of an offset.
TT&C	Telemetry, tracking and control.
Unit Vector	A vector with a magnitude of one. It only indicates the direction of the vector, not the length.
Vector	A line going from one point to a second point. A vector has magnitude and direction. Often drawn as an arrow.
Velocity	A combination of speed and direction. The change in position with respect to time.

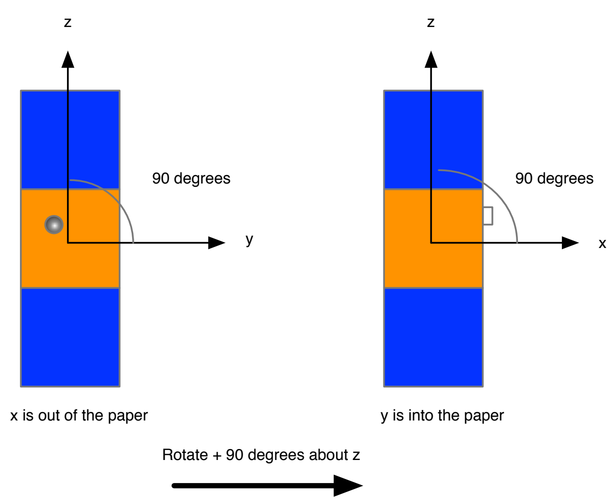
APPENDIX C

COORDINATE FRAMES

There are three Cartesian coordinate frames that will be important in CubeSat design. A coordinate frame is three axes, x, y, z each of which is at right angles (we usually say orthogonal) to the others.

The first is the body or CubeSat fixed frame. The frame is attached to the CubeSat and rotates and moves with the CubeSat. The origin of the frame (where $x = 0$, $y = 0$ and $z = 0$) is at the geometric center of the CubeSat. Figure C-1 shows the CubeSat fixed frame. We call the spacecraft the "body". The figure shows the zy-plane and the zx-plane. A plane is just a view of the coordinates in which the other axis comes in of or goes out the paper. As can be seen the z axis is along the long axis of the CubeSat. The $+x$ axis points in the direction of the camera.

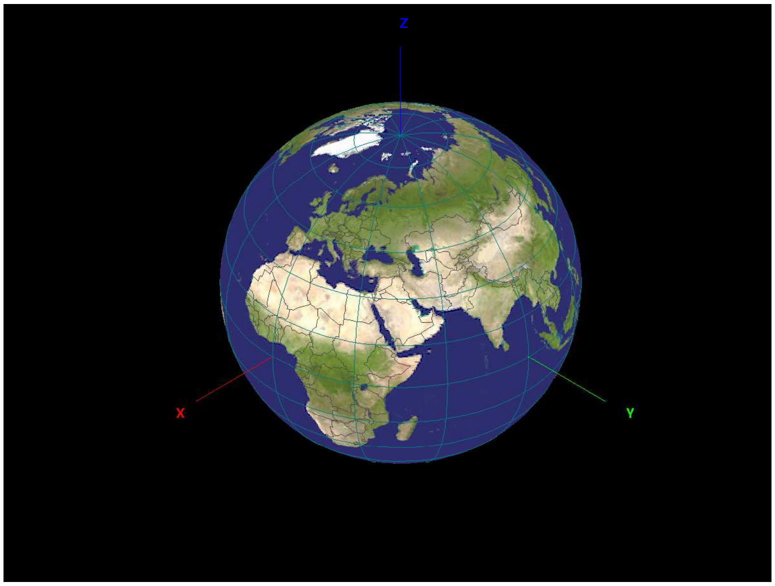
Figure C-1. CubeSat or body fixed frame



The second important reference frame is the Earth-fixed frame. Figure C-2 on the following page shows the earth fixed coordinate system. The x -axis is along the Greenwich Meridian and goes from the earth center through the equator. The z-axis goes through the north pole. If you are east of Greenwich England your y coordinate is positive. If you are west it is negative. If you are north of the equator your z-coordinate is positive. This coordinate frame rotates with the earth so it makes one revolution per day.

The inertial reference frame used is the J2000.0 frame. J2000.0 defines the date January 1, 2000 at 12h Universal Time. This frame has xy-plane parallel to the mean Earth equator at epoch J2000.0 and its z4-axis pointing towards the mean north celestial pole of J2000.0. Its origin is at the center of the earth. The x-axis points toward the mean vernal equinox of J2000.0.

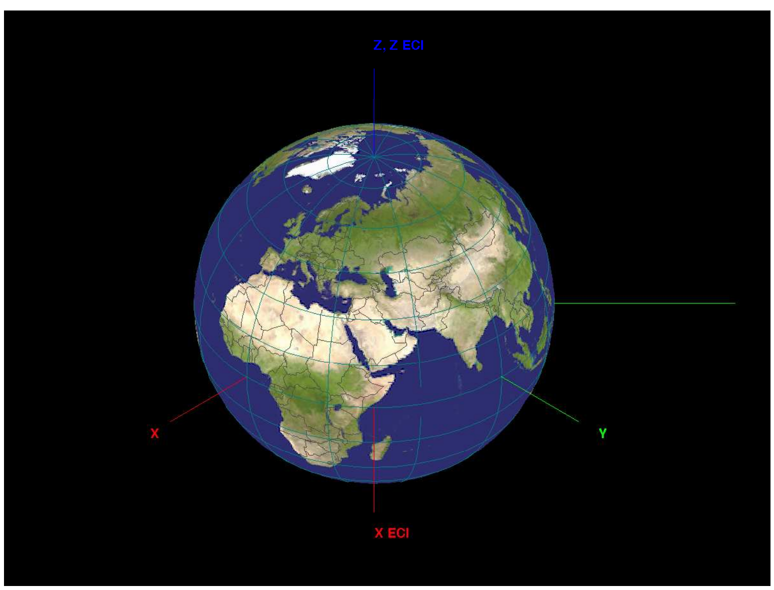
Figure C-2. Earth map. The x -axis is along the Greenwich Meridian and goes from the earth center through the equator. The z-axis goes through the north pole.

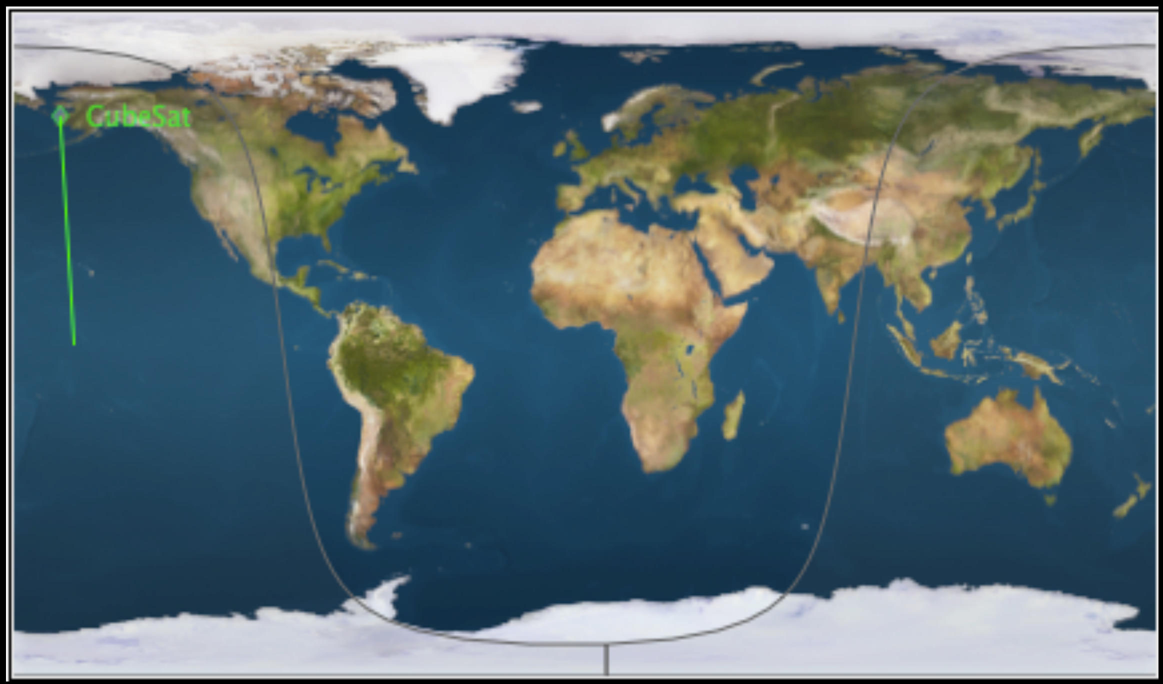


The vernal equinox is in spring (in late March) when the sun is in the earth's equatorial plane. Because the axis of the earth is tilted the sun's angle with respect to the equator varies during the year. In the winter (for Princeton) it is in the southern hemisphere and in the summer (for Princeton) it is in the north hemisphere.

This frame is also sometimes called the Earth-Centered Inertial frame (ECI). It is shown in Figure **??** on page ??. The reason we say "mean" equator and north pole is because the earth axes wobble. So the coordinates are fixed to the average plane of the earth's equator and the average north pole.

Figure C-3. Coordinate Frames





The CubeSat Book is a self-contained introduction to the math, physics and engineering needed by every CubeSat engineer. It assumes no minimal background in math and science. Students in 6th grade and older will be able to master the material.

Each chapter is self-contained and includes numerous examples to walk the reader through the technology. Answers to all problems are included in the back of the book.