Gateway To Space
ASEN 1400 / ASTR 2500

Class #18

Colorado Space Grant Consortium
Today:

- Mid Semester Team Evaluations Due now

- One Minute Report Questions

- Latest Grades

- Passwords

- Orbits and Mission Design – Part I

- Launch is in 30 days
Grades:

- My method is “old school”
- Use password to find your line of grades
- Sheet for Overall, Attendance, 1 min, and HW
- YES, I know its hard to read…

<table>
<thead>
<tr>
<th>Overall</th>
<th>Turtle</th>
<th>Pepper</th>
<th>Penny</th>
<th>Nike</th>
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</table>
Grades:

- Posted on website and handouts now

- Questions on grades to Prof.koehler@gmail.com

- Or in person
Next Tuesday…

In-Class Team Time

Bring all hardware and be prepared for in-class inspections
Next Tuesday…

In-Class Inspection

Bring Hardware and questions
Plan on working in classroom

Community Service Approvals DUE

Colorado Space Grant Consortium
Next Thursday...

Guest Lecture

Spacecraft Propulsion

Then Spring Break

Colorado Space Grant Consortium
One Minute Report Questions:

- What type of orbit is the space station in?
  - 51.65 degrees inclination, ~415 km altitude

- Re-boost
One Minute Report Questions:

- How many GEO sats are around Earth?
- How many man-made sats are in space?

- Union of Concerned Scientists…

<table>
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<th>Satellite Quick Facts</th>
</tr>
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<tbody>
<tr>
<td>Total number of operating satellites: 1084</td>
</tr>
<tr>
<td>LEO: 530</td>
</tr>
<tr>
<td>United States: 461</td>
</tr>
<tr>
<td>Total number of U.S. Satellites: 461</td>
</tr>
</tbody>
</table>

*includes launches through 8/31/2013*
One Minute Report Questions:

- How many GEO sats are around Earth?
- How many man-made sats are in space?

- Union of Concerned Scientists...

### Satellite Quick Facts (includes launches through 7/31/14)

<table>
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<tr>
<th>Total number of operating satellites: 1,235</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States: 512</td>
</tr>
<tr>
<td>LEO: 655</td>
</tr>
<tr>
<td>Total number of U.S. satellites: 512</td>
</tr>
<tr>
<td>Civil: 18</td>
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</tbody>
</table>
One Minute Report Questions:

- Union of Concerned Scientists’ Database and Google Earth Demo...http://www.satellitedebris.net/whatsup/whatsup.htm
Orbit Introduction:

What is an orbit?
- The path of a satellite around the Earth (or any central body)

What shape is it?
- Orbits are conic sections
- Circles, Ellipses, Parabolas, Hyperbolas

How are orbits described?
- Position and Velocity at any one time
- Keplerian Elements (from Kepler’s Laws)
**Orbit Introduction:**

- What is an orbit?
Orbit Introduction:

• How fast can you throw a baseball?

• Could you throw any of these in to an orbit?
  - How fast would it have to be going?
Orbit Introduction:

• Let’s figure it out…

\[ v = \sqrt{\frac{GM}{R}} \]

\( v \) is velocity
\( G \) is Universal Gravitational Constant
\( M \) is mass of planet or satellite
\( R \) is radius of planet or satellite

\[ G = 6.67 \times 10^{-11} \frac{m^3}{(kg \cdot s^2)} \]

\[ M_{Earth} = 5.974 \times 10^{24} \text{ kg} \quad R_{Earth} = 6367000 \text{ m} \]

\[ v_{Earth} = 7910 \frac{m}{s} = 17694 \text{ mph} \]
Orbit Introduction:

- When in space why do you float? i.e. Weightlessness

\[ \frac{mV^2}{r} = \frac{MmG}{r^2} \]

\[ V = \sqrt{\frac{MG}{r}} \]
Kepler and Newton BFFs:

Orbits are conic sections:
- Circle
- Ellipse
- Parabola
- Hyperbola

From Kepler’s Law, the central body is at a focus of the conic section

\[ V = \sqrt{\frac{2MG}{r} - \frac{MG}{a}} \]
Orbit Introduction:

What is an orbit?
- The *path of a satellite around* the Earth
  (or *any central body*)

What shape is it?
- Orbits are *conic sections*
- Circles, Ellipses, Parabolas, Hyperbolas

How are orbits described?
- *Position* and *Velocity* at any one time
- *Keplerian Elements* (from Kepler’s Laws)
Orbit Definition:

Velocity & Position

- Given **position** and **velocity** of a satellite at time $t$, you can calculate the position and velocity at any other time
Orbit Definition:

Keplerian Elements

- Semi major axis (a)
- Size
- Eccentricity (e)
- Shape
Orbit Definition:

Keplerian Elements

- Inclination (i)
  - Angle to the Equator
Orbit Definition:
**Orbit Definition:**

**Keplerian Elements**

- Right Ascension of Ascending Node (RAAN, \( \Omega \))
- **Rotation** about the Earth’s Spin Axis
Orbit Definition:

Keplerian Elements

- Argument of Perigee ($\omega$)
- Rotation of the conic section in the plane
**Keplerian Elements**

- True Anomaly (θ)
- Defines the position of a body in orbit
- Angle between the Position Vector and the vector to Perigee
- Elliptical only

**Orbit Definition:**

- Keplerian Elements
  - True Anomaly (θ)
  - Defines the position of a body in orbit
  - Angle between the Position Vector and the vector to Perigee
  - Elliptical only
Orbit Definition:
Types of Orbits:

• Geosynchronous/Geostationary (equator)
Types of Orbits:

Geostationary VS. Geosynchronous
Types of Orbits:

- Critical Inclination
Types of Orbits:

- Repeating Ground Trace
Types of Orbits:

- Polar/ Sun Synchronous
Types of Orbits:

- Molniya
Types of Orbits:

- STK Orbit Tuner Demo HERE
Earth, the Moon, Mars, and the Stars Beyond

A Brief Discussion on Mission Design
Universal Gravitation, Applied:

• When in space why do you float? i.e. Weightlessness

\[ \frac{mV^2}{r} = \frac{MmG}{r^2} \]

\[ V = \sqrt{\frac{MG}{r}} \]
Orbit History:

• 1665 A.D.
  Isaac Newton
  • At 23, plague while at Cambridge
  • Went to be one with nature
  • He studied gravity
  • Discovered “Newton’s Laws of Motion”
  • 1666, he understood planetary motion
  • Did zip for 20 years until Edmund Halley
Newton’s Laws:

1st Law…

Body at rest stays at rest, a body in motion stay in motion

2nd Law…

\[ F = m \times a \]

3rd Law…

For every action, there is an equal and opposite reaction
Newton’s Laws:

Newton Continued...

• 1687, Principia Published
• Law of Universal Gravitation (Attraction)

\[ F = \frac{m_1 m_2 G}{r^2} \]
Newton’s Laws:

Newton Continued...

- 1687, Principia Published
- Law of Universal Gravitation (Attraction)

\[ F = ma = \frac{m_2 v^2}{r} \quad \text{and} \quad F = \frac{m_1 m_2 G}{r^2} \]
Universal Gravitation, Applied:

• When in space why do you float? i.e. Weightlessness

\[ \frac{mV^2}{r} = \frac{MmG}{r^2} \]

\[ V = \sqrt{\frac{MG}{r}} \]
• 1600 A.D.
  Johannes Kepler
  • Used Tycho’s careful Mars observations to smash Aristotle theories
  • Presented 3 laws of planetary motion
  • Basis of understanding of spacecraft motion
  • However, “Why was not understood”
  • Calculus?
Kepler’s 3 Laws of Planetary Motion:

1. All planets move in **elliptical orbits**, sun at one focus
Kepler’s 3 Laws of Planetary Motion:

2. A line joining any planet to the sun, sweeps out equal areas in equal times
Kepler’s 3 Laws of Planetary Motion:

3. The square of the **period** of any planet about the sun is **proportional** to the cube of the of the planet’s mean **distance** from the sun.

\[ T^2 \alpha R^3 \]

\[ \frac{4\pi^2}{T^2} = \frac{GM}{R^3} \]

\[ T = 2\pi \sqrt{\frac{R^3}{\mu}} \]

<table>
<thead>
<tr>
<th>Planet</th>
<th>P (yr)</th>
<th>a (AU)</th>
<th>T^2</th>
<th>R^3</th>
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</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>0.24</td>
<td>0.39</td>
<td>0.06</td>
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<tr>
<td>Venus</td>
<td>0.62</td>
<td>0.72</td>
<td>0.39</td>
<td>0.37</td>
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<tr>
<td>Earth</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
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<tr>
<td>Mars</td>
<td>1.88</td>
<td>1.52</td>
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<tr>
<td>Jupiter</td>
<td>11.9</td>
<td>5.20</td>
<td>142</td>
<td>141</td>
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<tr>
<td>Saturn</td>
<td>29.5</td>
<td>9.54</td>
<td>870</td>
<td>868</td>
</tr>
</tbody>
</table>

*If you can observe the period of rotation, you can determine the distance*
Orbit History:

Gottfried Leibniz  

Isaac Newton
Kepler and Newton BFFs:

Kepler’s Laws...Orbits described by conic sections

Velocity of an orbit described by following equation

\[
v = \sqrt{\frac{2\mu}{r} - \frac{\mu}{a}}
\]

\(\mu = GM\)

For a circle (\(a=r\)): 
\[
v = \frac{\sqrt{(\mu)}}{r}
\]

For a ellipse (\(a>0\)): 
\[
v = \sqrt{\frac{2\mu}{r} - \frac{\mu}{a}}
\]

For a parabola (\(a=\infty\)): 
\[
v = \sqrt{\frac{2\mu}{r}}
\]
**Orbit Introduction:**

• Let’s figure it out...

$$v = \sqrt{\frac{GM}{R}}$$

- $v$ is velocity
- $G$ is Universal Gravitational Constant
- $M$ is mass of planet or satellite
- $R$ is radius of planet or satellite

$$G = 6.67 \times 10^{-11} \frac{m^3}{kg \cdot s^2}$$

$$M_{\text{Earth}} = 5.974 \times 10^{24} \text{ kg} \quad R_{\text{Earth}} = 6367000 \text{ m}$$

$$v_{\text{Earth}} = 7910 \frac{m}{s} = 17694 \text{ mph}$$
Orbit Introduction:

• On the moon?

\[ v = \sqrt{\frac{GM}{R}} \]

- \( v \) is velocity
- \( G \) is Universal Gravitational Constant
- \( M \) is mass of planet or satellite
- \( R \) is radius of planet or satellite

\[ G = 6.67 \times 10^{-11} \text{ m}^3/(\text{kg s}^2) \]

\[ M_{\text{Earth}} = 5.974 \times 10^{24} \text{ kg} \quad R_{\text{Earth}} = 6367000 \text{ m} \]
\[ M_{\text{Moon}} = 7.350 \times 10^{22} \text{ kg} \quad R_{\text{Moon}} = 1738000 \text{ m} \]

\[ v_{\text{Moon}} = 1679 \text{ m/s} = 3756 \text{ mph} \]
\[ v_{\text{Earth}} = 7910 \text{ m/s} = 17694 \text{ mph} \]
Circular Orbit:

For a 250 km circular Earth Orbit

 Orbital Velocity

\[ v = \sqrt{\frac{\mu}{r}} \]

\[ v = \sqrt{\frac{398600.4}{(250 + 6378.14)}} \]

\[ v = 7.75 \frac{km}{sec} = 17,347 \text{ mph} \]
Circular Orbit:

Orbital Period

\[ P^2 = a^3 \]

\[ P = \frac{\text{circumference}}{\text{velocity}} \]

\[ P = 2\pi \sqrt{\frac{r^3}{\mu}} \]

\[ P = 2\pi \sqrt{(250 + 6378.14)^3} \]

\[ P = 2\pi \sqrt{\frac{398600.4}{398600.4}} \]

\[ P = 5370 \text{ sec} = 89.5 \text{ min} \]
Circular Orbit:

For a 500 km circular Earth Orbit

Orbital Velocity

\[ v = \sqrt{\frac{\mu}{r}} \]

\[ v = \sqrt{\frac{398600.4}{(500 + 6378.14)}} \]

\[ v = 7.61 \frac{km}{sec} = 17,028 \text{ mph} \]
Circular Orbit:

For a 500 km circular Earth Orbit

Orbital Period

\[ P = 2\pi \sqrt{\frac{r^3}{\mu}} \]

\[ P = 2\pi \sqrt{\frac{(500 + 6378.14)^3}{398600.4}} \]

\[ P = 5,676 \text{ sec} = 94.6 \text{ min} \]

Conclusions???
Changing Orbits:

How about 250 km to 500 km

How would you do it?
Changing Orbits:

Changing orbits usually involves an elliptical orbit or Transfer Orbit

Perigee = close
Apogee = far

\[ \Delta v_1 = v_{per} - v_i \]
\[ \Delta v_2 = v_f - v_{apo} \]
Changing Orbits:

1) Velocity of initial orbit

\[ v_i = 7.75 \text{ km/sec} \]

2) Velocity of final orbit

\[ v_f = 7.61 \text{ km/sec} \]

3) Velocity at perigee

4) Velocity at apogee

\[ \Delta v_1 = v_{per} - v_i \]

\[ \Delta v_2 = v_f - v_{apo} \]
Changing Orbits:

Since orbit is elliptical at $V_{per}$ and $V_{apo} a > 0$, so

$$v = \sqrt{\frac{(2\mu)}{r} - \left(\frac{\mu}{a}\right)}$$

where

$$a = \frac{(r_1 + r_2)}{2}$$

$$a = \frac{((250 + 6378.14) + (500 + 6378.14))}{2}$$

$$a = 6753 \text{ km}$$
Changing Orbits:

So back to our $\Delta V$’s

3) Velocity at perigee

\[ v_{per} = \sqrt{\frac{2 \mu}{r}} - \left( \frac{\mu}{a} \right) \]

\[ v_{per} = \sqrt{\frac{(2 \times 398600.4)}{(250 + 6378.14)}} - \left( \frac{398600.4}{6753} \right) \]

\[ v_{per} = 7.83 \ \frac{km}{sec} \]
Changing Orbits:

So back to our $\Delta V$’s

4) Velocity at apogee

$$v_{per} = \sqrt{\frac{(2\mu)}{r} - \left(\frac{\mu}{a}\right)}$$

$$v_{per} = \sqrt{\frac{(2 \times 398600.4)}{(500 + 6378.14)} - \left(\frac{398600.4}{6753}\right)}$$

$$v_{per} = 7.54 \frac{km}{sec}$$
### Changing Orbits:

1) Velocity of initial orbit

\[ v_i = 7.75 \text{ km/sec} \]

2) Velocity of final orbit

\[ v_f = 7.61 \text{ km/sec} \]

3) Velocity at perigee

\[ v_{per} = 7.83 \text{ km/sec} \]

4) Velocity at apogee

\[ v_{apo} = 7.54 \text{ km/sec} \]

\[ \Delta v_1 = v_{per} - v_i \]

\[ \Delta v_2 = v_f - v_{apo} \]
Changing Orbits:

Therefore: \( \Delta V_1 \) is to start transfer

\[
\Delta v_1 = v_{\text{per}} - v_i
\]

\[
\Delta v_1 = 7.83 - 7.75
\]

\[
\Delta v_1 = 0.08 \frac{km}{sec}
\]

\[
\Delta v_1 = 178.9 \text{ mph}
\]
Changing Orbits:

$\Delta V_2$ is to circularize orbit

$\Delta v_2 = v_f - v_{apo}$

$\Delta v_2 = 7.61 - 7.54$

$\Delta v_2 = 0.07 \frac{km}{sec}$

$\Delta v_2 = 156.6 \text{ mph}$
Changing Orbits:

What if we did the whole thing in reverse?

Go from 500 to 250 km?

What happens to the answer?

\[
\Delta v_1 = v_{apo} - v_i \\
\Delta v_2 = v_f - v_{per}
\]
Changing Orbits:

1) Velocity of initial orbit
\[ v_i = 7.61 \text{ km/sec} \]

2) Velocity of final orbit
\[ v_f = 7.75 \text{ km/sec} \]

3) Velocity at perigee
\[ v_{per} = 7.83 \text{ km/sec} \]

4) Velocity at apogee
\[ v_{apo} = 7.54 \text{ km/sec} \]

\[ \Delta v_1 = v_{apo} - v_i \]
\[ \Delta v_2 = v_f - v_{per} \]
Changing Orbits:

Therefore:

$\Delta V_1$ is to start transfer

$\Delta v_1 = v_{apo} - v_i$

$\Delta v_1 = 7.54 - 7.61$

$\Delta v_1 = -0.07 \frac{km}{sec}$

$\Delta v_1 = -156.5 \text{ mph}$
Changing Orbits:

$\Delta V_2$ is to circularize orbit

$\Delta v_2 = v_f - v_{per}$

$\Delta v_2 = 7.75 - 7.83$

$\Delta v_2 = -0.08 \frac{km}{sec}$

$\Delta v_2 = -178.9 \text{ mph}$
Changing Orbits:

Time to do transfer is the same

\[ P = 2\pi \sqrt{\frac{a^3}{\mu}} \times 0.5 \]

\[ P = 2\pi \sqrt{\frac{(6753)^3}{398600.4}} \times 0.5 \]

\[ P = 2,761 \text{ sec} \]

\[ P = 46 \text{ min} \]
How well do you understand Hohmann Transfers?

• 1 to 2?
• 2 to 3?
• 3 to 1?
• 1 to 3?
Circular Orbit:
Changing Orbits:

Also something called “Fast Transfer”

• It is more direct and quicker

• However it takes more fuel

• $\Delta V_1$ and $\Delta V_2$ are much bigger
From Earth Orbit to the Moon:

• Same as changing orbits but....
  - At apogee you don’t have empty space
  - Instead, you have a large and massive object

• Gravity from this object can act as a $\Delta V$ against your spacecraft

• When going to the Moon the following could happen:
  1) Gravity will cause your spacecraft to crash into the surface
  2) Gravity will cause your spacecraft to zip off into space for a long time
Getting to the Moon:

- Gravity Assist

\[ \Delta v_1 \quad \Delta v_2 \]
One Minute Report…

Venus 1 Flyby
26 Apr 1998

Venus 2 Flyby
24 Jun 1999

Launch
15 Oct 1997

Earth Flyby
18 Aug 1999

Venus Targeting Maneuver
3 Dec 1998

Saturn Orbit Insertion
1 Jul 2004

Jupiter’s Orbit
11.8 Years

Jupiter Flyby
30 Dec 2000

Saturn’s Orbit
29.4 Years

Cassini’s speed related to Sun
Apollo XIII:

1. Liftoff, April 11, 1970, 3:13 p.m. CDT

2. Saturn V third stage propels Odyssey and Aquarius toward moon, April 11, 3:48 p.m.

3. Odyssey docks with Aquarius, pulling it from third stage, April 11, 5:14 p.m.

4. Odyssey fires engine to leave free-return trajectory, April 12, 7:53 p.m.

5. Oxygen tank two in Odyssey explodes, April 13, 9:07 p.m.

6. Aquarius fires engine to correct trajectory, April 15, 10:31 p.m.

7. Aquarius fires engine for PG-2 speed-up burn, April 14, 8:40 p.m.

8. Aquarius fires engine to return to free-return trajectory, April 14, 2:43 a.m.

9. Damaged service module jettisoned, April 17, 7:14 a.m.

10. Aquarius jettisoned, April 17, 10:43 a.m.

11. Odyssey splashes down, April 17, 12:07 p.m.
Apollo XIII:

1. Liftoff, April 11, 1970, 1:13 p.m. CST

2. Saturn V third stage propels Odyssey and Aquarius toward moon, April 11, 3:48 p.m.

3. Odyssey docks with Aquarius, pulling it from third stage, April 11, 5:14 p.m.

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Odyssey splashes down,
April 17, 12:07 p.m.

10
Aquarius jettisoned,
April 17, 10:43 a.m.

9
Damaged service module
jettisoned, April 17, 7:14 a.m.

1
Liftoff, April 11, 1970,
1:13 p.m. CST
So...

- One switch controls the light bulb
- Light bulb is on 2nd floor
- Can’t see it unless you go upstairs
- Can flip switches as many times
- Can go upstairs once

- Which switch is it?

- If you could go up twice, how would you do it?
- What does a light bulb do?
- Besides light?
- What about heat?
To the Moon for Money:
To the Moon for Money:

- Post lunar fly-by
- Earth perigee (42,000 km)
- May 16

- Trans-lunar injection
- May 7

- Final geosynchronous orbit (36,000 km)
- late May

- (214,000 km)
- April 28

- (321,000 km)
- May 4

- 5 ¾ days to moon
- 3 ¼ days return to Earth

- Perilune (8000 km) May 13
To the Moon for Money:
Earth to L1:

Lagrangian Points are orbits about an equilibrium point
There are 5 Lagrangian Points
Earth to L1:
Earth to Mars:

Initial Orbit → Earth Orbit → Transfer Orbit → Final Orbit

$\Delta v_1$ -> $\Delta v_2$
Earth to Beyond:

Say you are in a 250 km orbit...

Orbital Velocity:

$$v_i = 7.75 \frac{km}{sec}$$

$$v_i = 17,336 mph$$
Earth to Beyond:

Velocity on parabolic (a=∞) escape trajectory:

\[ v = \sqrt{\frac{2\mu}{r}} \]

\[ v_{esc} = \sqrt{\frac{2 \times 398600.4}{250 + 6378.14}} \]

\[ v_{esc} = 10.97 \frac{km}{sec} \]

\[ v_{esc} = 24,539 \text{ mph} \]

\[ \Delta v_{esc} = 3.22 \frac{km}{sec} \]
Earth to Beyond:

$\Delta V$ needed is…

$\Delta v_{esc} = v_{esc} - v_i$

$= 10.97 - 7.75$

$\Delta v_{esc} = 3.22 \frac{km}{sec}$

$\Delta v_{esc} = 7,202 \text{ mph}$
Questions?
Orbits:  
A Brief Historical Look

Arthur C. Clarke

Discovered This Orbit
Ancient Orbit History:

“ORBIT” from Latin word “orbita”
orbitus = circular; orbis = orb

• 1800 B.C.
  Stonehenge
    - Study of the vernal equinox
1500 B.C.: Egyptians and Babylonians

- Written evidence of stellar observations
- Solar Calendar of 365 days
- Time divided into 60 even units
350 B.C.: Greek Thoughts

Aristotle

- Said earth is center of the universe
- Dominated scientific thought for 1800 years
Start of the Heliocentric Model:

1543 A.D.

Nicholas Copernicus
  • Said Sun-centered rotations
  • Measurements crude but thinking shifts
  • Didn’t release findings until the end of his life
Orbit History:

• 1580 A.D.
  Tycho Brahe
  • Accurate measurements of planets (Mars) as a function of time
  • Even though telescope had not been invented
Orbit History:

• 1610 A.D.
  Galileo Galilei
  • Good friends with Copernicus
  • Observations with TELESCOPE reinforced
  • Discovered Venus has phases