Astronautics

- Introduction to space systems concepts
- Space environment
- Orbital mechanics
- Attitude dynamics and control
- Propulsion and launch vehicles
- Space law and policy
- Space industry
## Sample Space Applications

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<th>Navigation</th>
<th>Relay</th>
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Basic Elements of Space Missions

- **Subject** - the “thing” which interacts with or is sensed by the payload
- **Space segment** - spacecraft comprised of payload and spacecraft bus
- **Launch segment** - launch facilities, launch vehicle, upper stage. Constrains spacecraft size.
- **Orbit/constellation** - spacecraft’s trajectory or path through space
- **C³ Architecture** - command, control and communications
- **Ground segment** - fixed and mobile ground stations necessary for TT&C
- **Mission operations** - the people, policies and procedures occupying the ground (and possibly space) segments
Space segment

Payload

Bus

Ground Segment

Mission Operations

Orbit and Constellation

Launch Segment

Command, Control and Communications Architecture

Subject

Reference: Larson & Wertz, *Space Mission Analysis and Design*
Payload and Bus Subsystems

Basic requirements
- Payload must be pointed
- Payload must be operable
- Data must be transmitted to users
- Orbit must be maintained
- Payload must be "held together"
- Energy must be provided
Deep Space 1 Deployed
A-Train Formation

The A-Train

PARASOL 1:33
Aura 1:38
CALIPSO 1:31:15
CloudSat 1:31
Aqua 1:30
OCO 1:15
Encounter Configuration

- Low Gain Antenna
- Medium Gain Antenna
- High Gain Antenna
- Deployed Aerogel
- Open SRC
- Cometary & Interstellar Dust Analyzer
- Launch Vehicle Adapter
- Solar Arrays
In the LV
MESSENGER Vibration Test
Thoughts on Space
Some comments overhead at the Officer’s Club

• It’s a really big place with no air.

• There’s nothing out there, is there?

• How many g’s is that satellite pulling when the ground track makes those turns?

• Why can’t I have my spy satellite permanently positioned over Moscow?
Useful Characteristics of Space

- **Global perspective** or “There’s nothin’ there to block your view”
- **Above the atmosphere** or “There’s no air to mess up your view”
- **Gravity-free environment** or “In free-fall, you don’t notice the gravity”
- **Abundant resources** or “Eventually, we will mine the asteroids, collect more solar power, colonize the moon, . . .”
Amount of Earth that can be seen by a satellite is much greater than can be seen by an Earth-bound observer.

Low-Earth orbit is closer than you think.

Space isn't remote at all. It's only an hour's drive away if your car could go straight upwards.

— Fred Hoyle
A friend of mine once sent me a post card with a picture of the entire planet Earth taken from space. On the back it said, “Wish you were here.”

— Steven Wright

\[ IAA = K_A (1 - \cos \lambda) \]

\[ K_A = 2.55604187 \times 10^8 \text{ km}^2 \]

\[ \cos \lambda = \frac{R_e}{R_e + H} \]

Example: Space shuttle

\[ R_e = 6378 \text{ km} \]

\[ H = 300 \text{ km} \]

\[ \cos \lambda = 0.9551 \Rightarrow \lambda = 17.24^\circ \]

\[ IAA = 11,476,628 \text{ km}^2 \]
Above the Atmosphere

- This characteristic has several applications
  - Improved astronomical observations
  - “Vacuum” for manufacturing processes
  - Little or no drag to affect vehicle motion

- However, there really is “air” in space
  - Ionosphere affects communications signals
  - “Pressure” can contaminate some processes
  - Drag causes satellites to speed up (!) and orbits to decay, affecting lifetime of LEO satellites
Vacuum Effects

• While space is not a perfect vacuum, it is better than Earth-based facilities
  – 200 km altitude: pressure = $10^{-7}$ torr = $10^{-5}$ Pa
  – Goddard vacuum chambers: pressure = $10^{-7}$ torr

• Outgassing
  – affects structural characteristics
  – possibility of vapor condensation

Wake Shield Facility
(shuttle experiment)
Atmospheric Drag

- Can be modeled same as with “normal” atmospheric flight

\[ D = \frac{1}{2} C_D A \rho V^2 \]

\[ \rho \approx \rho_{SL} e^{-h/H} \]

- Key parameter is the “ballistic coefficient”:

\[ m/(C_D A) \]

- Larger ballistic coefficient (small massive satellite) implies slower orbital decay
- Smaller ballistic coefficient implies faster orbital decay
- Energy loss per orbit is \( \approx 2 \pi r D \)

Better not take a dog on the space shuttle, because if he sticks his head out when you're coming home his face might burn up. — Jack Handey
This illustration from Jules Verne’s *Round the Moon* shows the effects of “weightlessness” on the passengers of The Gun Club’s “bullet” capsule that was fired from a large gun in Florida.

The passengers only experienced this at the half-way point between the Earth and the Moon. Physically accurate?
This plot shows how gravity drops off as altitude increases. Note that at LEO, the gravitational acceleration is about 90% of that at Earth’s surface.
Microgravity

- Weightlessness, free fall, or zero-g
- Particles don’t settle out of solution, bubbles don’t rise, convection doesn’t occur
- Microgravity effects in LEO can be reduced to $10^{-1}$ g (1 µg)

On Earth, gravity-driven buoyant convection causes a candle flame to be teardrop-shaped (a) and carries soot to the flame's tip, making it yellow. In microgravity, where convective flows are absent, the flame is spherical, soot-free, and blue (b).
A Brief History of Orbital Mechanics

Aristotle (384-322 BC)
Ptolemy (87-150 AD)
Nicolaus Copernicus (1473-1543)
Tycho Brahe (1546-1601)
Johannes Kepler (1571-1630)
Galileo Galilei (1564-1642)
Sir Isaac Newton (1643-1727)
Kepler’s Laws

I. The orbit of each planet is an ellipse with the Sun at one focus.
II. The line joining the planet to the Sun sweeps out equal areas in equal times.
III. The square of the period of a planet’s orbit is proportional to the cube of its mean distance to the sun.
Kepler’s First Two Laws

I. The orbit of each planet is an ellipse with the Sun at one focus.

II. The line joining the planet to the Sun sweeps out equal areas in equal times.
Kepler’s Third Law

III. The square of the period of a planet’s orbit is proportional to the cube of its mean distance to the sun.

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

Here \( T \) is the period, \( a \) is the semimajor axis of the ellipse, and \( \mu \) is the gravitational parameter (depends on mass of central body)

\[ \mu_\oplus = GM_\oplus = 3.98601 \times 10^5 \text{ km}^3\text{s}^{-2} \]

\[ \mu_{\text{sun}} = GM_{\text{sun}} = 1.32715 \times 10^{11} \text{ km}^3\text{s}^{-2} \]
Earth Satellite Orbit Periods

<table>
<thead>
<tr>
<th>Orbit Altitude (km)</th>
<th>Period (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEO 300</td>
<td>90.52</td>
</tr>
<tr>
<td>LEO 400</td>
<td>92.56</td>
</tr>
<tr>
<td>MEO 3000</td>
<td>150.64</td>
</tr>
<tr>
<td>GPS 20232</td>
<td>720</td>
</tr>
<tr>
<td>GEO 35786</td>
<td>1436.07</td>
</tr>
</tbody>
</table>

You should be able to do these calculations! Don’t forget to add the radius of the Earth to the altitude to get the orbit radius.
For circular orbits, we commonly let the orbit radius be the distance unit (or DU) and select the time unit so that the period of the orbit is $2\pi$ TUs

$$T = 2\pi \sqrt{\frac{a^3}{\mu}}$$

Clearly these choices lead to a value of the gravitational parameter of

$$\mu = 1 \text{ DU}^3/\text{TU}^2$$

For the Earth’s orbit around the Sun, 1 DU = 1 AU ≈ 90,000,000 miles

What is the duration of 1 TU?
Examples

• The planet Saturn has an orbit radius of approximately 9.5 AU. What is its period in years?

• The GPS satellites orbit the Earth at an altitude of 20,200 km. What is the period of the orbit of a GPS satellite in minutes? …hours?

• The Hubble Space Telescope orbits the Earth at an altitude of 612 km. What is the period of the orbit in minutes? …hours?
Newton’s Laws

• **Kepler’s Laws** were based on observation data: “curve fits”

• **Newton** established the theory
  – Universal Gravitational Law
    \[ F_g = -\frac{GMm}{r^2} \]
  – Second Law
    \[ \vec{F} = m\ddot{\vec{r}} \]

**AOE 4134 Astromechanics** covers the formulation and solution of this problem
Elliptical Orbits

- Planets, comets, and asteroids orbit the Sun in ellipses
- Moons orbit the planets in ellipses
- Artificial satellites orbit the Earth in ellipses
- To understand orbits, you need to understand ellipses (and other conic sections)
- But first, let’s study circular orbits
  - a circle is a special case of an ellipse
Circular Orbits

- The speed of a satellite in a circular orbit depends on the radius
  \[ v_c = \sqrt{\frac{\mu}{r}} \]

- If an orbiting object at a particular radius has a speed \(< v_c\), then it is in an elliptical orbit with lower energy

- If an orbiting object at radius \(r\) has a speed \(> v_c\), then it is in a higher-energy orbit which may be elliptical, parabolic, or hyperbolic
Examples

• The Hubble Space Telescope orbits the Earth at an altitude of 612 km. What is its speed?

• The Space Station orbits the Earth at an altitude of 380 km. What is its speed?

• The Moon orbits the Earth with a period of approximately 28 days. What is its orbit radius? What is its speed?
The Energy of an Orbit

- Orbital energy is the sum of the kinetic energy, \( \frac{mv^2}{2} \), and the potential energy, \( -\frac{\mu m}{r} \).
- Customarily, we use the specific mechanical energy, \( E \) (i.e., the energy per unit mass of satellite)
  \[
  E = \frac{v^2}{2} - \frac{\mu}{r} \quad \Leftrightarrow \quad E = -\frac{\mu}{2a}
  \]
- From this definition of energy, we can develop the following facts
  
  \( E < 0 \quad \Leftrightarrow \quad \text{orbit is elliptical or circular} \)
  
  \( E = 0 \quad \Leftrightarrow \quad \text{orbit is parabolic} \)
  
  \( E > 0 \quad \Leftrightarrow \quad \text{orbit is hyperbolic} \)
Examples

• A satellite is observed to have altitude 500 km and velocity 7 km/s. What type of conic section is its trajectory?

• A satellite is observed to have altitude 380 km and velocity 11 km/s. What type of conic section is its trajectory?

• What type of trajectory do comets follow? Asteroids?
Conic Sections

Any conic section can be visualized as the intersection of a plane and a cone.

The intersection can be a circle, an ellipse, a parabola, or a hyperbola.
## Properties of Conic Sections

Conic sections are characterized by **eccentricity**, \( e \) (shape) and **semimajor axis**, \( a \) (size).

<table>
<thead>
<tr>
<th>Conic</th>
<th>( e )</th>
<th>( a )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circle</td>
<td>( e = 0 )</td>
<td>( a &gt; 0 )</td>
</tr>
<tr>
<td>Ellipse</td>
<td>( 0 &lt; e &lt; 1 )</td>
<td>( a &gt; 0 )</td>
</tr>
<tr>
<td>Parabola</td>
<td>( e = 1 )</td>
<td>( a = \infty )</td>
</tr>
<tr>
<td>Hyperbola</td>
<td>( e &gt; 1 )</td>
<td>( a &lt; 0 )</td>
</tr>
</tbody>
</table>
Properties of Ellipses

- $p = a(1 - e^2)$
- $r = ae$
- $2a - p$
- $a(1 + e)$
- $a(1 - e)$
Facts About Elliptical Orbits

- Periapsis is the closest point of the orbit to the central body
  \[ r_p = a(1-e) \]

- Apoapsis is the farthest point of the orbit from the central body
  \[ r_a = a(1+e) \]

- Velocity at any point is
  \[ v = (2E+2\mu/r)^{1/2} \]

- Escape velocity at any point is
  \[ v_{esc} = (2\mu/r)^{1/2} \]
Examples

• A satellite is observed to have altitude 500 km and velocity 7 km/s. What is its energy? What is its velocity at some later time when its altitude is 550 km?

• A satellite is in an Earth orbit with semimajor axis of 10,000 km and an eccentricity of 0.1. What is the speed at periapsis? ...at apoapsis?

• A Mars probe is in an Earth parking orbit with altitude 400 km. What is its velocity? What is its escape velocity? What change in velocity is required to achieve escape velocity?
Orbit is defined by 6 orbital elements (oe’s):

- semimajor axis, $a$;
- eccentricity, $e$;
- inclination, $i$;
- right ascension of ascending node, $\Omega$;
- argument of periapsis, $\omega$;
- and true anomaly, $\nu$
Orbital Elements (continued)

- Semimajor axis $a$ determines the size of the ellipse
- Eccentricity $e$ determines the shape of the ellipse
- Two-body problem
  - $a$, $e$, $i$, $\Omega$, and $\omega$ are constant
  - 6th orbital element is the angular measure of satellite motion in the orbit – 2 angles are commonly used:
    - True anomaly, $\nu$
    - Mean anomaly, $M$
- In reality, these elements are subject to various perturbations
  - Earth oblateness ($J_2$)
  - atmospheric drag
  - solar radiation pressure
  - gravitational attraction of other bodies
Ground Track

This plot is for a satellite in a nearly circular orbit.
Ground Track

This plot is for a satellite in a highly elliptical orbit

1997065B

longitude

latitude

0 60 120 180 240 300 360

−90 −60 −30 0 30 60 90

0 60 120 180 240 300 360

−90 −60 −30 0 30 60 90
Algorithm for SSP, Ground Track

- Compute position vector in ECI
- Determine Greenwich Sidereal Time $\theta_g$ at epoch, $\theta_{g0}$
- Latitude is $\delta_s = \sin^{-1}(r_3/r)$
- Longitude is $L_s = \tan^{-1}(r_2/r_1) - \theta_{g0}$

- Propagate position vector in “the usual way”
- Propagate GST using $\theta_g = \theta_{g0} + \omega_\oplus(t-t_0)$
  where $\omega_\oplus$ is the angular velocity of the Earth

Notes:
http://www.aoe.vt.edu/~chall/courses/aoe4134/sidereal.pdf
http://aa.usno.navy.mil/data/docs/WebMICA_2.html
Elevation angle, $\varepsilon$, is measured up from horizon to target.

Minimum elevation angle is typically based on the performance of an antenna or sensor.

IAA is determined by the same formula, but the Earth central angle, $\lambda$, is determined from the geometry shown.

The angle $\eta$ is called the nadir angle.

The angle $\rho$ is called the apparent Earth radius.

The range from satellite to target is denoted $D$. 
Geometry of Earth-Viewing

• Given altitude $H$, we can state
  \[
  \sin \rho = \cos \lambda_0 = \frac{R_\oplus}{(R_\oplus + H)}
  \]
  \[
  \rho + \lambda_0 = 90^\circ
  \]

• For a target with known position vector, $\lambda$ is easily computed
  \[
  \cos \lambda = \cos \delta_s \cos \delta_t \cos \Delta L + \sin \delta_s \sin \delta_t
  \]

• Then \( \tan \eta = \frac{\sin \rho \sin \lambda}{1 - \sin \rho \cos \lambda} \)

• And \( \eta + \lambda + \epsilon = 90^\circ \) and \( D = \frac{R_\oplus \sin \lambda}{\sin \eta} \)
Earth Oblateness Perturbations

• Earth is non-spherical, and to first approximation is an oblate spheroid
• The primary effects are on $\Omega$ and $\omega$:

$$\dot{\Omega} = \frac{3J_2 n R_e^2}{2a^2 (1 - e^2)^2} \cos i$$

$$\dot{\omega} = \frac{-3J_2 n R_e^2}{4a^2 (1 - e^2)^2} (4 - 5 \sin^2 i)$$

The Oblateness Coefficient

$$J_2 = -1.0826 \times 10^{-3}$$
Main Applications of $J_2$ Effects

- **Sun-synchronous orbits:**
The rate of change of $\Omega$ can be chosen so that the orbital plane maintains the same orientation with respect to the sun throughout the year.

- **Critical inclination orbits:**
The rate of change of $\omega$ can be made zero by selecting $i \approx 63.4^\circ$.
Sun-Synchronous Orbit

Orbit rotates to maintain same angle with sun
Basic Space Propulsion Concepts

• Three functions of space propulsion
  – place payload in orbit (launch vehicles)
  – transfer payload from one orbit to another (upper stages)
  – control spacecraft position and pointing direction (thrusters)

• Rockets provide a change in momentum according to the impulse-momentum form of Newton’s 2nd law:
  \[
  \vec{F}(t_2 - t_1) = \vec{p}_2 - \vec{p}_1 \iff \vec{F}\Delta t = \Delta \vec{p}
  \]
  – usually we talk about the change in velocity provided by a rocket — its “Delta Vee” \( \Delta \vec{V} \)
  – generally involves change in magnitude and direction
Thrust, Mass Flow Rate, & Exhaust Velocity

• The simplest model of thrust generated by a rocket is
  \[ F = -\dot{m}V_e \]
  \( \dot{m} \) is the rate at which propellant is ejected (negative)
  \( V_e \) is the exhaust velocity relative to the rocket

• An important performance measure is the **Specific Impulse**
  \[ I_{sp} = \frac{V_e}{g} \]
  \( I_{sp} \) has units of seconds
  – is the number of pounds of thrust for every pound of propellant burned in one second

• Using \( I_{sp} \) the thrust generated by a rocket is
  \[ F = -\dot{m}gI_{sp} \]

• The \( g \) that is used is ALWAYS the standard mean acceleration due to gravity at the Earth’s surface
Typical Functional Requirements

• Launch from Earth to LEO: \( \Delta V \approx 9.5 \) km/s
  – initial velocity is \( \approx 0 \)
  – LEO circular orbit velocity is \( v_c = \sqrt{\frac{\mu}{r}} \approx 7.7 \) km/s
  – add a bit for losses due to drag

• LEO-to-GEO orbit transfer: \( \Delta V \approx 4 \) km/s
  – use Hohmann transfer
  – perigee burn: \( \Delta v_1 \approx 2.4257 \) km/s
  – apogee burn: \( \Delta v_2 \approx 1.4667 \) km/s
Hohmann Transfer

- Initial LEO orbit has radius $r_1$, velocity $v_{c1}$
- Desired GEO orbit has radius $r_2$, velocity $v_{c2}$
- Impulsive $\Delta v$ is applied to get on geostationary transfer orbit (GTO) at perigee
  \[ \Delta v_1 = \sqrt{\frac{2\mu}{r_1}} - \sqrt{\frac{2\mu}{r_1 + r_2}} - \sqrt{\frac{\mu}{r_1}} \]
- Coast to apogee and apply another impulsive $\Delta v$
  \[ \Delta v_2 = \sqrt{\frac{\mu}{r_2}} - \sqrt{\frac{2\mu}{r_2}} - \frac{2\mu}{r_1 + r_2} \]
Other Typical Requirements

- **Orbit maintenance for GEO satellites**
  - East-West stationkeeping 3 to 6 m/s per year
  - North-South stationkeeping 45 to 55 m/s per year

- **Reentry for LEO satellites** 120 to 150 m/s

- **Attitude control typically requires 3-10% of the propellant mass**