RADIOMETRIC TRACKING
Space Navigation
Space Navigation Elements

• SC orbit determination
  • Knowledge and prediction of SC position & velocity
• SC flight path control
  • Firing the attitude control thrusters to alter SC state vector (p, v, t)
• How do you know when, and by how much, to alter SC velocity vector?
  • Compare derived SC trajectory with destination object
  • Compare SC trajectory to destination object trajectory
Why Do We Need The Data?

• Don’t SC usually travel along conic sections?
• Two complicating factors
  • Orbits can be perturbed by:
    • Solar pressure
    • Gas leaks
    • Thruster firings
    • Gravity fields, etc.
  • The 3-D state of the SC must be inferred from measurements barely more than 1-D
What Can Be Measured From Earth?

• SC distance from earth (range)
• SC velocity component directly toward or away from Earth
• SC position in the earth’s sky
• Some SC have optical instruments
  • Allows ground to view destination object with background of stars
• Nav predictions aid ground station in locating and tracking the SC
**Navigation Process**

**Iterative process**

**Ephemeris**: list of successive locations of a planet, satellite, or spacecraft.
• The Celestial Sphere
  • Infinite radius
  • Center of the earth is the center of the Celestial Sphere
  • Sphere’s poles and equatorial plane are coincident with the earth’s
  • **Zenith**: point on the Celestial Sphere directly overhead an observer
  • **Nadir**: direction opposite zenith
  • **Meridian**: arc passing through the celestial poles and Zenith

• The Ecliptic Plane
  • Plane in which earth orbits the sun

\[ 23.4° \]
• **Declination (DEC)**
  - Celestial sphere’s equivalent of latitude
  - Expressed in degrees
    - + and – refer to north and south
    - Celestial equator is 0° DEC
    - Poles are +90° and -90°

• **Right Ascension (RA)**
  - Celestial equivalent of longitude
  - Specified in hours, minutes, and seconds
  - An hour of RA is 15° of sky rotation
  - **RA zero point**
    - Where ecliptic circle intersects the equatorial circle
    - Where the sun crosses into the northern hemisphere; i.e., vernal equinox
• Unfortunately, the intersection of the earth’s equator and the ecliptic gradually moves with time
  • Vernal equinox is defined as a specific date
    • 12:00 January 1, 2000 or Julian date 2451545.0
    • J2000
• For improved accuracy, it’s become much more complex
  • Celestial reference frame defined by the position of quasars in the International Celestial Reference Frame (ICRF)
• Fortunately, we are going to ignore this inconvenience
Telecommunications

- KPFK on Mt. Wilson 20 km from LA: 112 kW @ 90.7 MHz
- Typical SC might have only 20 W to cover billions of km
  - Signal decreases as $1/R^4$
  - Concentrate power into a narrow beam
  - Cassegrain dish high-gain antenna (HGA)
  - 20 W transmitter with a 47-dbi gain HGA
    - Effective power of 1 MW along highly directional beam
- No significant sources of noise in space
- DSN provides up to 74 dbi gain at X-band
  - Cryogenically-cooled low-noise amps, receivers, software
  - Extract data from vanishingly small signals
• Unless it is bent by a gravitational field, electromagnetic radiation travels through space in a straight line

• Objective of antenna design
  • Focus incoming microwave energy from a large area into a narrow beam
  • Concentrated energy is then collected into a receiver

Early Dish Design  Cassegrain Design
Antenna Applications

- **Antenna design must accommodate**
  - Mission coverage
  - Orbital parameters
  - Attitude control characteristics
  - Bit rate requirements

- **Key tradeoffs**
  - Beamwidth, gain, and effective aperture (size)
  - Narrow-beam antenna: high gain and large size
  - Broad-beam antenna: low gain and small size
Antennas

- **Gain**: power density radiated along the bore sight relative to an isotropic radiator
- An isotropic radiator is a point source that radiates equally in all directions. \( G = 0 \)
- **Gain equation**

\[
G = \eta \frac{4\pi f^2 A}{c^2} = \eta \left( \frac{\pi f D}{c} \right)^2 = \eta \left( \frac{\pi D}{\lambda} \right)^2
\]

\[
G = 10 \log(\eta) + 20 \log(D) + 20 \log(f) + 20 \log\left(\frac{\pi}{c}\right)
\]

or

\[
G = 10 \log(\eta) + 20 \log(D) - 20 \log(\lambda) + 20 \log(\pi)
\]

- \( f \) = transmission frequency
- \( D \) = antenna diameter
- \( c \) = speed of light \((3 \times 10^8 \text{ m/s})\)
- \( \lambda = c/f \) = wavelength
- \( \eta \approx \text{Antenna efficiency (0.50–0.80)} \)
Antennas

• Consider a transmission power level $P_t$, antenna gain $= G_t$
• Receiver is $R$ meters away
• $F = \text{Flux density} = \text{power per unit area (W/m}^2\text{)}$
• Transmitter produces a spherically expanding wave front that arrives at the receiving antenna with the flux density:

$$F = \frac{G_t P_t}{4 \pi R^2}$$

• At the receiver
  • Antenna has physical area $A_r$ and effective area $A_e = \eta A_r$
  • Gain at the receiving antenna: $G_r = \eta \frac{4 \pi f^2 A}{c^2} = \frac{4 \pi A e}{\lambda^2} \quad \lambda = \frac{c}{f}$
  • Total received power: $P_r = FA_e = P_t G_t G_r \left(\frac{\lambda}{4 \pi R}\right)^2$ Friis Transmission Equation
Antennas

• In practice, specify the **gain** or **area** of transmitter and receiver

\[ P_r = P_t \left( \frac{1}{\lambda R} \right)^2 A_r A_t \]  
both areas are fixed

\[ P_r = P_t \left( \frac{1}{4\pi R^2} \right) A_r G_t \]  
receiver area and transmitter gain fixed

\[ P_r = P_t \left( \frac{1}{4\pi R^2} \right) G_r A_t \]  
receiver gain and transmitter area fixed

• Path loss = \( \left( \frac{4\pi R}{\lambda} \right)^2 \)  
dilution of the transmitted energy

• \[ P_r = P_t G_t \frac{G_r}{PATH \ LOSS} \]

• \( P_t G_t \equiv \text{EIRP} \) (Effective Isotropic Radiated Power)
• Isotropic antenna radiates equally in all directions
  • Gain = 0
  • Does not exist
• Steradian
  • 3-D radian
  • Area = $r^2$
• Sphere
  • Sphere surface area = $4\pi r$
  • $4\pi r^2/r^2 = 4\pi \text{ sr}$ on a sphere
  • $\text{sr} = (180/\pi)^2 = 3282.8 \text{ deg}^2$
• $G\theta^2 = 2.6\pi(3282.8) = 27,000$
  • $\theta = 70 \lambda/D$
Spacecraft Velocity Measurement

- Based on the Doppler shift phenomenon
  - Toward you
    - Light shifts to shorter wavelengths
      - Blue Shift
  - Away from you
    - Light shifts to longer wavelengths
      - Red Shift

- Computing radial component of SC’s earth-relative velocity
  - Measure the Doppler shift of a coherent downlink carrier
  - Hydrogen-maser-based frequency standard
    - Generates a very stable uplink frequency for the SC to use
    - SC receives stable uplink, multiplies that frequency by a constant
    - That becomes SC’s stable downlink frequency
What is a Coherent Downlink?

- **Uplink**: radio signals from Earth to SC
- **Downlink**: radio signals from SC to Earth
- **Carrier**: a pure RF tone used in uplink/downlink signals
  - Uplink: Very stable
  - Downlink: difficult for SC to maintain stable carrier
- Carrier can be “modulated” to carry information
- Used for SC tracking and navigation
  - Ground sends very stable carrier signal to SC
  - SC multiplies the uplink frequency by a predetermined constant
  - Uses that value to generate a **coherent** downlink frequency
Spacecraft Distance Measurement

• A ranging pulse is added to the uplink
  • Transmission time recorded
    • The time to go from ground computers to antenna is known
  • SC receives pulse to the ground
    • The time it takes to turn the pulse around is known
    • Returns the pulse to the ground
  • On the ground, elapsed time is computed in light speed
  • Corrections applied for atmospheric effects
  • Range computed:
    • Speed of light $\times$ elapsed time
Angular Location of the SC

- Position in the sky is expressed by **Right Ascension** and **Declination**
- Ground antenna pointing may be accurate to thousandths of a degree
  - not good enough
- **Very Long Baseline Interferometry: VLBI**
  - Independent of Doppler and range
  - Two ground stations far apart track same SC simultaneously
  - Each makes high speed recordings of downlink wave fronts and timing data
  - After a few minutes, both antennas slew to a quasar
    - Recordings are made of the quasar’s radio-noise wave fronts
    - Analysis yields a precise triangulation – quasar’s RA and DEC are known
    - SC position determined by comparison to the RA and DEC of the quasar

“delta DOR”
DOR=differenced one-way ranging
Figure 4.3-3 Example of a functional flow block diagram