Interplanetary Navigation

Examples from the Cassini/Huygens Mission

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Agenda

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  - Objectives
  - Functions
- Trajectory Design
  - Direct versus Indirect Trajectories
  - Flybys versus orbiters
- Estimation
  - General Techniques
  - Measurements
  - Models
  - Typical Results
- Control
  - General Techniques
  - Propulsion/Control Systems
  - Navigation Simulation
  - Typical Results
Overview

• Navigation Objective: Delivery instrument fields of view to the desired location subject to the constraints of the spacecraft and ground system design.

• Support the design of the reference trajectory
  • The reference trajectory provides a “road map” for the execution of the mission
  • Estimate the “state” at all times during the mission
    • “State” may include:
      • spacecraft state,
      • satellite ephemerides,
      • satellite masses,
      • model parameters
  • Control the mission trajectory
Task Phases

• Planning and Prediction
  • Planning the trajectory
  • Defining the navigation strategy
  • Prediction of the capabilities (Accuracy, propellant,…)

• Execution
  • Collecting the measurements
  • Processing the measurements and estimating the model parameters
  • Correcting the trajectory

• Reconstruction
  • After the fact estimating where the spacecraft has been and the associated model parameters
Trajectory Design

• Objective: Find a trajectory which meets the scientific objectives within the capability of the launch vehicle and the spacecraft.

• Considerations:
  
  • Launch Window - The duration of the time interval that launch can occur
    • Can vary from instaneous to hours
      • Cassini’s daily launch window varied from 5 minutes to 140 minutes
  
  • Launch Period - The number of days during which a launch can occur
    • Cassini’s launch period for the primary mission was about 1 month.

  • Launch Opportunities - The number of available launch periods
    • Cassini identified 3 separate launch periods. Significant variations in the fundamental trajectory for different launch opportunities
Trajectory Design (Continued)

• Direct versus Gravity Assist Trajectories

  • Direct trajectories proceed from launch to their target with only propulsive maneuvers to modify the flight path
    
    • Minimizes the transfer time (cost) from launch to the target.
    
    • Gravity assist trajectories use the “sling shot” effect to change (increase or decrease) the orbital energy and inclination.
      
      • Maximizes the payload capability at the expense of time.
        
        • Cassini used two Venus flybys, one Earth flyby and one Saturn flyby to increase the orbital energy by 21 km$^2$/sec$^2$, but took 6.7 years to reach Saturn
          
          • Voyagers 1 & 2 used a direct trajectory that took about 4.1 to reach Jupiter

• Low Thrust Trajectories

  • Use low thrust - high impulse to decrease transfer time and/or increase payload
B-Plane
Flyby Geometry

- Inbound \( v \) infinity
- Turn angle = 60 degrees
- Delta \( v \)
- Outbound \( v \) infinity
- Flyby Hyperbola
- Flyby Body

2/26/07
Gravity Assist

Changing an orbit parameters without propellant

\[ V_p = "Planet" \_ Velocity \]
\[ V^- = Spacecraft \_ velocity \_ before \_ the \_ flyby \]
\[ V^-_\infty = Asymptotic \_ velocity \_ before \_ the \_ flyby \]
\[ V^+ = Asymptotic \_ velocity \_ after \_ the \_ flyby \]
\[ V^+ = Spacecraft \_ velocity \_ after \_ the \_ flyby \]
\[ \delta = Turn \_ angle \_ during \_ the \_ flyby \]
\[ \Delta V = velocity \_ change \]

\[ \Delta V = 2V_{\infty} \sin(\delta/2) \]
\[ \sin(\delta/2) = \frac{1}{e} \]
\[ e = 1 + \frac{r_p V^2_{\infty}}{\mu} \]

Question: Where did the energy change come from?
Cassini Interplanetary Trajectory

VENUS FLYBY
26 APR 1998

VENUS FLYBY
24 JUN 1999

DEEP SPACE MANEUVER
3 DEC 1998

JUPITER FLYBY
30 DEC 2000

LAUNCH
15 OCT 1997

EARTH FLYBY
18 AUG 1999

 Orbit of Jupiter

SATURN ARRIVAL
1 JUL 2004

Phoebe
11 JUN 2004