Interplanetary Navigation

Past, Present and Future

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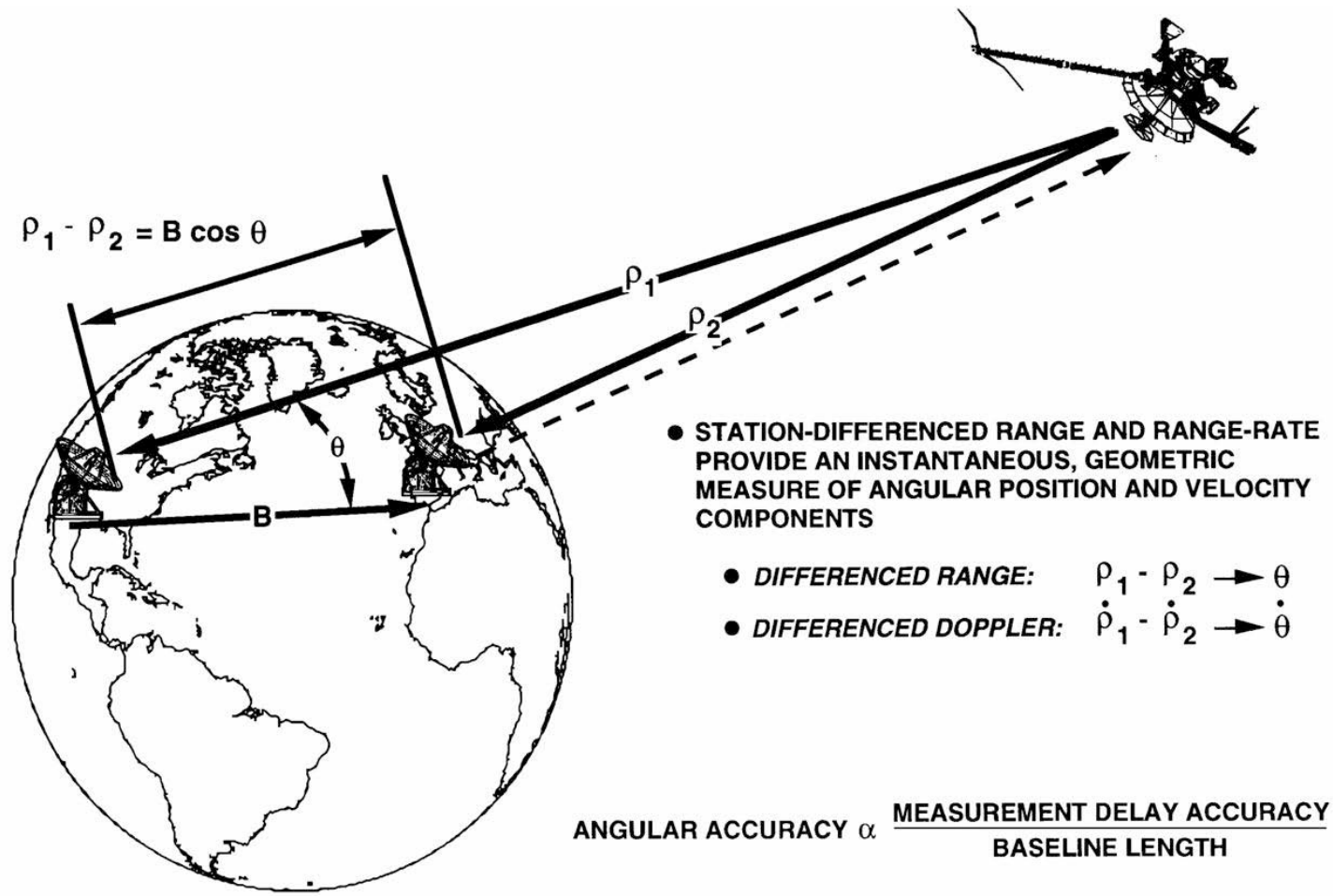
What is it?

- 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.

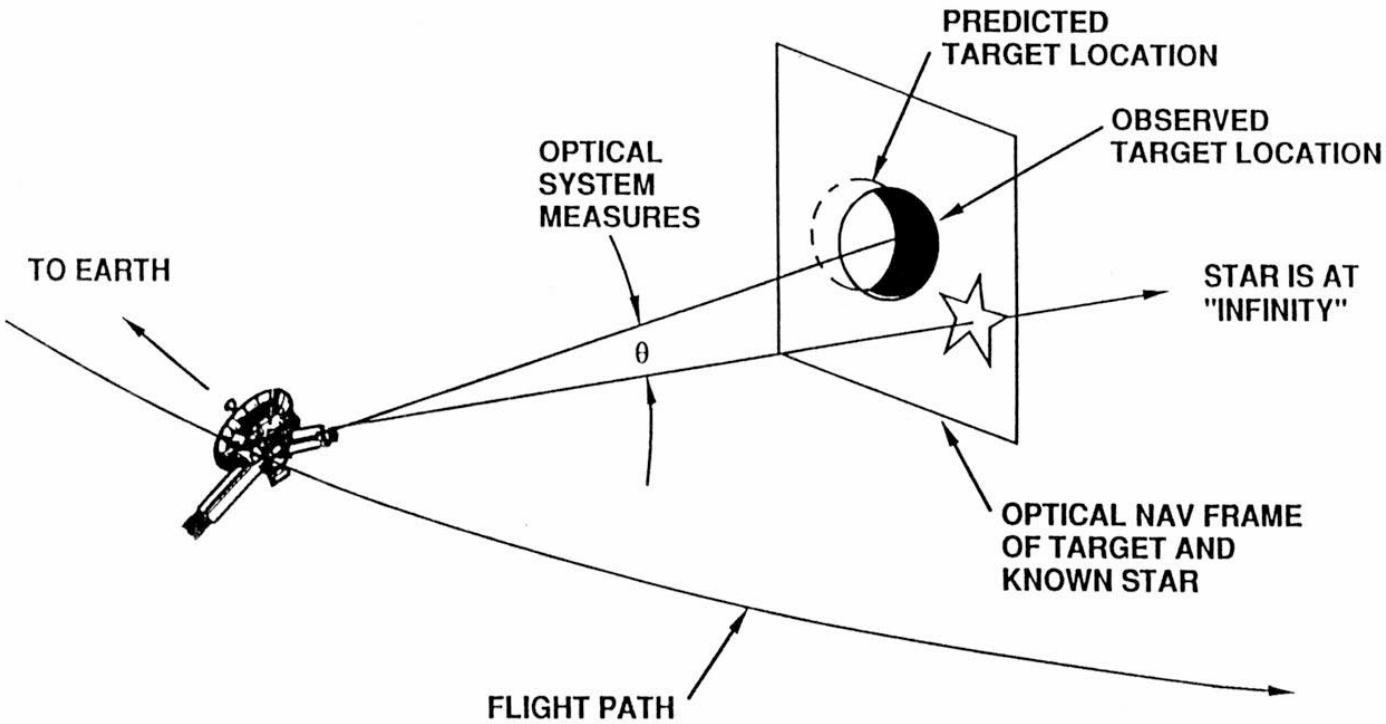
Δ-DOR



- STATION-DIFFERENCED RANGE AND RANGE-RATE PROVIDE AN INSTANTANEOUS, GEOMETRIC MEASURE OF ANGULAR POSITION AND VELOCITY COMPONENTS
  - *DIFFERENCED RANGE:* $\rho_1 - \rho_2 \rightarrow \theta$
  - *DIFFERENCED DOPPLER:* $\dot{\rho}_1 - \dot{\rho}_2 \rightarrow \dot{\theta}$

$$\text{ANGULAR ACCURACY} \propto \frac{\text{MEASUREMENT DELAY ACCURACY}}{\text{BASELINE LENGTH}}$$

Optical


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

Past Missions

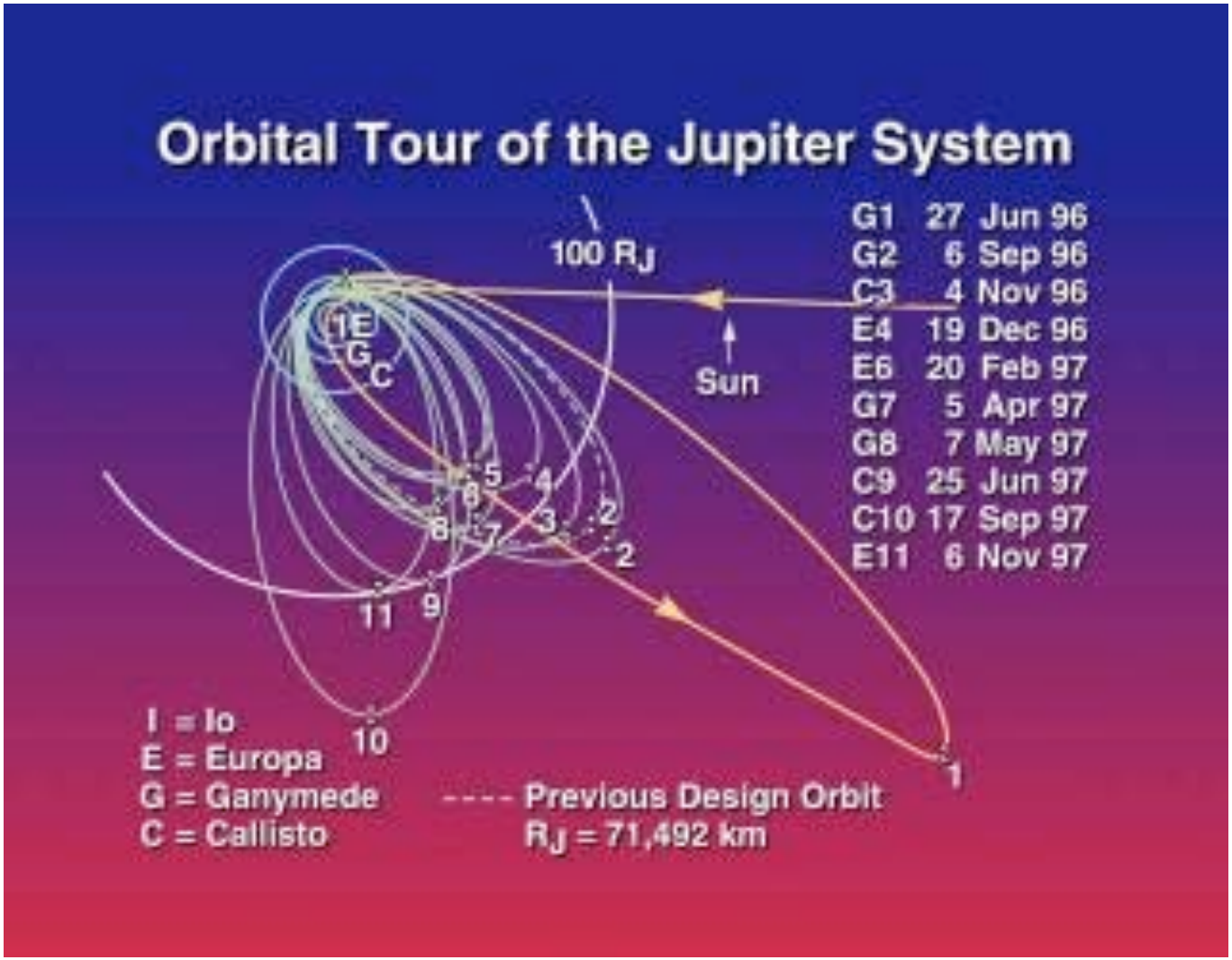
Successes

- 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)

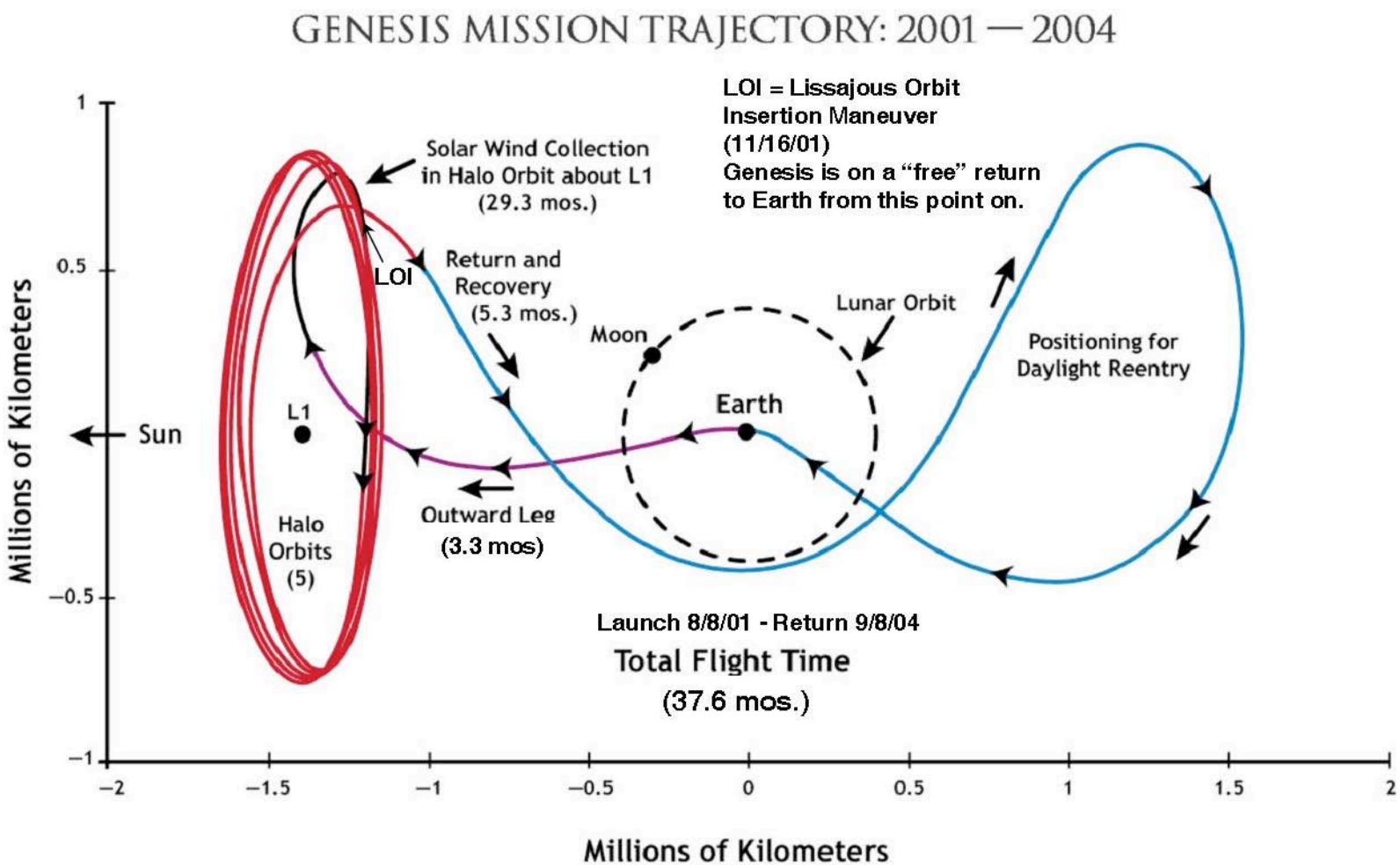
Failures

- Early Moon
  - Explorers, Pioneers, Rangers
- Mars Observer ('92)
- Mars Climate Orbiter ('98)
- Deep Space 2 ('99)
- Mars Polar Lander ('99)

Galileo Satellite Tour

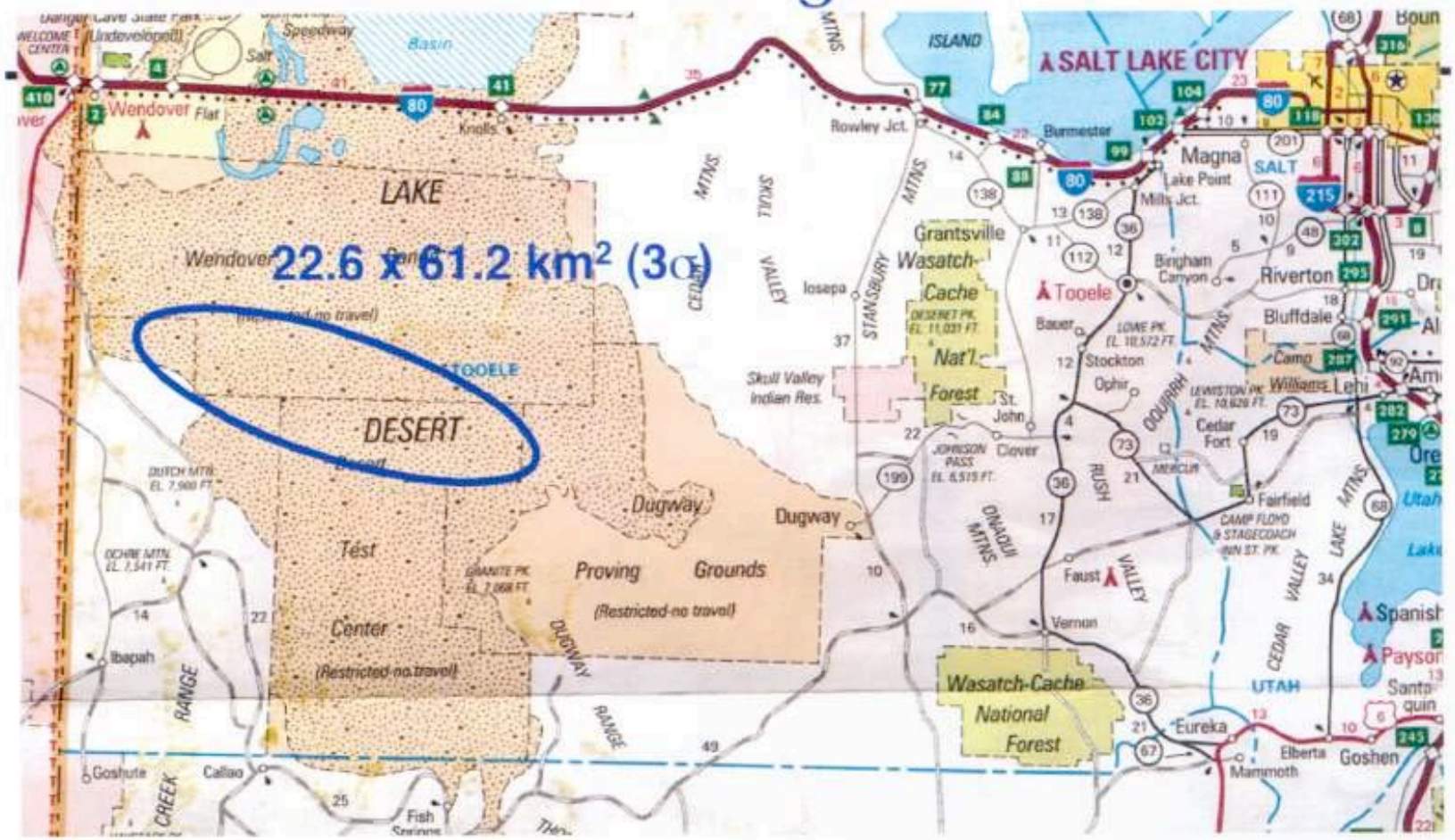


Genesis


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.
Solar Wind Collection in Halo Orbit about L1 (29.3 mos.)
LOI
Return and Recovery (5.3 mos.)
Lunar Orbit
Moon
Earth
Positioning for Daylight Reentry
Sun
L1
Halo Orbits (5)
Outward Leg (3.3 mos)
Launch 8/8/01 - Return 9/8/04
Total Flight Time (37.6 mos.)
Millions of Kilometers
Millions of Kilometers
1
0.5
−0.5
−1
−2
−1.5
−1
−0.5
0
0.5
1
1.5
2

Earth Return (Genesis and Stardust)

SRC Landing Site



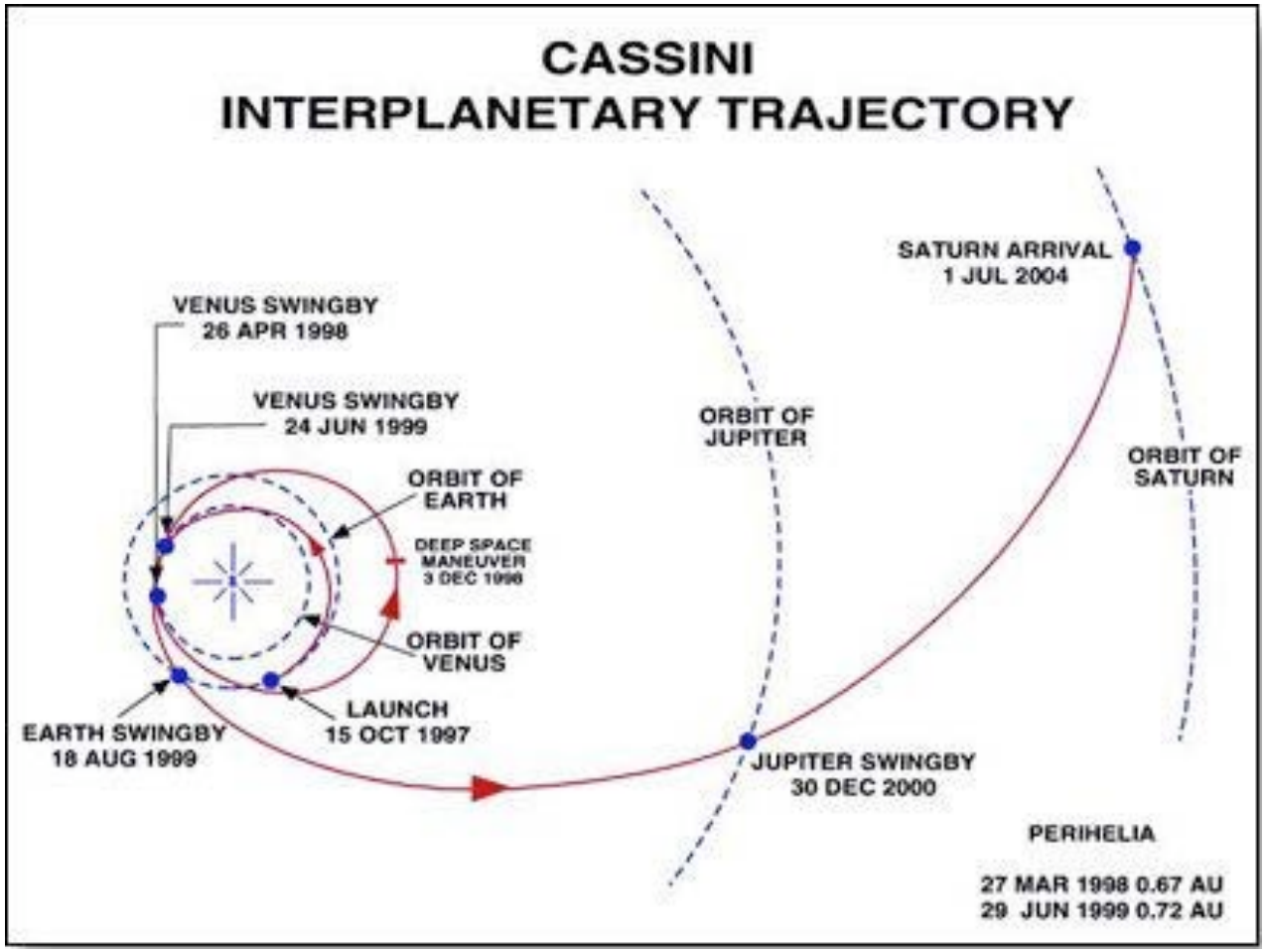
Current Missions

- 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

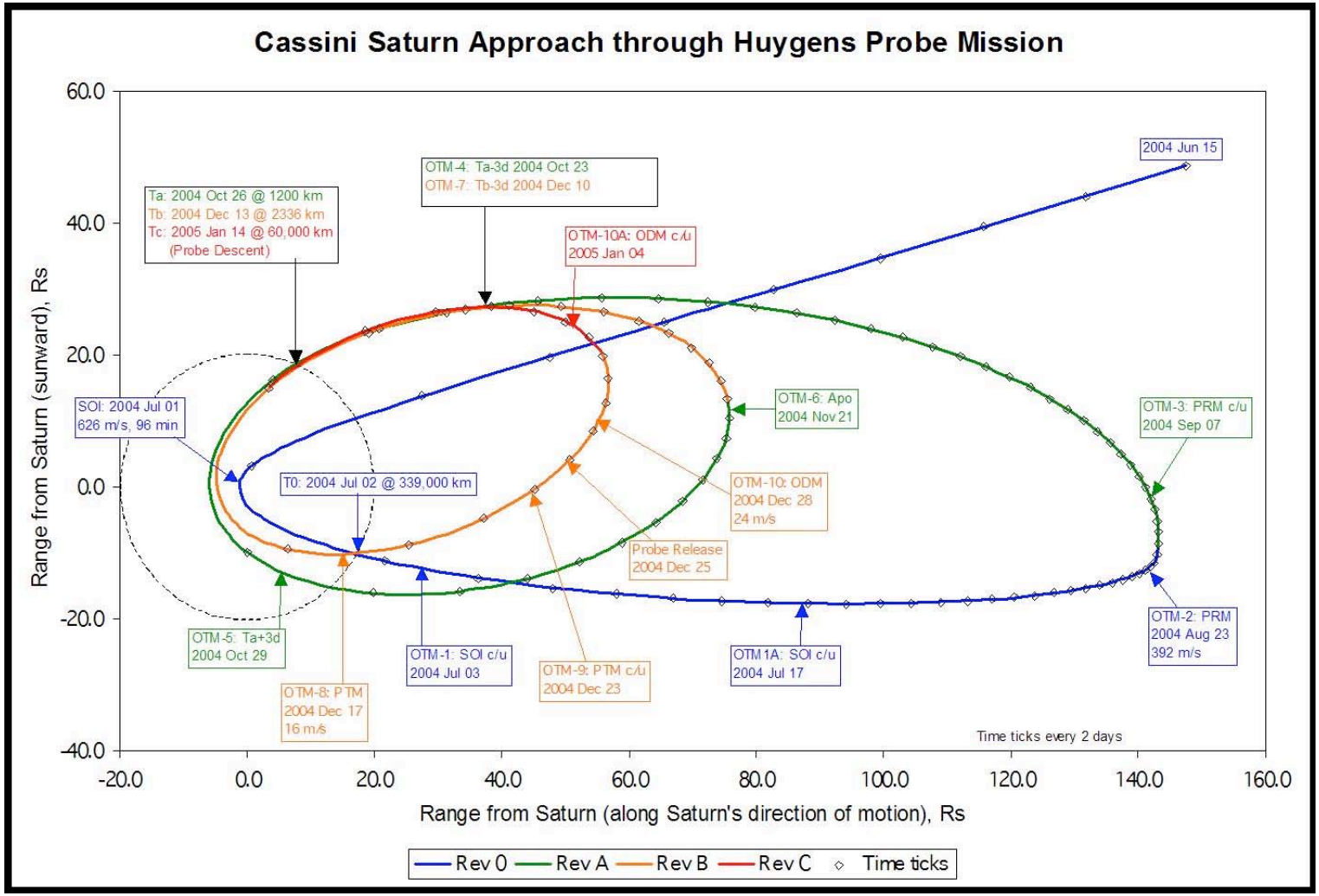
Cassini as an Example

- Interplanetary
- Tour
- Icy Satellites
- Navigation Techniques
- “On-the-fly” Changes
- Lessons

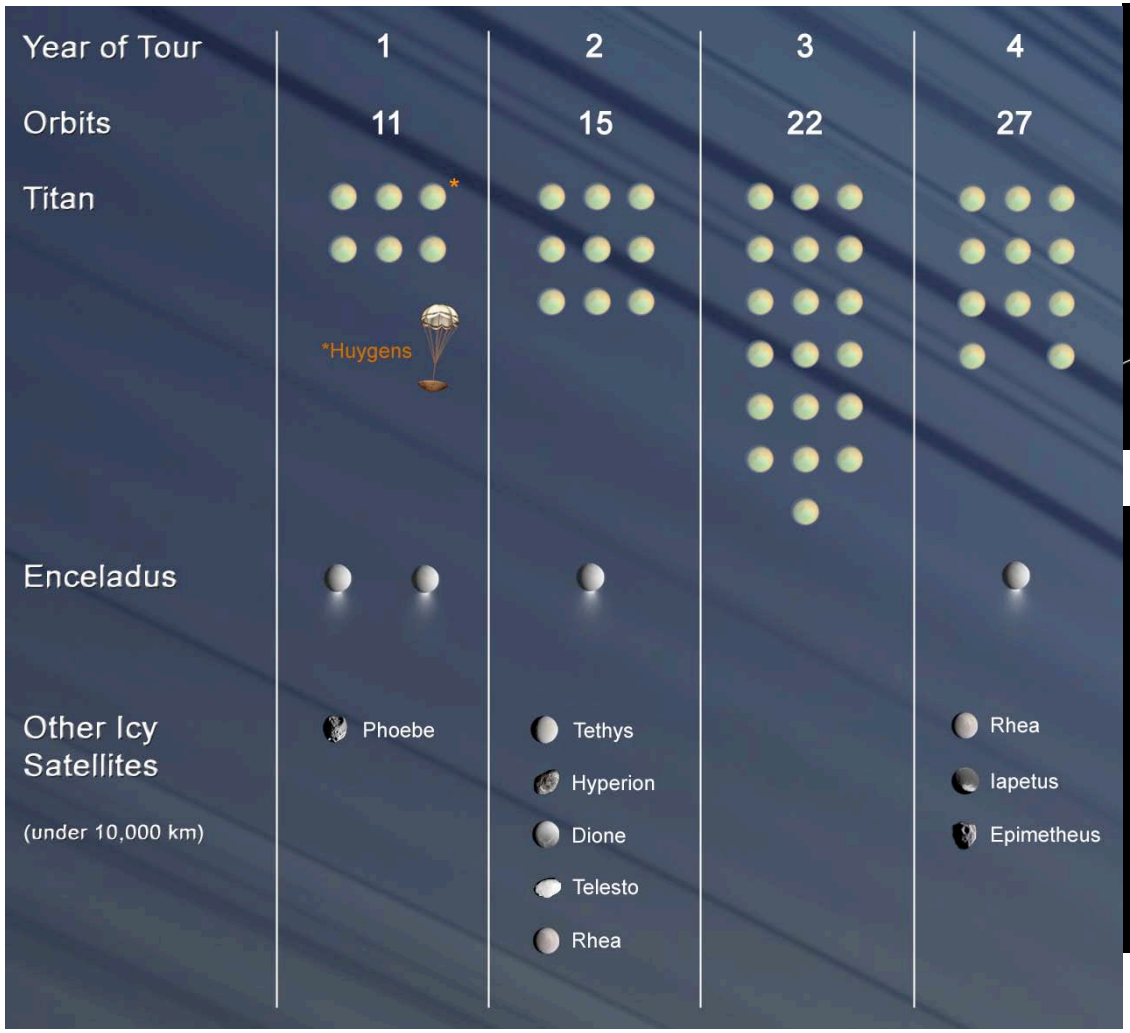
Cassini - Interplanetary

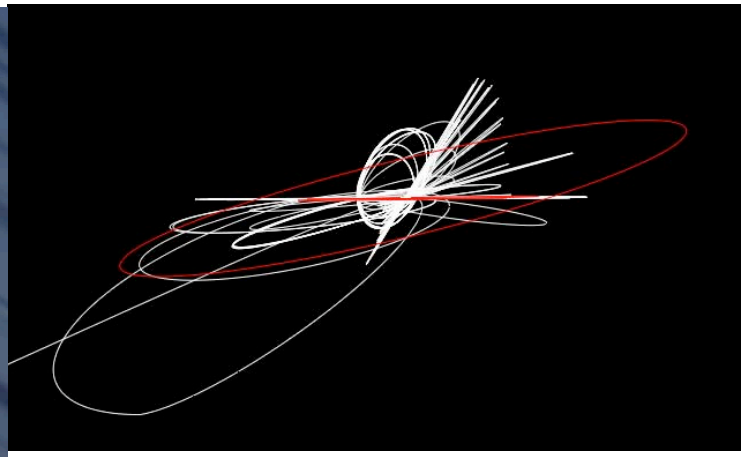


Initial Cassini Orbits

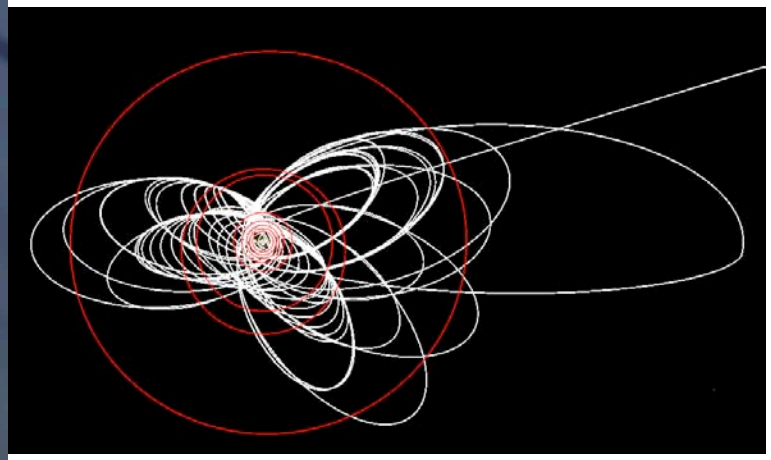


Cassini Mission Overview





View From Sun

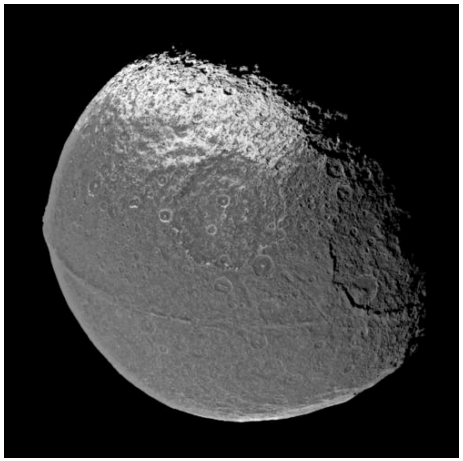


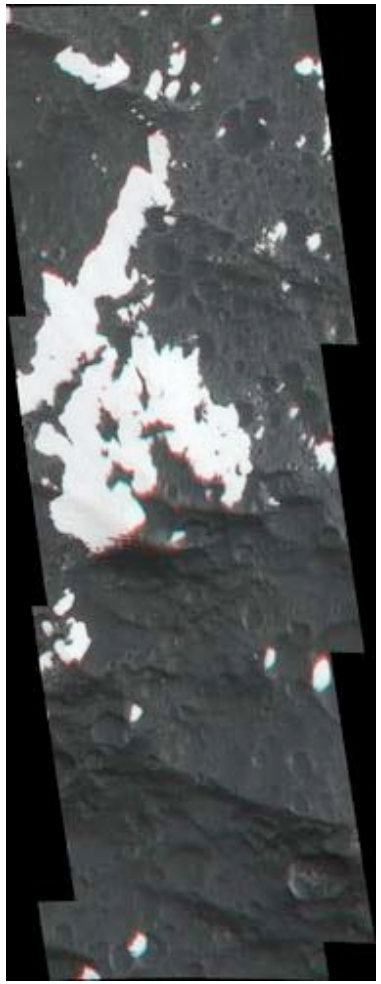
View From Saturn North Pole

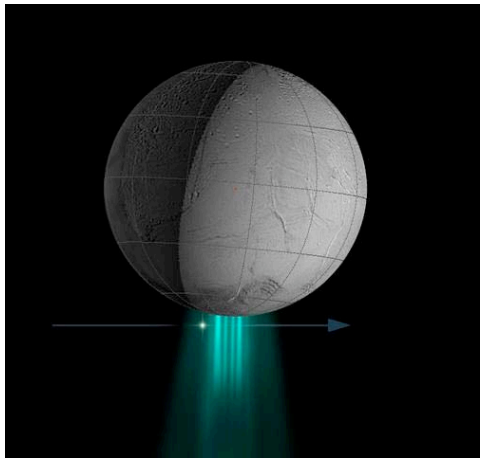
070209

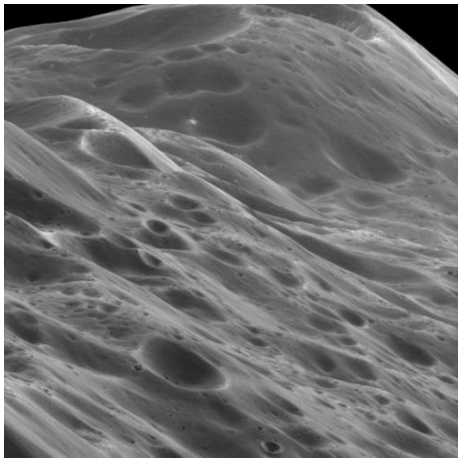
Science Tweaks (2)

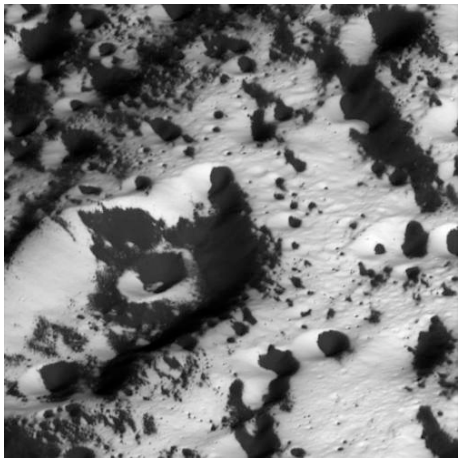
- Moved Stellar Occultation of Iapetus away from closest approach to free up time for close-in imaging
- Tweaked groundtrack closer to equatorial ridge
- Added distant stellar occultation through Enceladus plumes





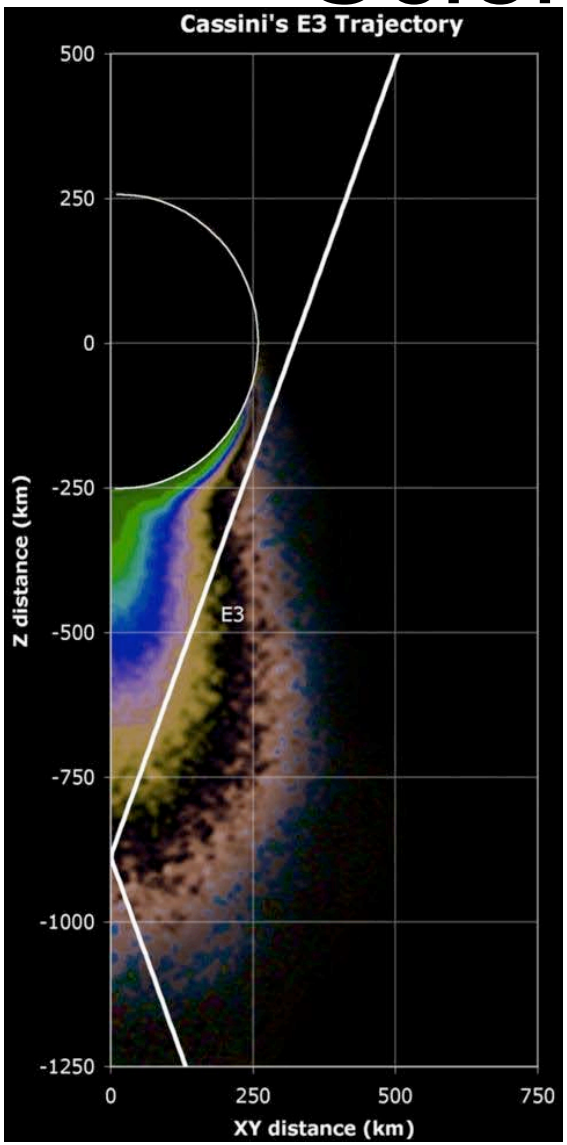




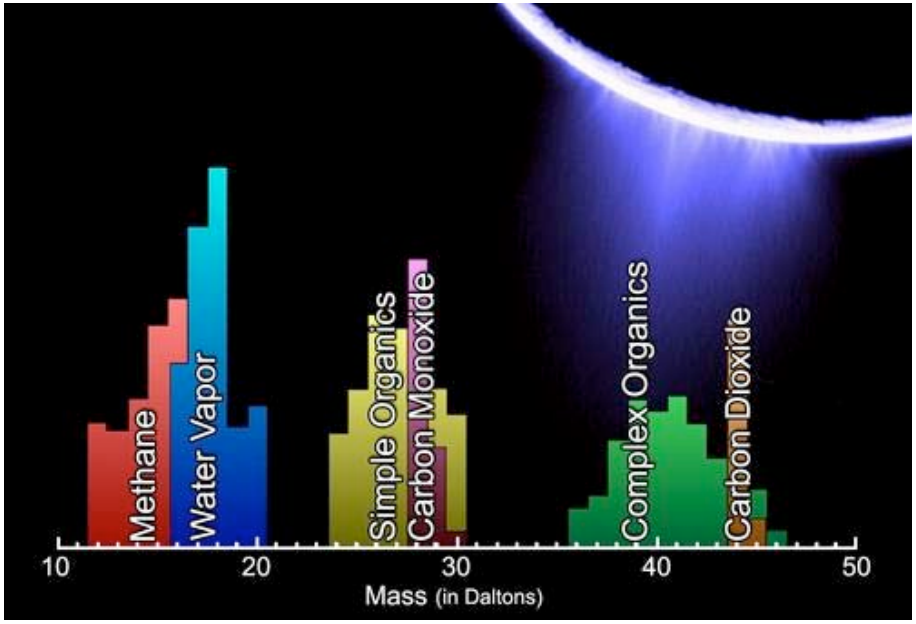


Science Tweaks (3)

070918

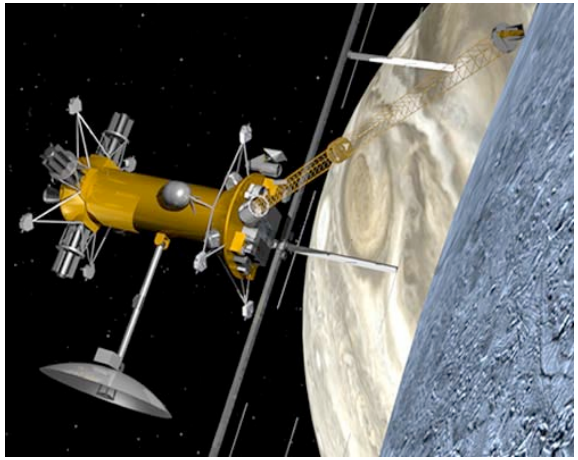


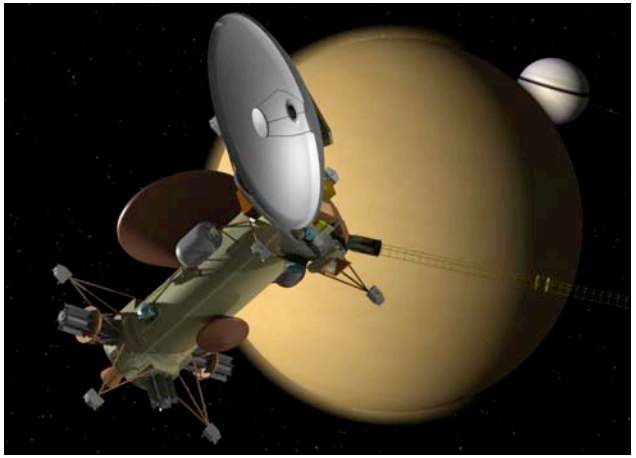
- E3 altitude changes through many reference updates
  - 1000 km →100 km → 25 km → 50 km
- This update set altitude to 50 km so as to confirm plume debris models
- There will be 25 km flybys in the extended mission



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

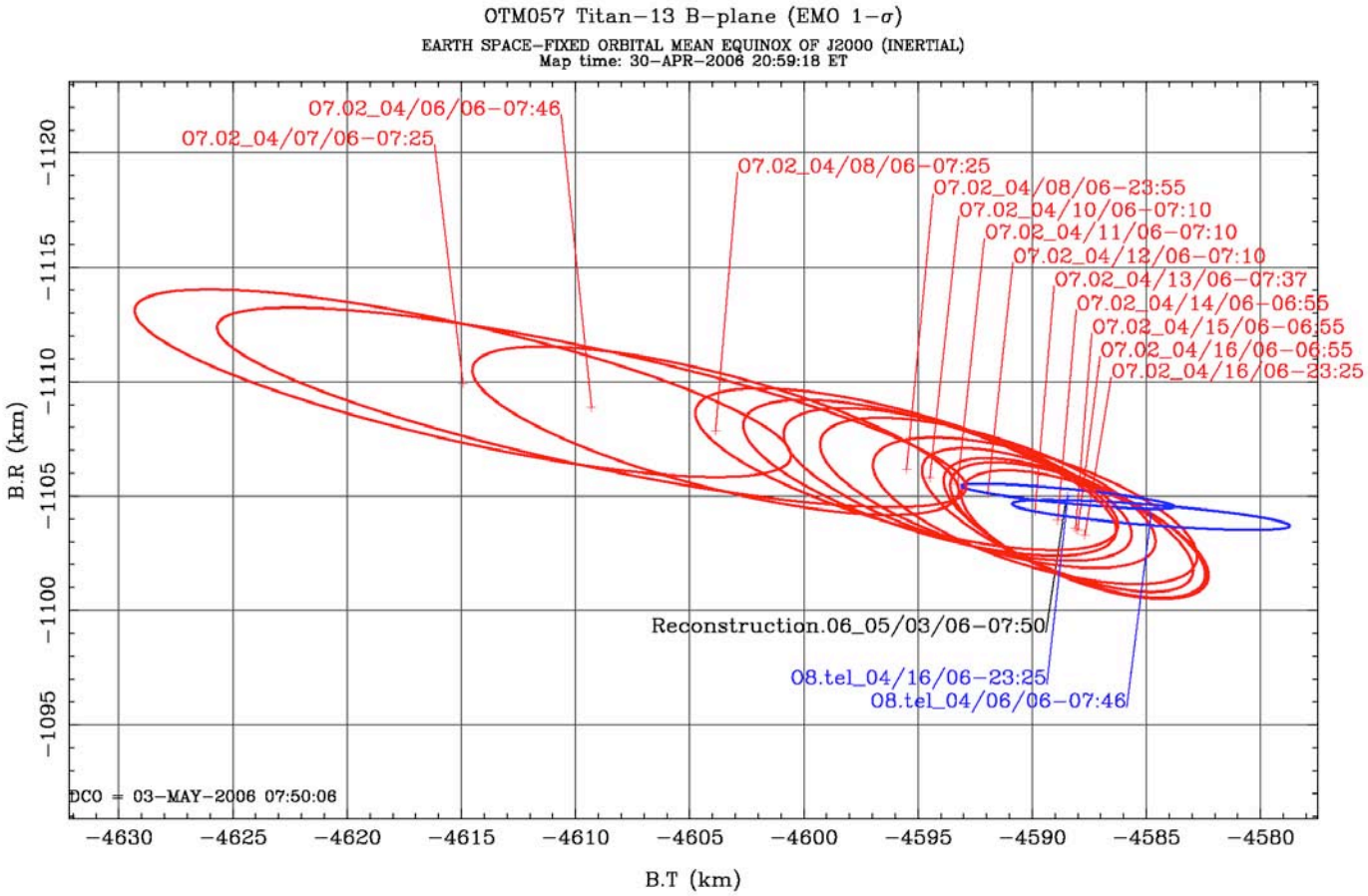




Cassini's Successor:

http://opfm.jpl.nasa.gov/

Navigation Benefit

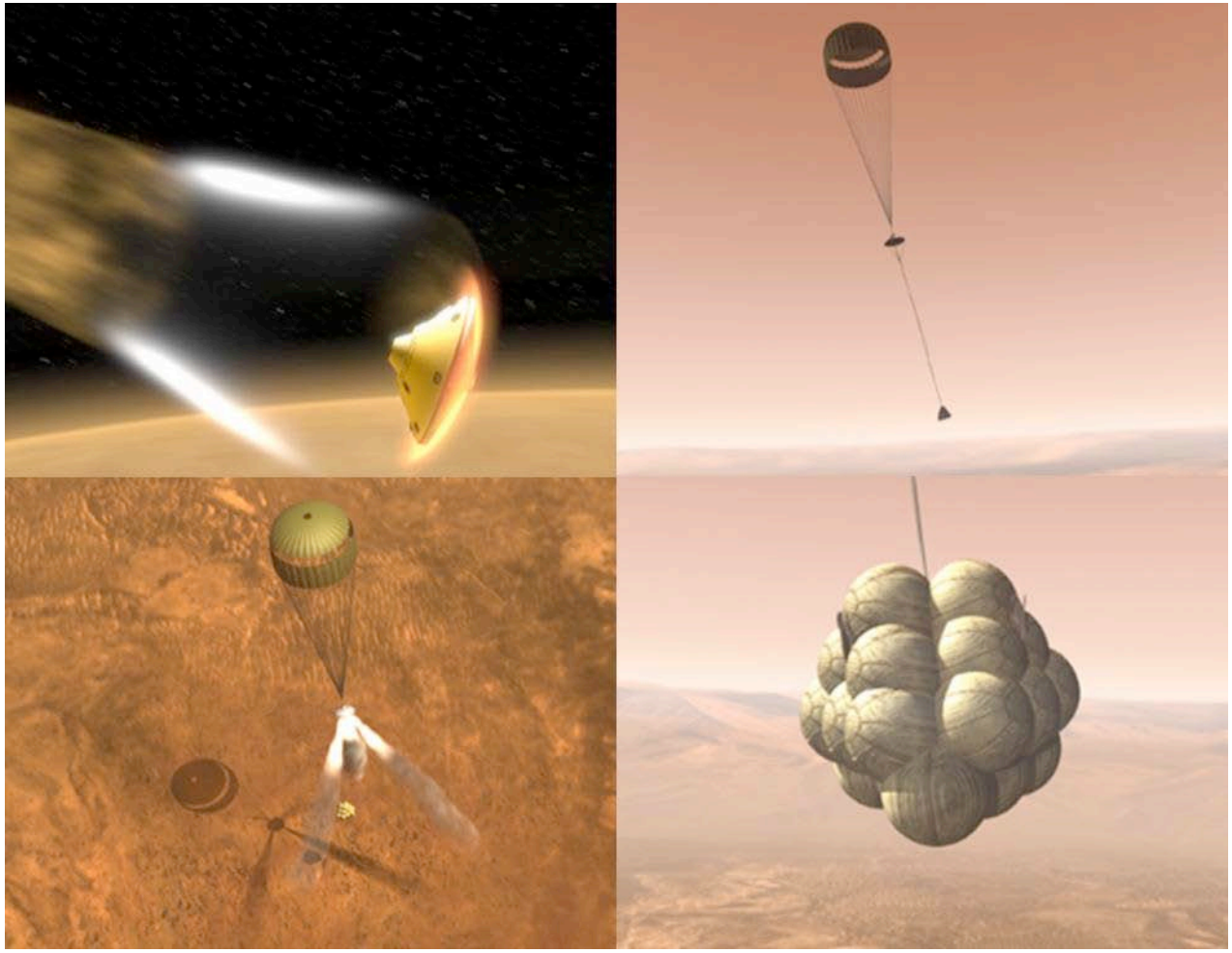


- Cassini Prime Mission successfully navigated!
  - Enceladus 50 km flyby successful
    - Achieved error of 0.9 km altitude error
    - Confidence for
      - 50 km E4 on Aug 11
      - 25 km E5 on Oct 9
    - Titan Encounters
      - 23 of 34 < 1 km error
      - 9 of these < 500 m error
      - Saturn and satellite masses determined < 0.2%

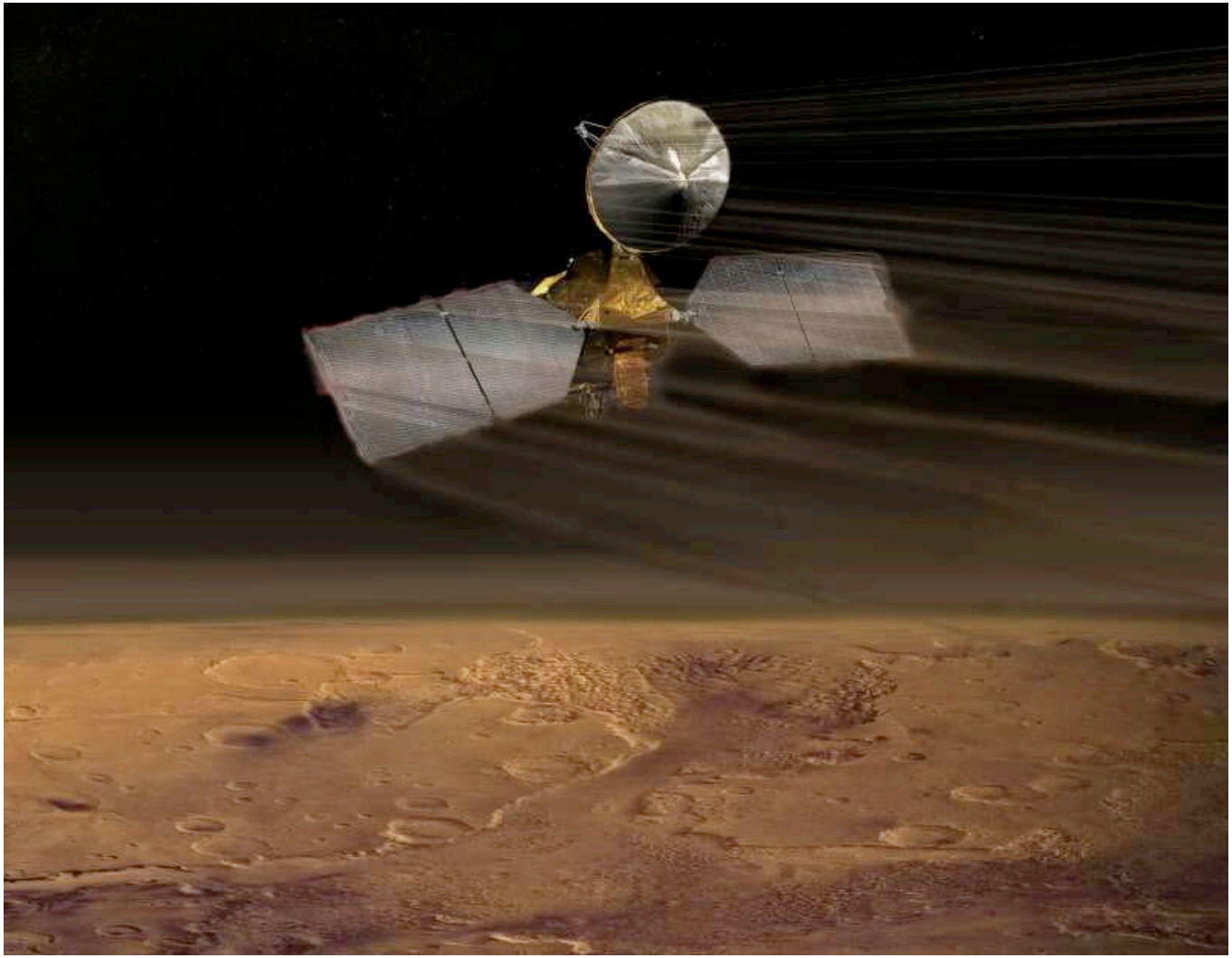
Mars Examples

- MER
- MRO
- Phoenix

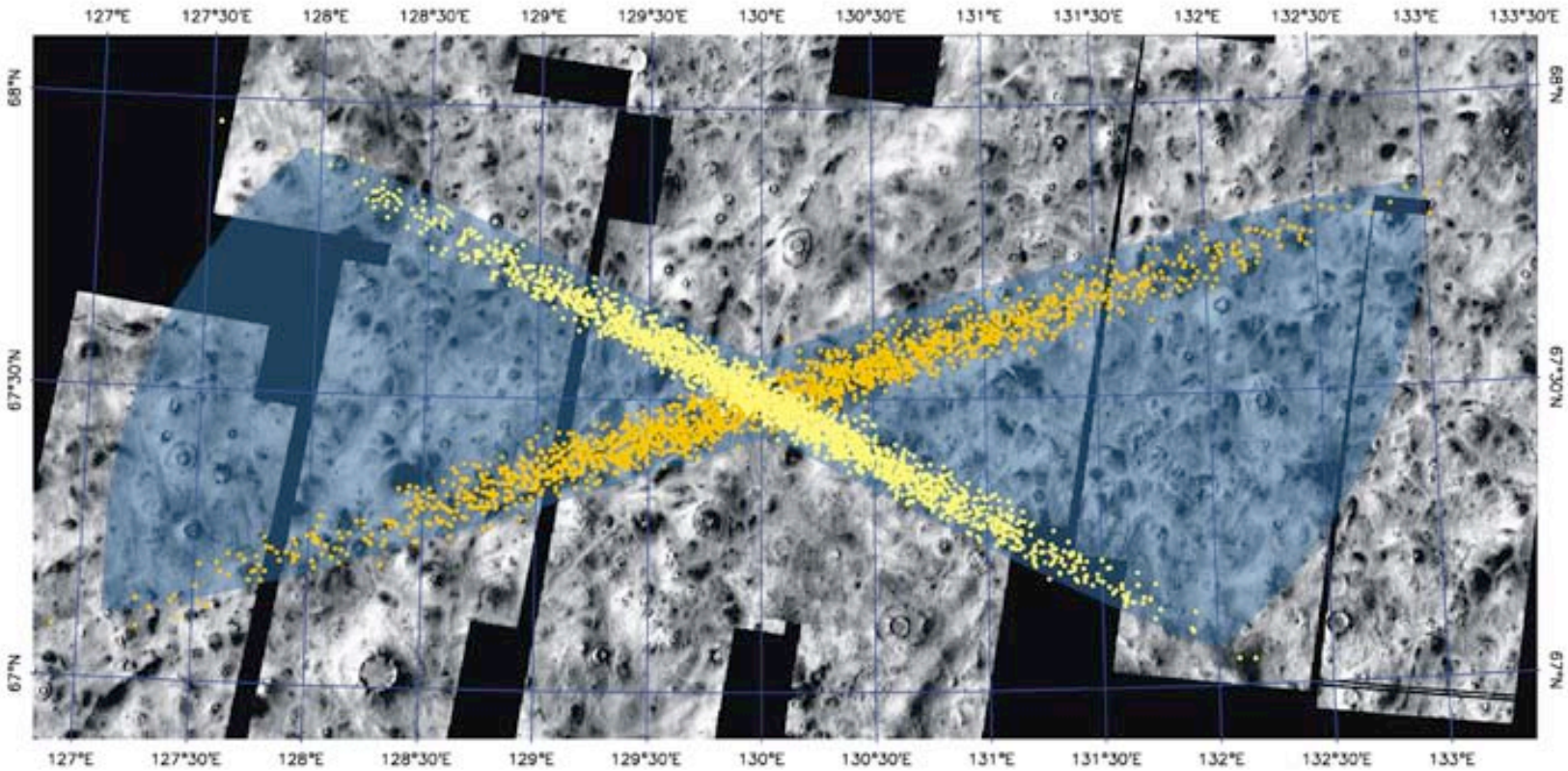
Mars Exploration Rovers



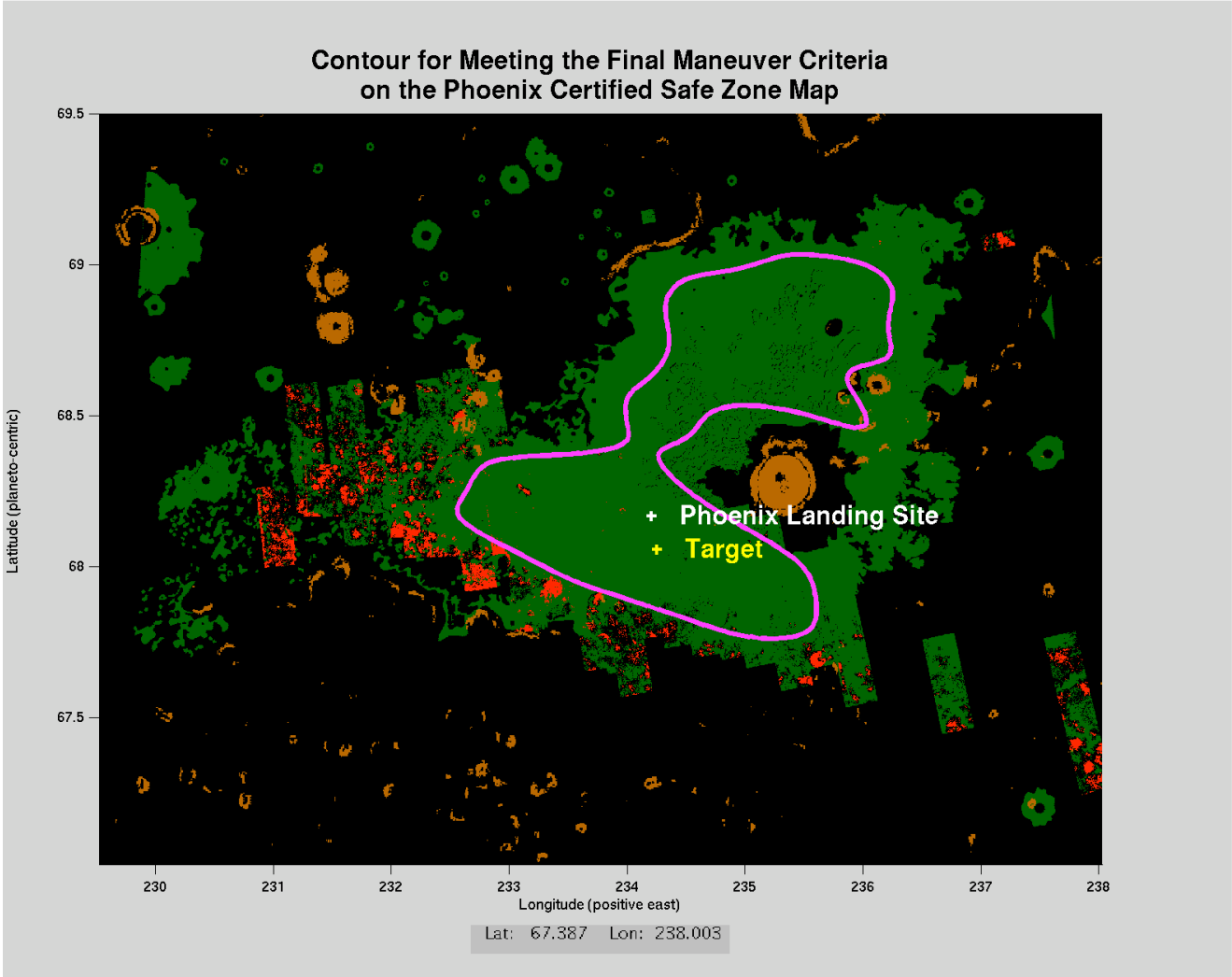
Mars Reconnaissance Orbiter



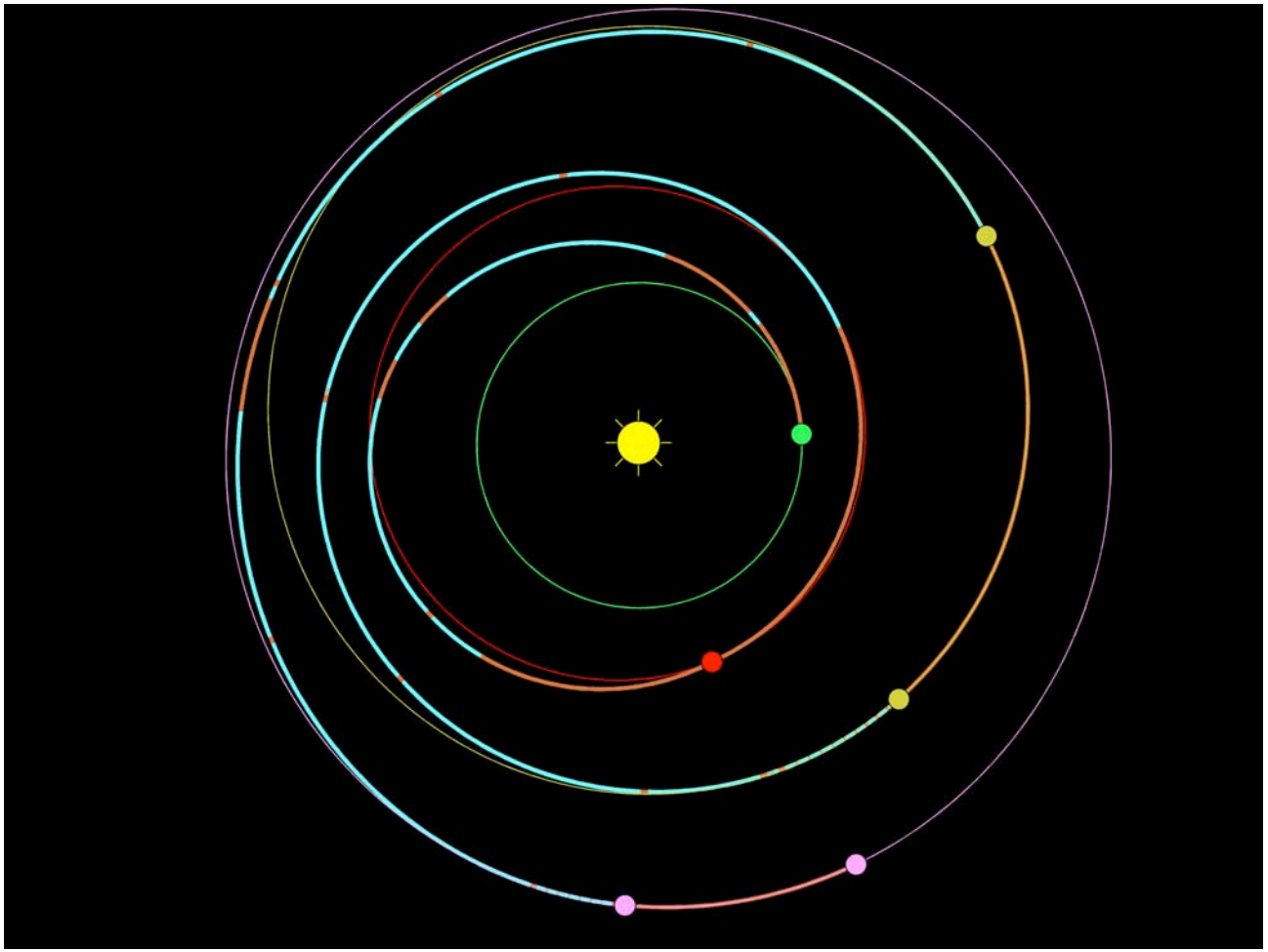
Phoenix Landing

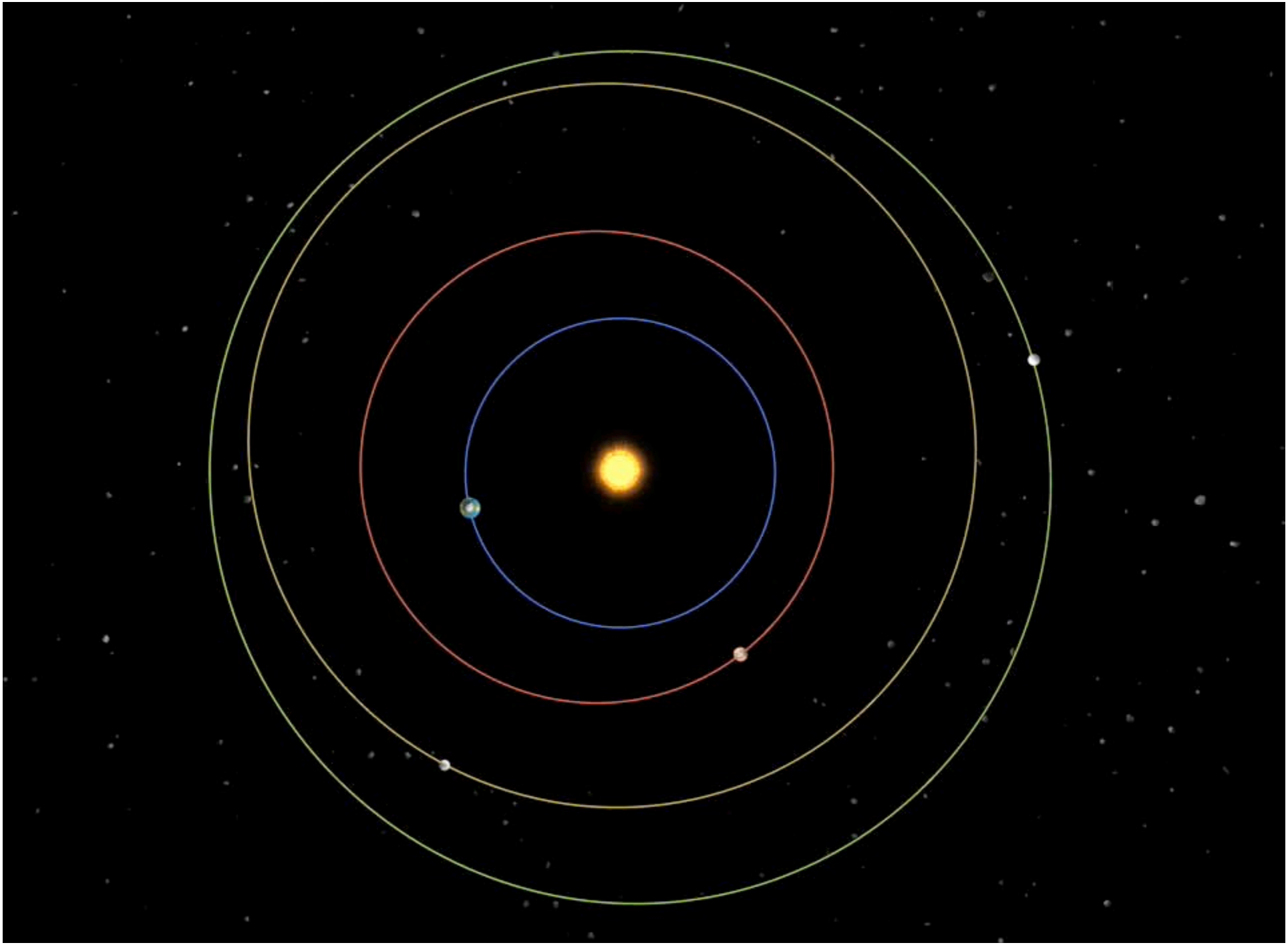


More Phoenix Landing

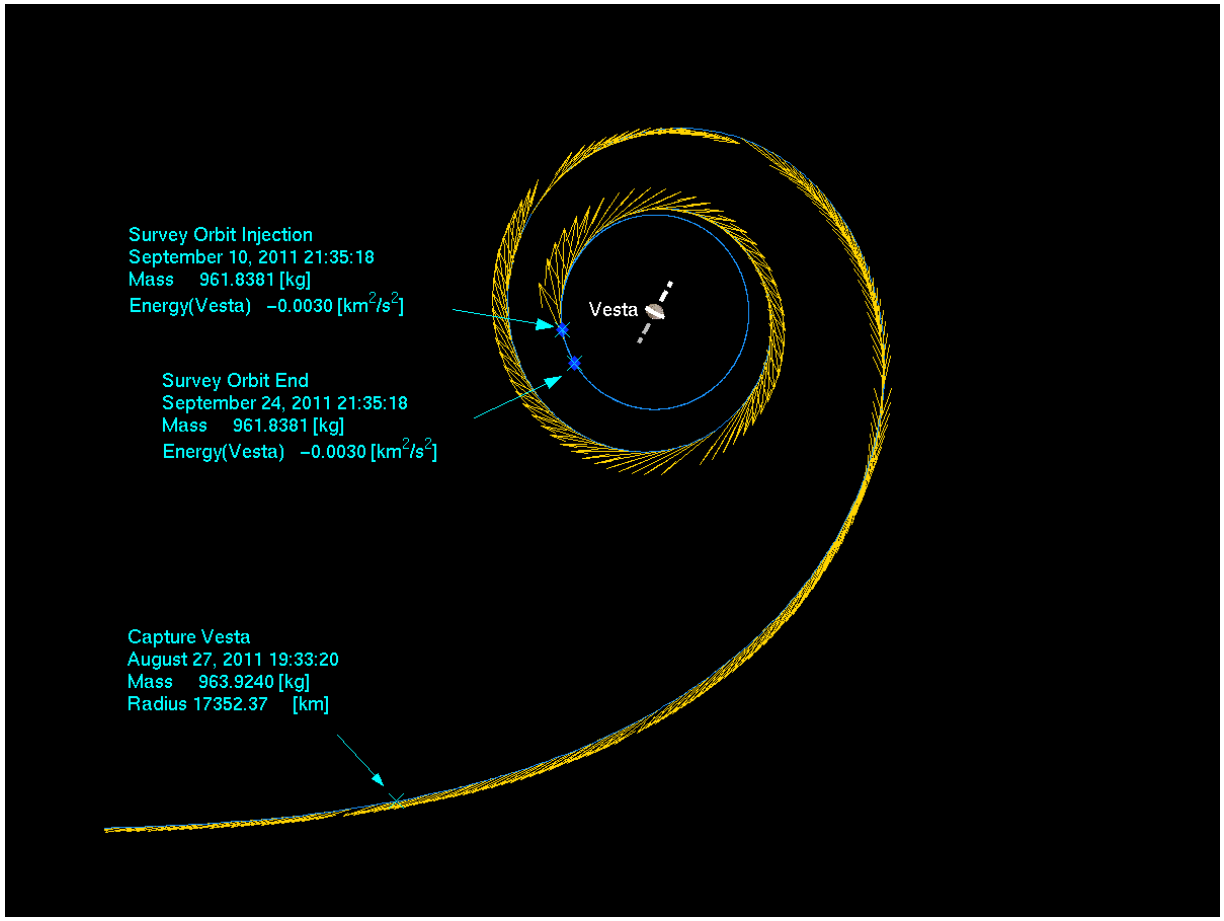


Dawn Interplanetary





Dawn – Vesta Arrival



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

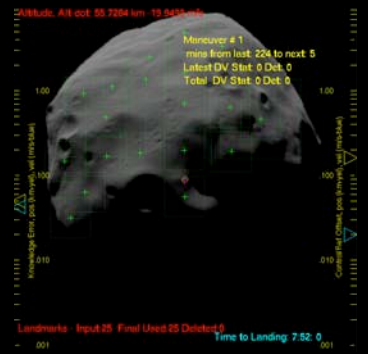
DS1 AutoNav
Deep Cruise, Navigation
Sept.1999

DS1 AutoNav
At Borrelly Sept., 2001

Stardust AutoNav
at Annefrank and Wild 2,
Nov. 2002, Jan. 2004.

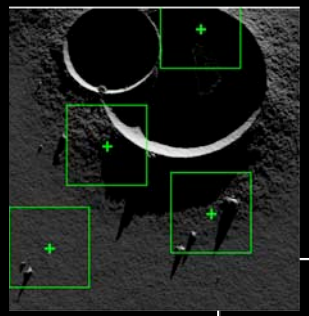
Deep Impact AutoNav
at Tempel 1 July 2005

Hayabusa Imaging
Science: Itokawa
Shape
Model, Sept. 2005



DI AutoNav
Phobos Landing
Simulation Dec.
2005

MRO OpNav
Camera
Validation Feb. 2006



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

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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