Satellites and Space Probes
Space System Design, MAE 342, Princeton University
Robert Stengel

- Atmospheric science and meteorology satellites
- Earth resources satellites
- Navigation satellites
- Communications satellites
- Astronomy satellites
- Military satellites
- Satellite buses
- Lunar spacecraft
- Deep-space spacecraft

Atmospheric Science Satellites

- Mission
  - Determine properties of the near-earth environment
- Typical instrumentation
  - Direct measurements of the ionosphere
    - Density, temperature, ionic concentrations, cosmic radiation
  - Magnetic and electric fields
  - Multi-spectral transmission measurements through the lower layers
    - Radio
    - Light
- Spacecraft charging

Upper Atmospheric Research Satellite (UARS)

- September 1991 launch
- 10 instruments; 6 still operational in 2005
- 700-km orbit altitude
- 5,900 kg

Two UARS Instruments

- CLAES: nitrogen, chlorine, ozone, water, and methane from IR signature
- Etalon: Fabry-Perot interferometer measures light wavelengths
- IR radiometer: temperature, water vapor, nitrogen oxides, volcanic aerosols
Meteorology Satellites

- Mission
  - Determine global and local weather
- Geostationary Operational Environmental Satellites, Defense Meteorological Satellite Program spacecraft operated by NOAA
- Typical instrumentation
  - Multi-spectral imaging of the atmosphere
  - Data relay from buoys, search & rescue beacons
  - Solar monitoring

Earth Observation Satellites

- Mission
  - Determine properties of the earth’s land and water features
- Typical instrumentation
  - Multi-spectral imaging (e.g., Aqua)
    - Scanning radiometer
    - Spectroradiometer
    - Microwave sounding
    - Infrared sounding
    - Humidity sounding
    - Earth’s radiation budget
- Integration with meteorological satellites
- Commercial and research operators
- High-resolution optical imagery

GOES Coverage Emphasizes the Western Hemisphere

Earth Observing Constellation

- Earth Observing System combines data from formation of satellites
- Successors to UARS
- Studying ozone, air quality, and climate
  - High-resolution dynamics limb sounder
  - Microwave limb sounder
  - Ozone monitoring instrument
  - Tropospheric emission spectrometer
- “A-Train” constellation also includes multi-national Cloudsat, Calipso, Metop-1, and Parasol satellites
Navigation Satellites

- **Mission**
  - Aid position and velocity determination
- **Global Positioning System (GPS) Implementation**
  - 24 satellites (minimum) in circular, medium earth orbit
  - 6 orbital planes, 55° inclination
  - Atomic clocks provide precise time reference
  - Broadcast ephemeris (i.e., orbital elements)
  - Pseudo-random pulse code
- **GLONASS, Galileo, Compass, DORIS, IRNSS, QZSS**

Communication Satellites

- **Mission**
  - Facilitate global communications
- **Implementation**
  - Transponders with dedicated coverage areas
  - Most satellites are in geosynchronous orbit
  - Iridium constellation of 66 satellites in low earth orbit
  - Direct connection from satellite to phone

Geosynchronous Communication Satellites in Orbit, June 2006

Astronomy Satellites: Hubble

- **Mission**
  - Conduct astronomical observations outside the earth’s atmosphere
- **Typical instrumentation**
  - Multi-spectral imaging
  - Hubble Telescope serviced by Space Shuttle missions (590-km orbit)
  - Telescope aberration repaired by astronauts
Astronomy Satellites

- Chandra X-ray observatory (Shuttle launch, 1999)
- James Webb Infrared Telescope to be located at L2 Lagrange point

Military Satellites

- Missions
  - Secure observations from space
  - Early warning
  - Reconnaissance
  - Intelligence
  - Communications
  - Navigation
  - Weather
  - Weaponry

Satellite Buses

- Standardization of common components for a variety of missions

- Bus reliability analysis
  - [http://www.satelliteonthenet.co.uk/white/frost3.html](http://www.satelliteonthenet.co.uk/white/frost3.html)
In-plane Parameters of Earth Escape Trajectories

- Dimensions of the orbit
  \[ p = \frac{h^2}{\mu} \]  
  \( h \) = Angular momentum about center of mass
  \[ \varepsilon = \sqrt{1 + \frac{2Ep}{\mu}} \]  
  Eccentricity \( \varepsilon \leq 1 \)
  \( E \) = Specific energy
  \[ a = \frac{p}{1-e^2} \]  
  Semi-major axis
  \( r_{\text{perigee}} = a(1-e) \) = Perigee radius

Solar Orbits

- Same equations used for earth-referenced orbits
  - Dimensions of the orbit
  - Position and velocity of the spacecraft
  - Period of elliptical orbits
  - Different gravitational constant

\[ \mu_{\text{Sun}} = 1.3327 \times 10^{11} \text{km}^3/\text{s}^2 \]

Transfer Orbits and Spheres of Influence

- Sphere of influence (Laplace):
  Radius within which gravitational effects of planet (or moon) are more significant than those of the sun (or moon’s planet)

- Patched-conic section planning
  - Transfer orbit outside of spheres of influence computed in heliocentric frame of reference
  - Trajectory within departure planet’s sphere of influence is computed with respect to planet’s frame

- Fly-by trajectories dip into intermediate object’s sphere of influence for gravity assist

- Orbits are conic sections
Launch Opportunities for Fixed Transit Time: The Synodic Period

- **Synodic Period, \( S \):** The time between conjunctions
  - \( P_A \): Period of Planet A
  - \( P_B \): Period of Planet B
- **Conjunction:** Two planets, \( A \) and \( B \), in a line or at some fixed angle

\[
S = \frac{P_A P_B}{P_A - P_B}
\]

<table>
<thead>
<tr>
<th>Planet</th>
<th>Synodic Period with respect to Earth, days</th>
<th>Period</th>
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</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>116</td>
<td>88 days</td>
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<tr>
<td>Venus</td>
<td>584</td>
<td>225 days</td>
</tr>
<tr>
<td>Earth</td>
<td>-</td>
<td>365 days</td>
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<tr>
<td>Mars</td>
<td>780</td>
<td>667 days</td>
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<tr>
<td>Jupiter</td>
<td>399</td>
<td>11.9 yr</td>
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<tr>
<td>Saturn</td>
<td>378</td>
<td>29.5 yr</td>
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<tr>
<td>Uranus</td>
<td>370</td>
<td>84 yr</td>
</tr>
<tr>
<td>Neptune</td>
<td>367</td>
<td>165 yr</td>
</tr>
<tr>
<td>Pluto</td>
<td>367</td>
<td>248 yr</td>
</tr>
</tbody>
</table>

Swing-By/Fly-By Trajectories

- **Hyperbolic encounters:** With planets and the moon provide gravity assist
  - Shape, energy, and duration of transfer orbit altered
  - Potentially large reduction in rocket \( \Delta V \) required to accomplish mission

Hyperbolic Encounter

- **Probe trajectory:** Gains or loses energy (wrt Sun) within the Sphere of Influence
- **Trajectory:** Deflected by target planet’s gravitational field
  - In-plane
  - Out-of-plane

Effect of Target Planet’s Gravity on Probe’s Velocity
**MESSENGER Fly-By Trajectories**

- MESSENGER mission
  - [http://www.youtube.com/watch?v=y-GALKLHY-s](http://www.youtube.com/watch?v=y-GALKLHY-s)

**Lunar Trajectories**

- Transfer orbit may be elliptic wrt Earth
- Travel time reduced for parabolic or hyperbolic transfer

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**Michielsen Chart for Lunar Encounter**

*(Kaplan, Modern Spacecraft Dynamics and Control, 1976)*

- Orbital velocity of the moon (wrt earth), $v_e \approx 1$ km/s, $v_r \approx 0$
- Probe’s approach $v_p$ and $v_r$ specified by transfer trajectory
- Probe’s approach deflection angle, $\delta$, specified by moon-relative hyperbolic trajectory
- Vector triangles predict probe’s departure velocity vector
- Transfer time to moon shown
- “Earth intercept zone” connotes return to earth without thrusting maneuver
- Earth escape also possible
**Apollo Free-Return Trajectory**

- Trajectories to lunar orbit or landing typically pass in front of the moon
- Thrusting maneuver on the far side required for lunar orbit or landing
- With proper approach velocity, trajectory is deflected to Figure 8 pattern for “free return”

**Early Lunar Spacecraft**

- Mission
  - Scientific discovery
  - Preparations for human voyages to the moon
- Robotic exploration of the moon

**Lunar Spacecraft**

- Lunar spacecraft launched by US, ESA, Russia, and Japan
- Future launches planned by China, Germany, and India

**Inner-Solar-System Spacecraft**

- Examples
  - MESSENGER (2004-2011)
    - Three fly-bys of Mercury beginning in 2008
    - Orbit Mercury for 1 year, 200 x 15,193 km
    - Image entire surface of Mercury
    - Characterize surface chemistry, geology, and magnetic field
  - Venus Express (ESA, 2006)
    - In orbit about Venus
    - Multi-spectral surface mapping
    - Measurements of interactions between solar wind and Venusian atmosphere, magnetic field, and temperature profile
Genesis Spacecraft

- Genesis Solar Wind Sample Return
  - Launch: August 2001
  - Return: September 2004 (parachute did not open)

Stardust Spacecraft

- Stardust Wild 2 Comet Tail Sample Return
  - Launch: February 1999
  - Return: January 2006

Mars Orbiters and Landers

- Mission
  - Determine physical characteristics
  - Search for life
  - Prepare for human exploration

Mars Rovers

- Mission
  - Scientific discovery
  - Search for life
  - Prepare for human exploration
- Sojourner
- Mars Exploration Rovers
  - http://www.youtube.com/watch?v=O74DxtrWkg
- Mars Science Laboratory
  - http://www.youtube.com/watch?v=noy8o0lN1fE
The Outer-Solar System and Beyond

- Asteroid Belt
- Kuiper Belt
- Oort Cloud
- Rock and metals
- Between Mars and Jupiter
- Water, ammonia, and methane
- Beyond Neptune
- Postulated home of comets
- > 50,000 AU

Galileo’s Asteroid Images

- Gaspra
- Ida and Dactyl

Outer-Solar-System Spacecraft: Galileo

- Mission
  - Explore Jupiter and its moons
  - Probe Jupiter’s atmosphere
  - Launch: October 1989 (Space Shuttle, boosted by Boeing Inertial Upper Stage)
  - Two Earth fly-bys, one Venus fly-by
  - Jupiter arrival: December 1995
- Mission terminated by 50-km/s descent into Jupiter’s atmosphere: September 2003
- First asteroid fly-by (951 Gaspra)
- Discovered first moon of an asteroid (Ida and Dactyl)
- Mass = 2,380 kg
**Galileo’s Probe**

- Mission:
  - Explore Saturn, its rings, and its moons
  - Launch: October 1997 (Titan 4B/Centaur)
  - Two Earth fly-bys, one Venus fly-by
  - Saturn arrival: July 2004
  - Huygens Probe entered atmosphere of Saturn’s moon Titan in January 2005
  - $3.26B mission


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**Outer-Solar-System Spacecraft: Cassini**

- Cassini’s Huygens Probe and Moon Images:
  - Titan
  - Hyperion
  - Tethys
  - Phoebe

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**Outer-Solar-System Spacecraft: Cassini**

- Mission:
  - Explore Saturn, its rings, and its moons
  - Launch: October 1997 (Titan 4B/Centaur)
  - Two Earth fly-bys, one Venus fly-by
  - Saturn arrival: July 2004
  - Huygens Probe entered atmosphere of Saturn’s moon Titan in January 2005
  - $3.26B mission

Outer-Solar-System Spacecraft: New Horizons

- Destination: Pluto and its moons
- Radioisotope thermal power generator
- Spin-stabilized in cruise, 3-axis control (hydrazine RCS) for science
- May also fly by Kuiper Belt objects, Trojan asteroids at Neptune’s L5 point
- Fastest spacecraft to date ($V_{\text{earth}} = 16.21 \text{ km/s}$, Atlas 5)
- 546,700-kg initial mass
- Payload = 478 kg
- Jupiter fly-by adds 4 km/s to speed

Next Time:
Spacecraft Structures

Outer-Solar-System Spacecraft: Dawn

- Destination: Will orbit both Vesta and Ceres ("proto-planets"), transit asteroid belt
- Ion thrusters provide $\Delta V$ of 13 km/s
- Mass = 1,285 kg