Interplanetary Navigation
Past, Present and Future

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What is it?

• Trajectory Design
  – Where do we want to go?

• Orbit Determination
  – Where are we actually going?

• Maneuver Design and Execution
  – Fix it!
Orbit Determination

• Data Types
  – Range
  – Doppler (range-rate)
  – Δ-DOR
  – Optical

• Mathematical Models
  – Solar System
  – Spacecraft Trajectory
  – Non-gravitational effects
    • Solar radiation pressure
    • Maneuvers
    • Attitude Control
    • Etc.
\[ \rho_1 - \rho_2 = B \cos \theta \]

- **Station-differenced range and range-rate** provide an instantaneous, geometric measure of angular position and velocity components.

- **Difference range:** \[ \rho_1 - \rho_2 \rightarrow \theta \]
- **Difference Doppler:** \[ \dot{\rho}_1 - \dot{\rho}_2 \rightarrow \dot{\theta} \]

**Angular accuracy**: \( \propto \) measurement delay accuracy / baseline length.
Optical

- TO EARTH
- OPTICAL SYSTEM MEASURES
- OPTICAL NAV FRAME OF TARGET AND KNOWN STAR
- PREDICTED TARGET LOCATION
- OBSERVED TARGET LOCATION
- STAR IS AT "INFINITY"
- FLIGHT PATH
Past Missions

**Successes**
- Early Moon, Mars, Venus, Mercury, Outer Solar System
  - Explorers, Pioneers, Rangers, Mariners, Surveyors, Viking, Magellan
- Galileo (Jupiter) (‘89)
- Mars (‘96)
  - MGS
  - Pathfinder
- Deep Space 1 (Tech Demo – Ion Engines) (‘98)
- Stardust (Comet Wild-2 and return) (‘99)
- Genesis (Earth-Sun L1 and return) (‘01)
- Deep Impact (Comet Tempel-1 !) (‘05)

**Failures**
- Early Moon
  - Explorers, Pioneers, Rangers
- Mars Observer (‘92)
- Mars Climate Orbiter (‘98)
- Deep Space 2 (‘99)
- Mars Polar Lander (‘99)
Galileo Satellite Tour

Orbital Tour of the Jupiter System

I = Io
E = Europa
G = Ganymede
C = Callisto

--- Previous Design Orbit

R_J = 71,492 km

G1 27 Jun 96
G2 6 Sep 96
C3 4 Nov 96
E4 19 Dec 96
E6 20 Feb 97
G7 5 Apr 97
G8 7 May 97
C9 25 Jun 97
C10 17 Sep 97
E11 6 Nov 97
Genesis

Genesis Mission Trajectory: 2001 — 2004

LOI = Lissajous Orbit Insertion Maneuver
(11/16/01)
Genesis is on a “free” return to Earth from this point on.

Launch 8/8/01 - Return 9/8/04
Total Flight Time
(37.6 mos.)
Earth Return (Genesis and Stardust)

SRC Landing Site

22.6 x 61.2 km² (3σ)
Current Missions

- Voyager (‘77)
  - “Grand Tour” of outer planets
  - Heliopause and beyond
- Ulysses Solar Polar (‘90)
  - Solar Poles via Jupiter
- Cassini-Huygens (‘97)
  - Saturn System
- Mars Odyssey (‘01)
- Mars Exploration Rovers (‘03)
  - Spirit and Opportunity
- Spitzer Space Telescope (‘03)
  - “Drift-Away” orbit
- Mars Reconnaissance Orbiter (‘05)
- Phoenix (Mars ‘07)
  - Polar Lander
- Dawn (‘07)
  - Low Thrust Ion Engines
  - Orbit Vesta in 2011, Orbit Ceres in 2015
- Stardust-NExT and EPOXI
  - “Recycled” Stardust and Deep Impact spacecraft busses
Cassini as an Example

- Interplanetary
- Tour
- Icy Satellites
- Navigation Techniques
- “On-the-fly” Changes
- Lessons
Cassini - Interplanetary Trajectory
Initial Cassini Orbits
# Cassini Mission Overview

## Year of Tour Orbits
<table>
<thead>
<tr>
<th>Year</th>
<th>Orbits</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>11</td>
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<tr>
<td>2</td>
<td>15</td>
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<tr>
<td>3</td>
<td>22</td>
</tr>
<tr>
<td>4</td>
<td>27</td>
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## Titan
- *Huygens*

## Enceladus
- Phoebe

## Other Icy Satellites (under 10,000 km)
- Tethys
- Hyperion
- Dione
- Telesto
- Rhea

- Rhea
- Iapetus
- Epimetheus

## Views
- **View From Saturn North Pole**
- **View From Sun**
Science Tweaks (2)

- Moved Stellar Occultation of Iapetus away from closest approach to free up time for close-in imaging
- Tweaked groundtrack closer to equatorial ridge
- Added distant stellar occultation through Enceladus plumes
Science Tweaks (3)

070918

- E3 altitude changes through many reference updates
  - 1000 km \(\rightarrow\) 100 km \(\rightarrow\) 25 km \(\rightarrow\) 50 km
- This update set altitude to 50 km so as to confirm plume debris models
- There will be 25 km flybys in the extended mission
Lessons For Future Missions

• Exploration means the discovery of new risks

• New discoveries mean new places to look

• A capable spacecraft is even more capable with flexible operations

Cassini’s Successor:
http://opfm.jpl.nasa.gov/
Navigation Benefit
• Cassini Prime Mission successfully navigated!
  – Enceladus 50 km flyby successful
    • Achieved error of 0.9 km altitude error
    • Confidence for
      – 50 km E4 on Aug 11
      – 25 km E5 on Oct 9
  • Titan Encounters
    – 23 of 34 < 1 km error
    – 9 of these < 500 m error
    – Saturn and satellite masses determined < 0.2%
Mars Examples

- MER
- MRO
- Phoenix
Mars Exploration Rovers
Mars Reconnaissance Orbiter
More Phoenix Landing

Contour for Meeting the Final Maneuver Criteria on the Phoenix Certified Safe Zone Map

- Phoenix Landing Site
- Target

**Location Coordinates:**
- Lat: 67.387
- Lon: 238.003
Dawn Interplanetary
Dawn – Vesta Arrival

Survey Orbit Injection
September 10, 2011 21:35:18
Mass 961.8381 [kg]
Energy(Vesta) $-0.0030$ [km$^2$/s$^2$]

Survey Orbit End
September 24, 2011 21:35:18
Mass 961.8381 [kg]
Energy(Vesta) $-0.0030$ [km$^2$/s$^2$]

Capture Vesta
August 27, 2011 19:33:20
Mass 963.9240 [kg]
Radius 17352.37 [km]
Future Technology - AutoGNC

• Advancement of AutoNav
  – Performed an onboard autonomous navigation function
    • Uses target body images
    • Processed onboard
    • Computes spacecraft/target relative position and orientation
  – Used on Deep Space 1, Stardust, and Deep Impact
    • AutoNav corrected spacecraft trajectory onboard for both DS1 and DI (guided impactor to collision)
  – Captured all NASA close-up images of comets

• Future Mission Requirements
  – Surface feature recognition
  – Integrated navigation, guidance and attitude control
  – Multi-mission capability
Recent Autonomous GN&C Successes

DS1 AutoNav
Deep Cruise, Navigation
Sept. 1999

Stardust AutoNav
at Annefrank and Wild 2,

DS1 AutoNav
At Borrelly Sept., 2001

Deep Impact AutoNav
at Tempel 1 July 2005

MRO OpNav
Camera
Validation Feb. 2006

Altair lunar landing and
“Touch and Go” on
Wirtanen, AutoGNC
simulations, Spring 2008

Hayabusa Imaging
Science: Itokawa
Shape
Model, Sept. 2005

DI AutoNav
Phobos Landing
Simulation Dec. 2005
Future Missions

- Kepler – Feb ’09 – “Drift-away”
- Mars Science Laboratory (MSL) - Sept/Oct ’09
- Juno – Aug ’11 – Jupiter Orbiter
- GRAIL – Sept/Oct ’11 – Lunar Orbiter
- Outer Planets Flagship Mission(s) – 2016/17?
  - Jupiter Europa Orbiter Mission
  - Titan Saturn System Mission
- Mars Sample Return – 2016-2020?
- More to come
http://www.jpl.nasa.gov

“Missions”

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