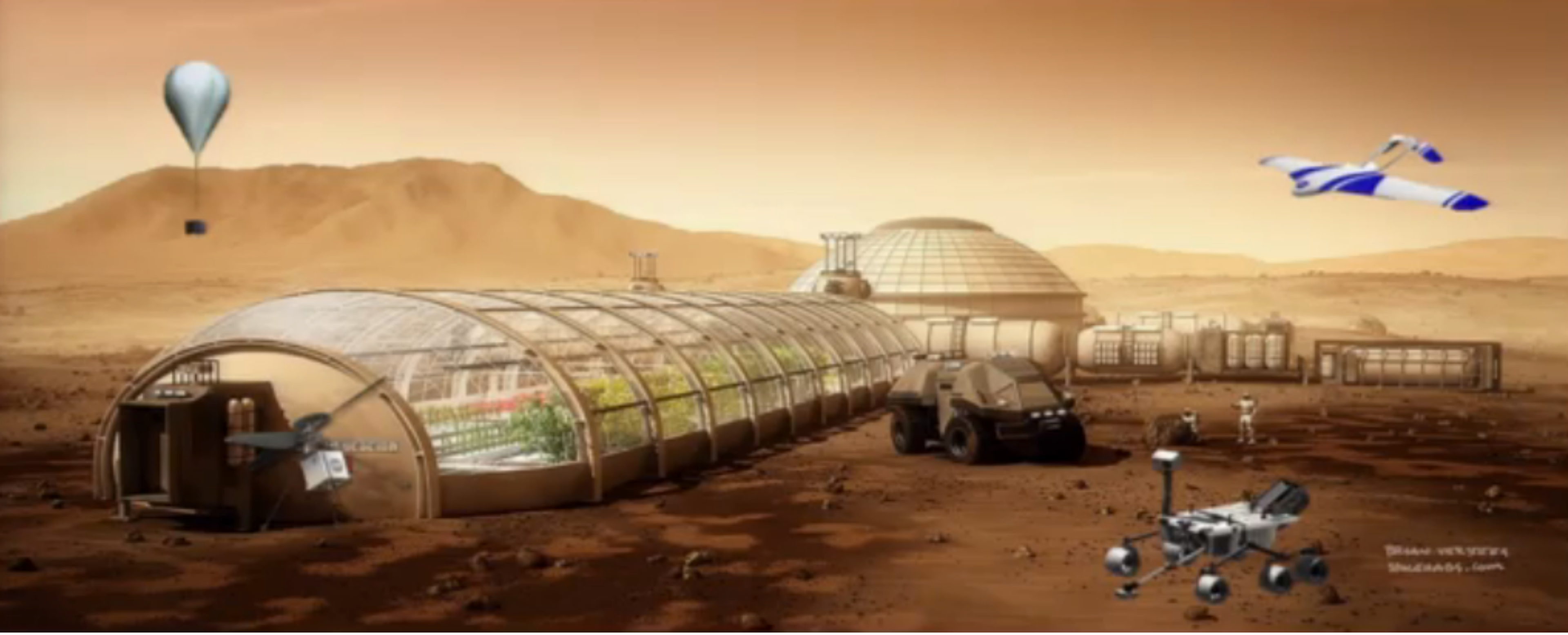


Deep Space Mission Design and Navigation

Joseph Guinn

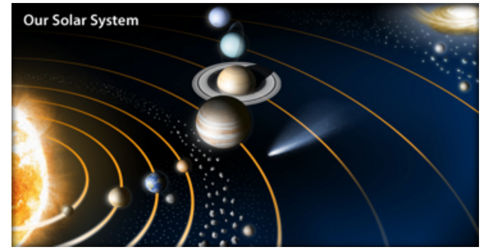
June 2019

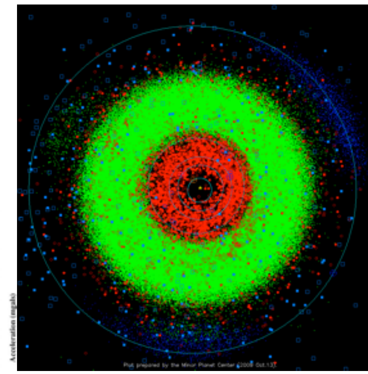
Presented by Sami Asmar

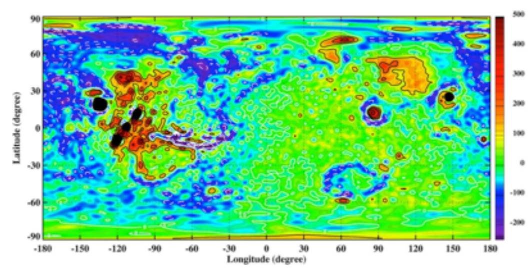
Jet Propulsion Laboratory
California Institute of Technology

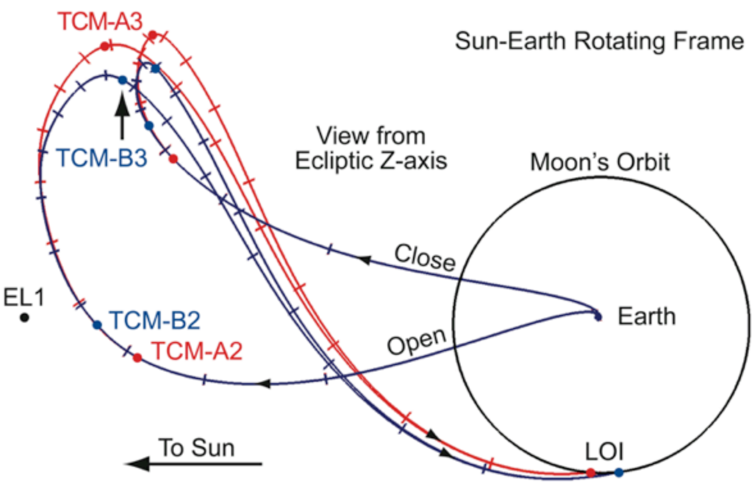
JPL Mission Design & Navigation – What we do

Build and maintain dynamical models and software tools for interplanetary navigation



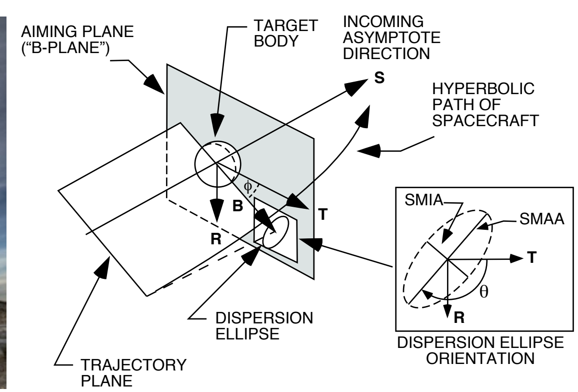






Design efficient routes for spacecraft to reach any remote Solar System location

Use deep space tracking measurements to safely pilot spacecraft to their ultimate destination

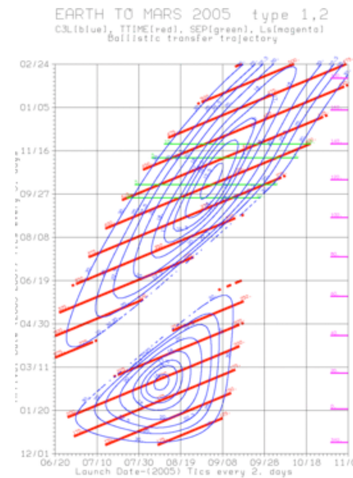


Optimal Trajectory Design

Complex constraints complicate the initial search…

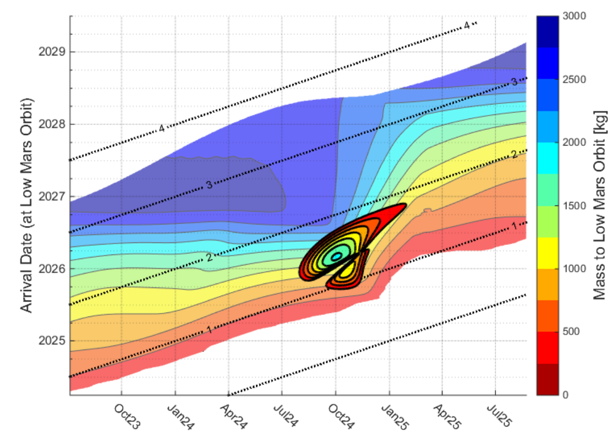
State of the art techniques are used to uncover exceptionally strong trajectory solutions…

Traditional Pork Chop Plot



Arrival Date

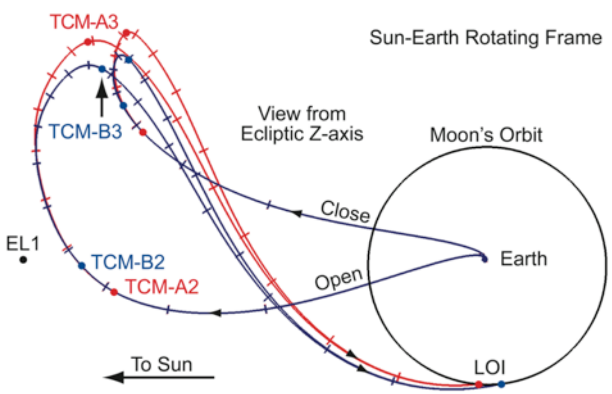
Low-Thrust Bacon Plot



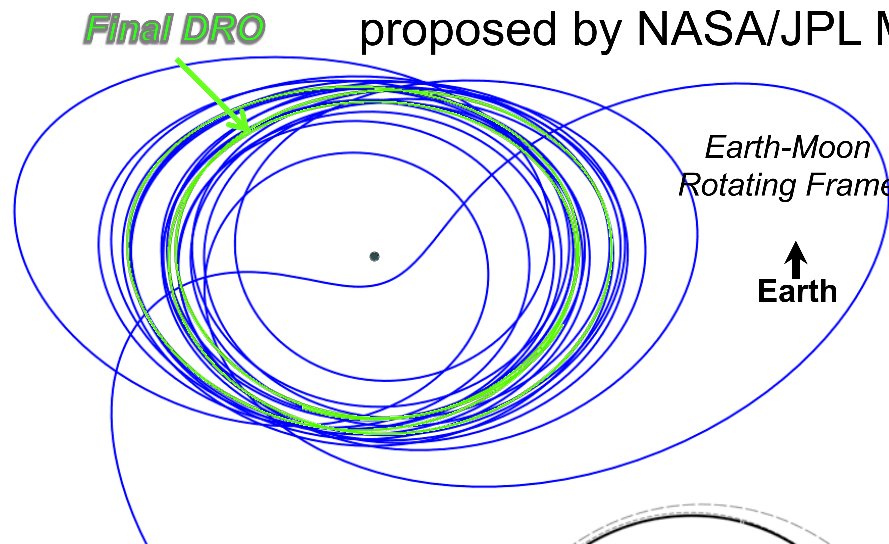
Launch Date

Low-Thrust & Low-Energy Trajectories

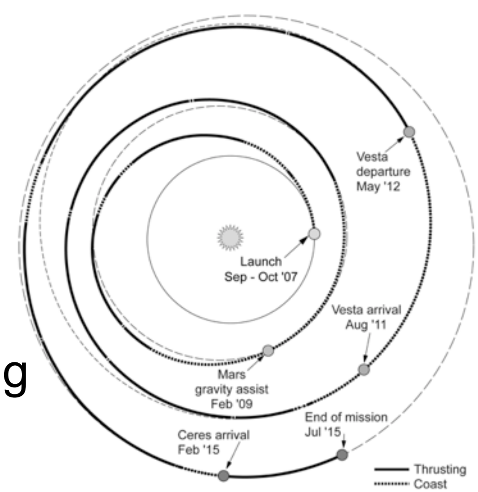
Proposed
Asteroid Retrieval Mission
Distant Retrograde Orbit (DRO)
Stable storage orbit (>100yrs)
proposed by NASA/JPL MD/Nav



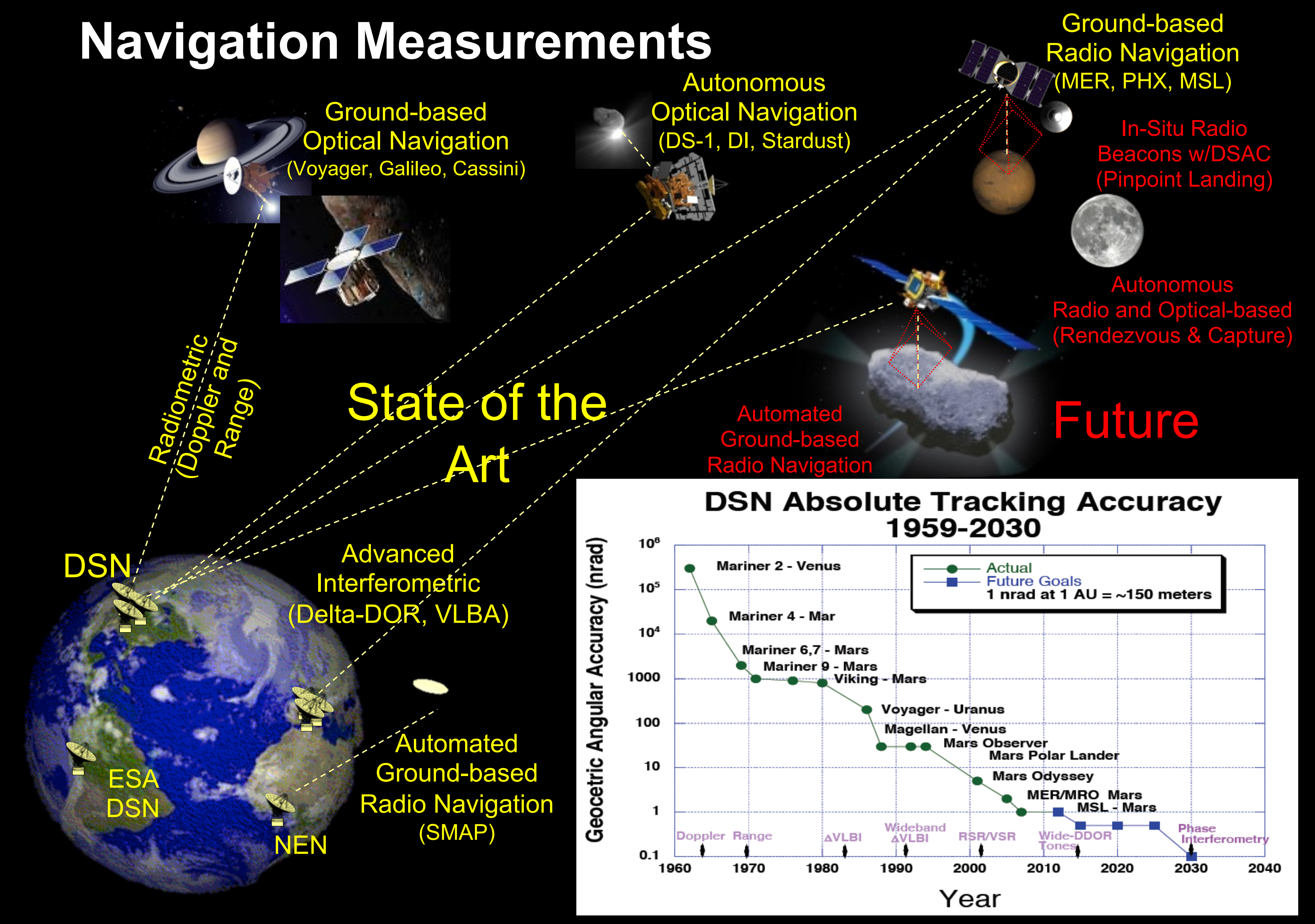
GRAIL low-energy trajectory enabled the mission to reduce fuel requirements and the lunar arrival velocity



Dawn low-thrust trajectory has achieved a total delta-v over 10 km/s. Allows reaching both Vesta and Ceres.



Navigation Measurements



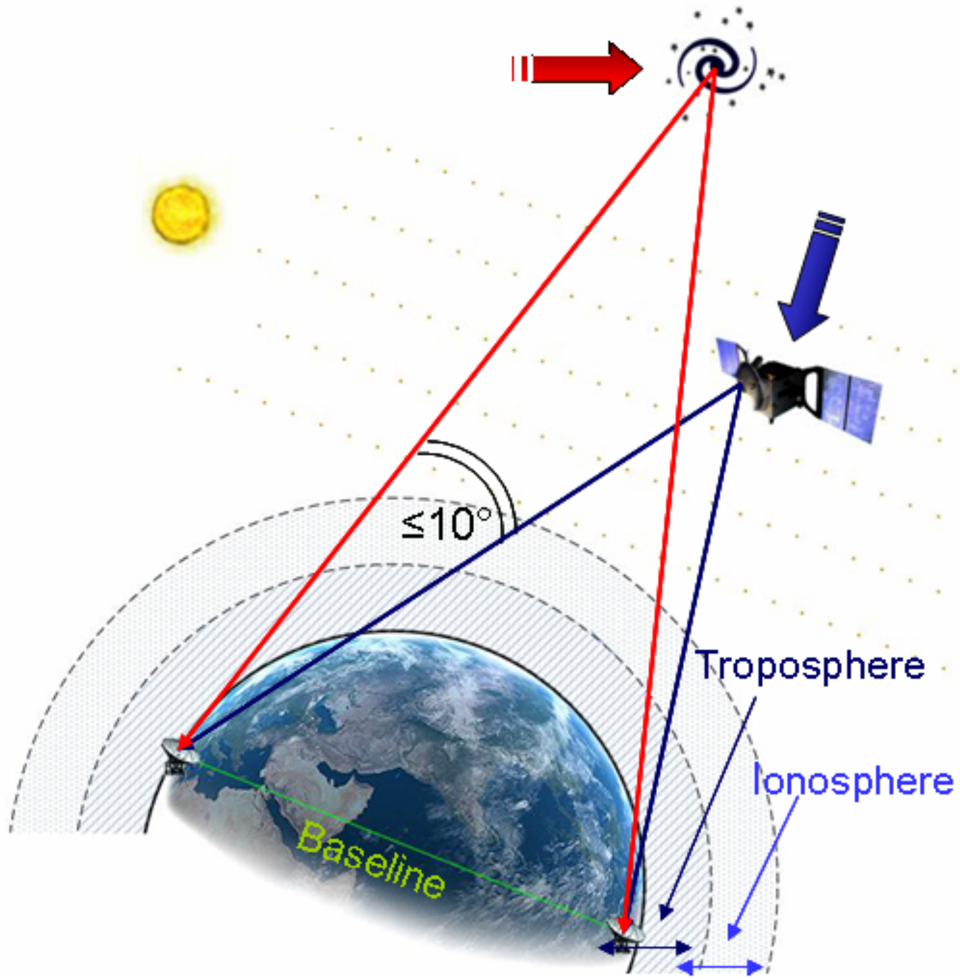
ΔDOR (Delta-Differential One-Way Range)

Essential Beyond Lunar Orbit

ΔDOR provides
Plane-of-Sky Information

Complementary to
Line-of-Sight from
Doppler & Range

Optical analogy is called
“Optical Astrometry”.
Uses star catalog instead
of quasars.



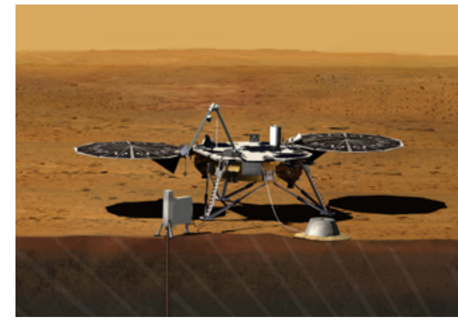
Selected Recent Accomplishments

NASA/JPL Missions

Cassini

Dawn

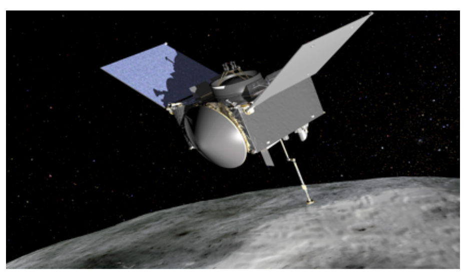
Juno



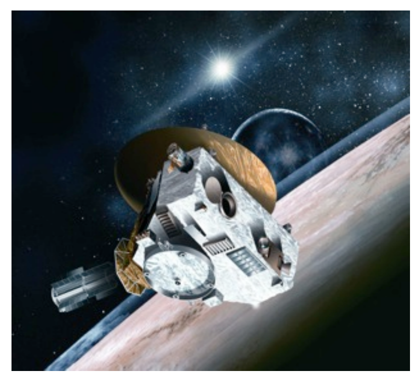
InSight

Partnership Missions

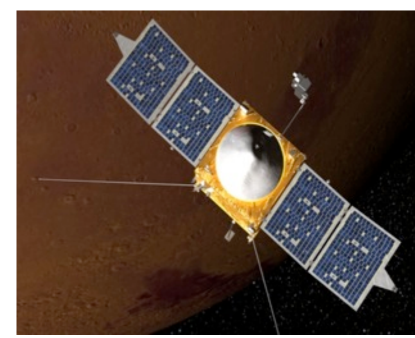
JAXA Hayabusa-2
Asteroid
Sample Return



GSFC OSIRIS-REx

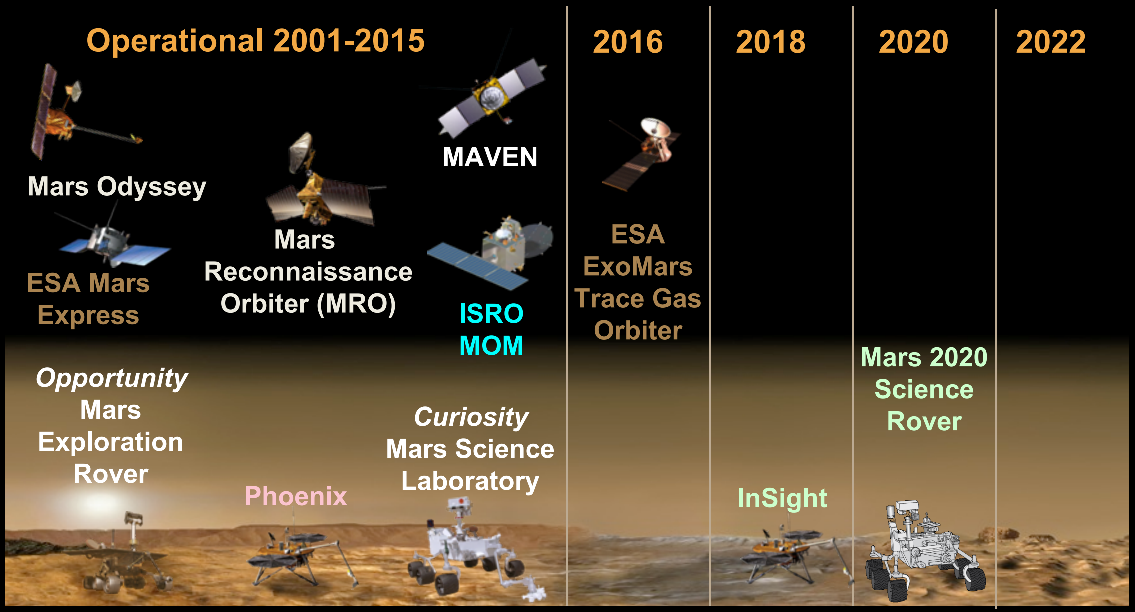


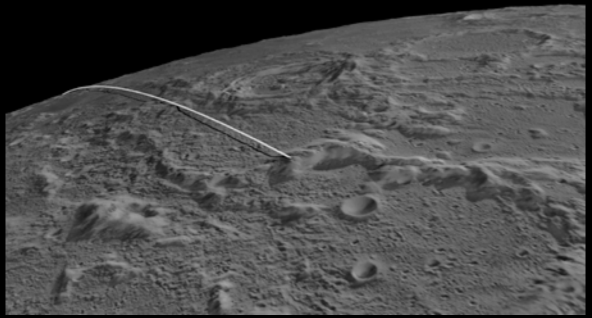
APL New Horizons
Pluto & MU69



GSFC Maven
Mars Orbiter

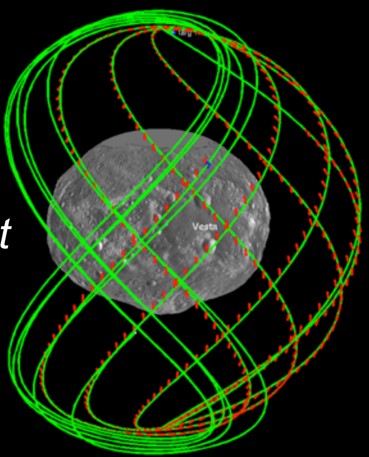
Mars, Lunar and Small Body Experience





GRAIL: Dual Spacecraft Formation (2011-2012)

Dawn: Low Thrust Asteroid Orbiter



Deep Impact: Comet Tempel 1 Impactor (2005)

Re-Purposed as EPOXI: Hartley 2 Flyby (2010)

Stardust: Comet Coma Sample Return

Earth Return (2006)

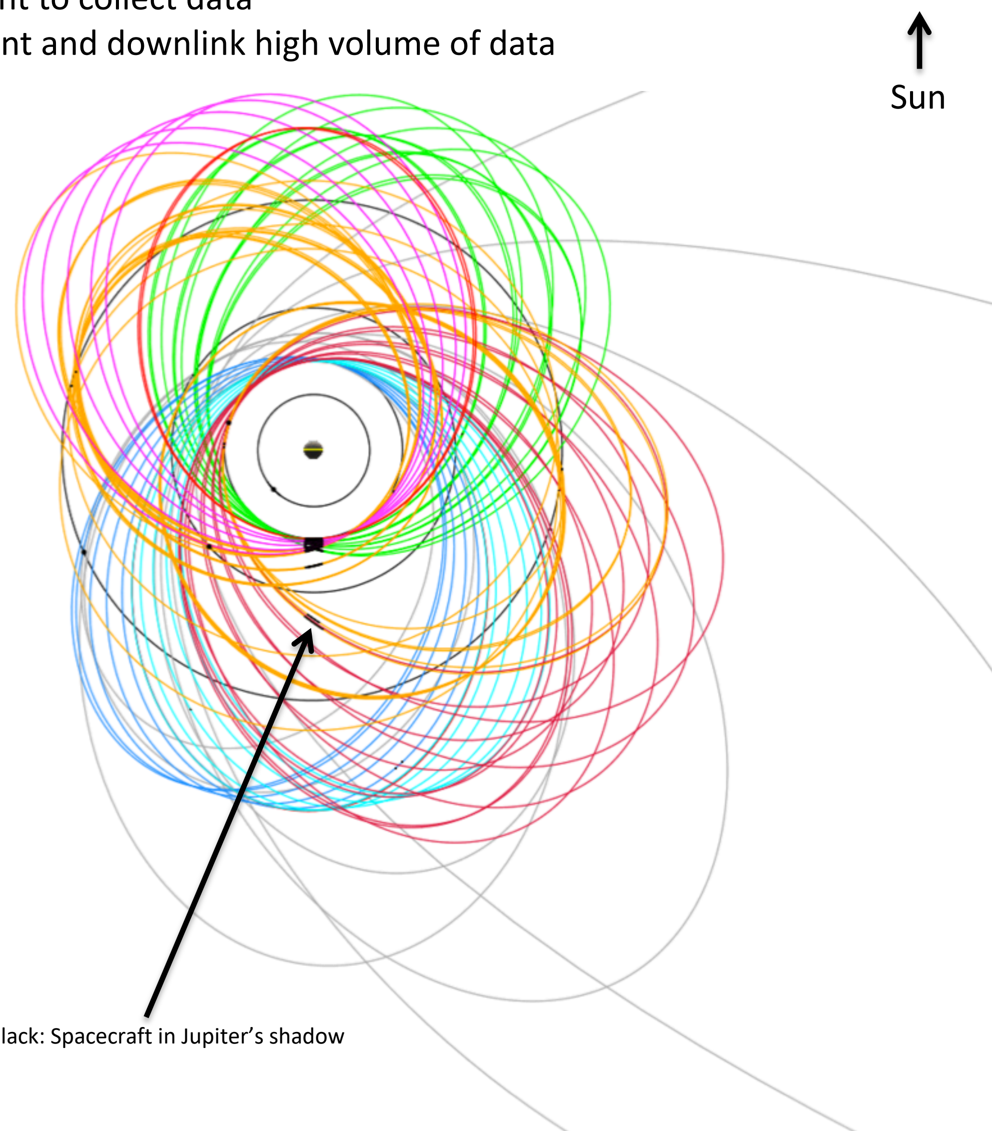
Europa Multiple Flyby Mission Concept

- Dip into the harsh radiation environment to collect data
- Get out of intense radiation environment and downlink high volume of data

Key Statistics	13F7-A21
Tour Duration	3.5 years
Number of Flybys: Europa Ganymede Callisto	 45 5 9
Time between Flybys: Maximum* Minimum Mean*	 57.2 days 5.5 days 18.9 days
Maximum Inclination	20.1°
Maximum Eclipse Duration	4.5 hours
Total Ionizing Dose** (TID)	2.8 Mrad
Deterministic ΔV (post-PRM)	164 m/s
Statistical ΔV (99%)	223 m/s
Total Mission ΔV	1596 m/s

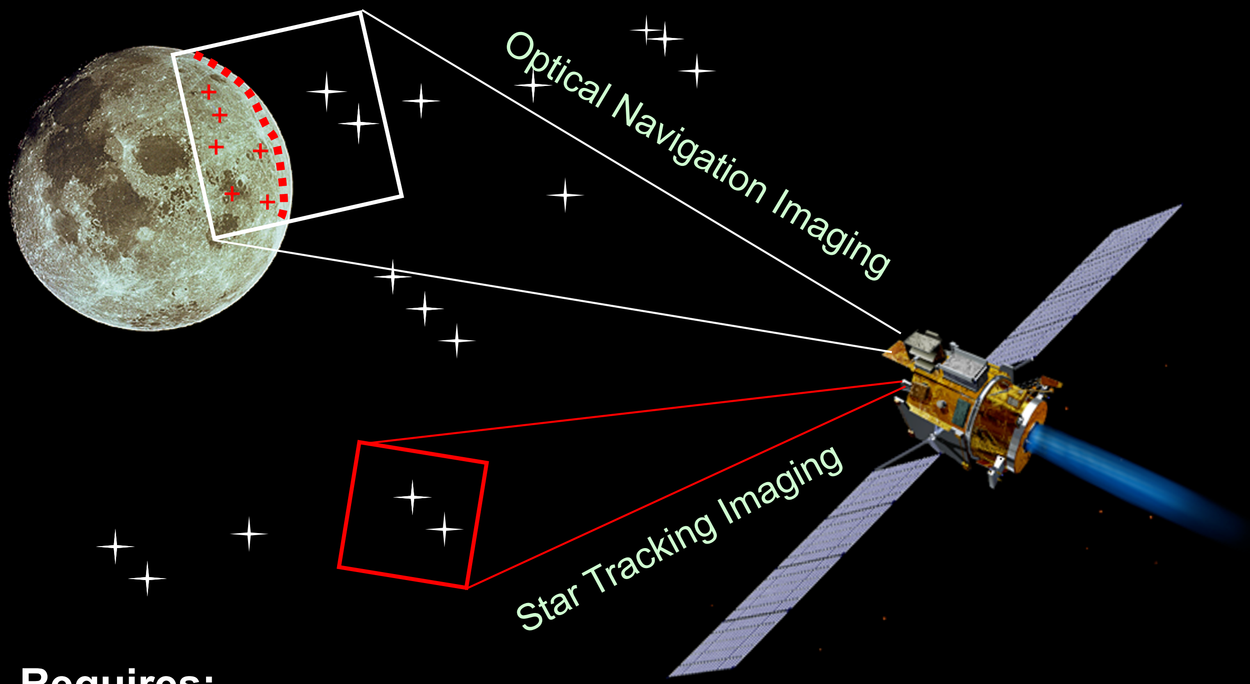
*Not including the 202-day capture orbit

**Si behind 100 mil Al, spherical shell (GIRE2)



What is Optical Navigation?

Vital for objects with uncertain positions or autonomous operations.



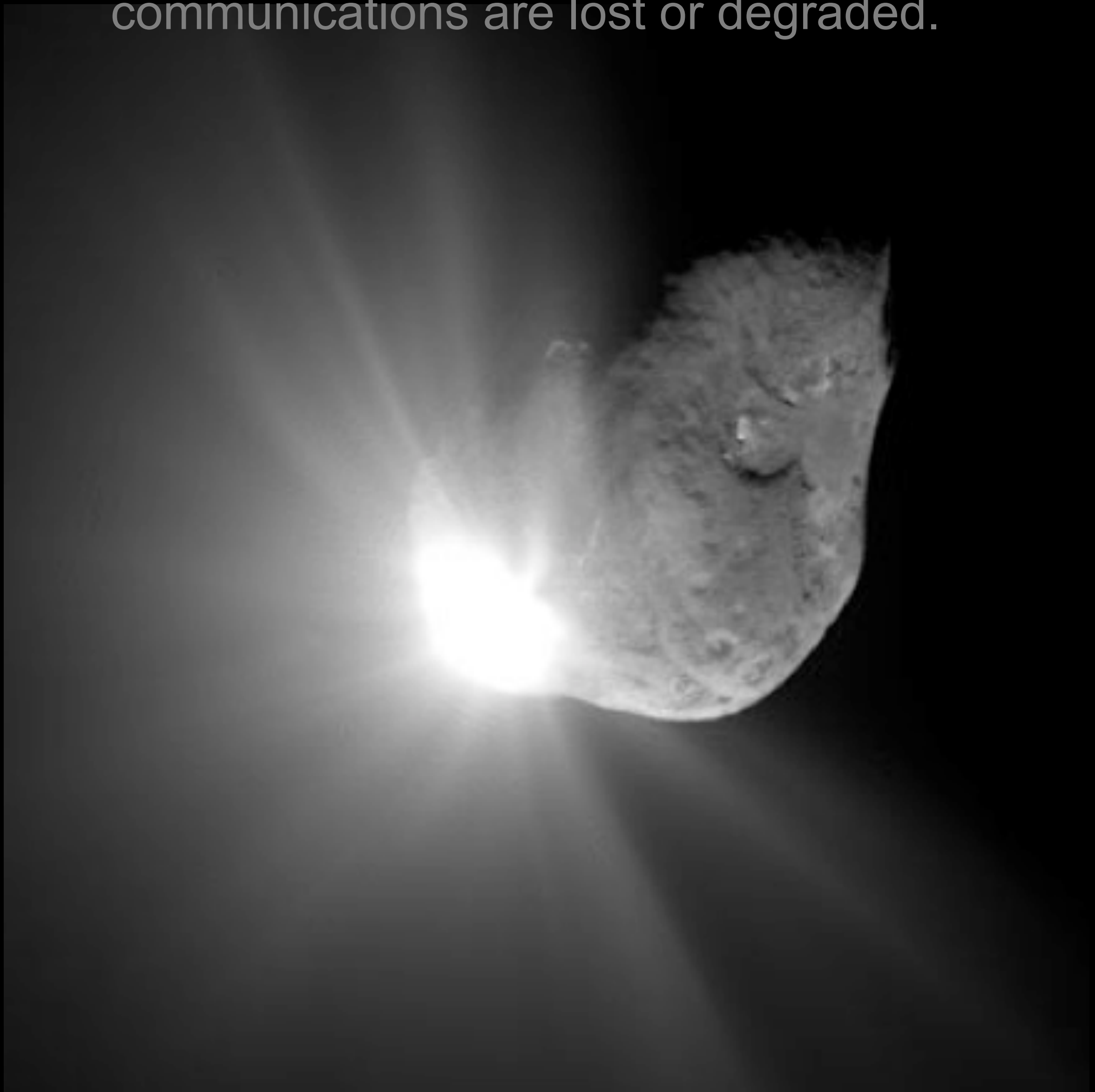
Determining the location of a near-field object (e.g. the Moon) relative to a well-known far-field object (e.g. the background starfield) or relative to well known camera attitude.

Requires:

- Accurate star catalogs, and physical body models, including landmarks.
- Accurate camera calibrations including geometric distortions and photometric modeling.
- Astrometric-quality imaging systems (often) with high-dynamic range.
- Filtering and estimation of optical-relevant parameters with s/c position and attitude.
- Ground-based Optical Navigation processing is very similar to radiometric ground processing - with the addition of (sometimes difficult and labor-intensive) image processing.

AutoNav

Enabling for high speed encounters or for contingencies where radio communications are lost or degraded.



On July 4, 2005, AutoNav enabled the third of NASA's first three comet nuclei missions DeepImpact at Templ1 (left); the other two being:

Borrelly, Sept 2001, and Wild 2, Nov. 2002, both also captured with AutoNav. These were followed by Hartley2 in 2010, and a Tempel 1 revisit in 2011.

AutoNav placed optical navigation elements onboard for otherwise impossible speedy turn-around of navigation operations.

Collaboration with NASA/JPL MD/Nav

Four Benefits:

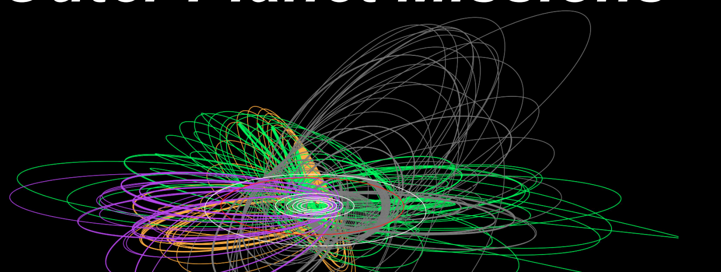
1. **Leverage decades of Deep Space development and operations experience**

2. **Deep bench of JPL personnel available to address surge needs and convey lessons learned**

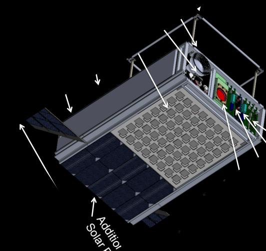
3. **Mature tools and techniques:**
   - For design and flight of various mission types (landers, orbiters, impactors and flyby vehicles)
   - For incorporating DSN and onboard measurements (Doppler, Ranging, ∆DOR, OpNav, AutoNav, GPS)
   - For high precision trajectory reconstruction, prediction and optimal targeting

4. **Significant automation built into JPL tools enabling efficient use of workforce and cost competitive services**

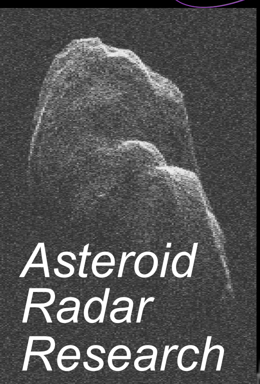
Outer Planet Missions



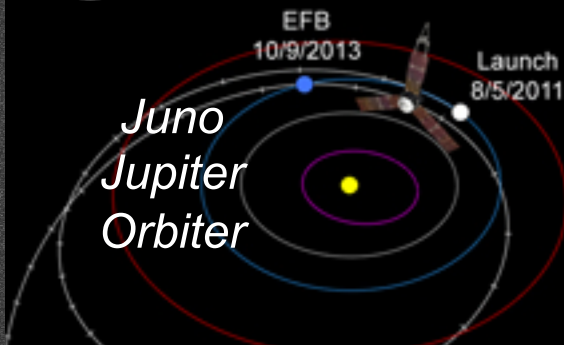
Cassini Saturn Tour



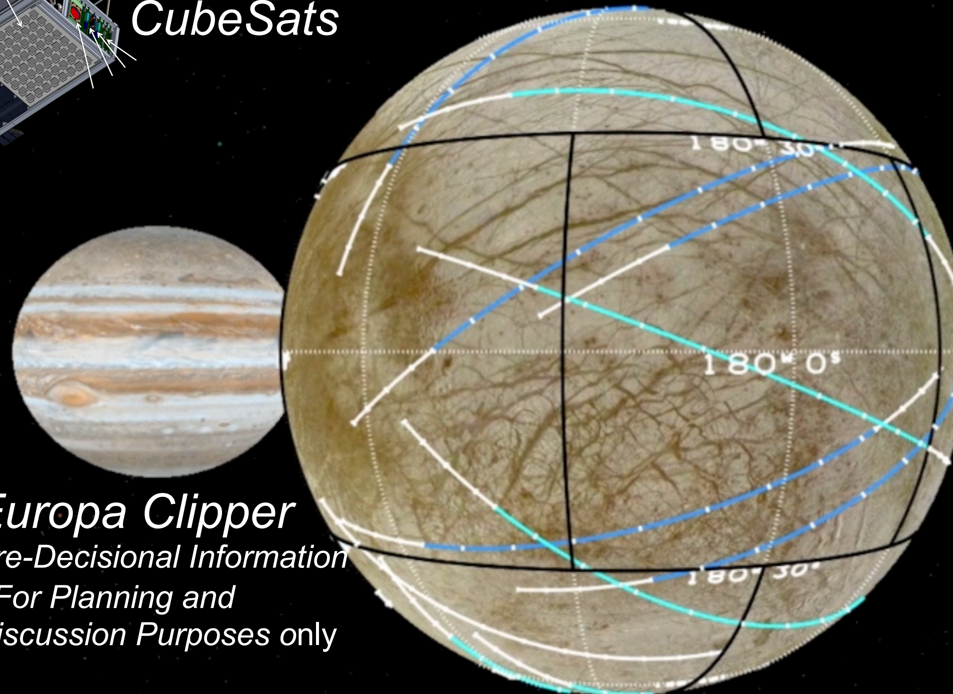
Interplanetary CubeSats



Asteroid Radar Research



Juno Jupiter Orbiter



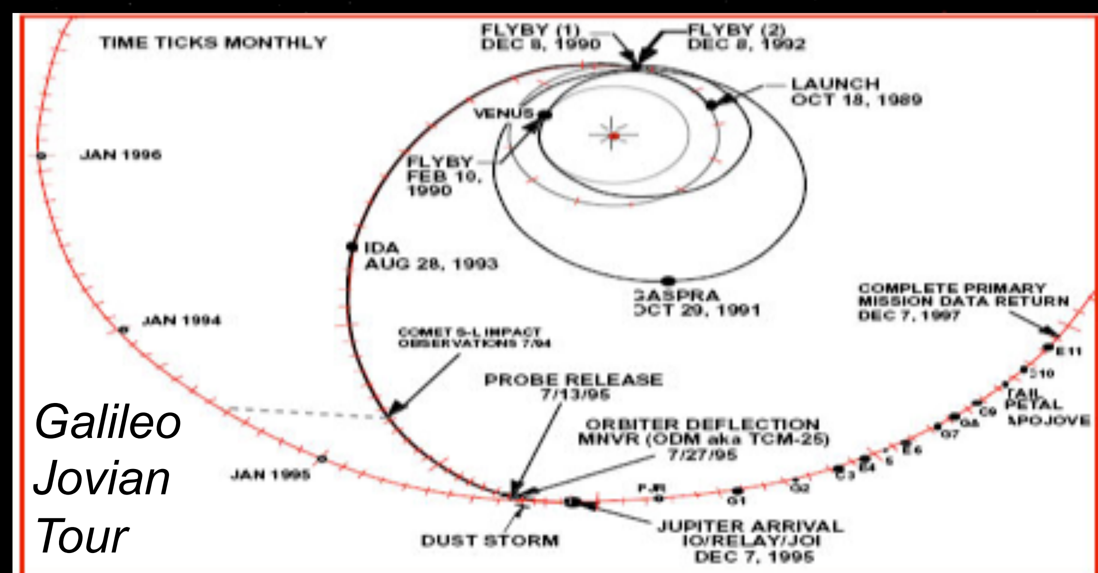
Europa Clipper

Pre-Decisional Information - For Planning and Discussion Purposes only

The Navigation and Ancillary Information Facility

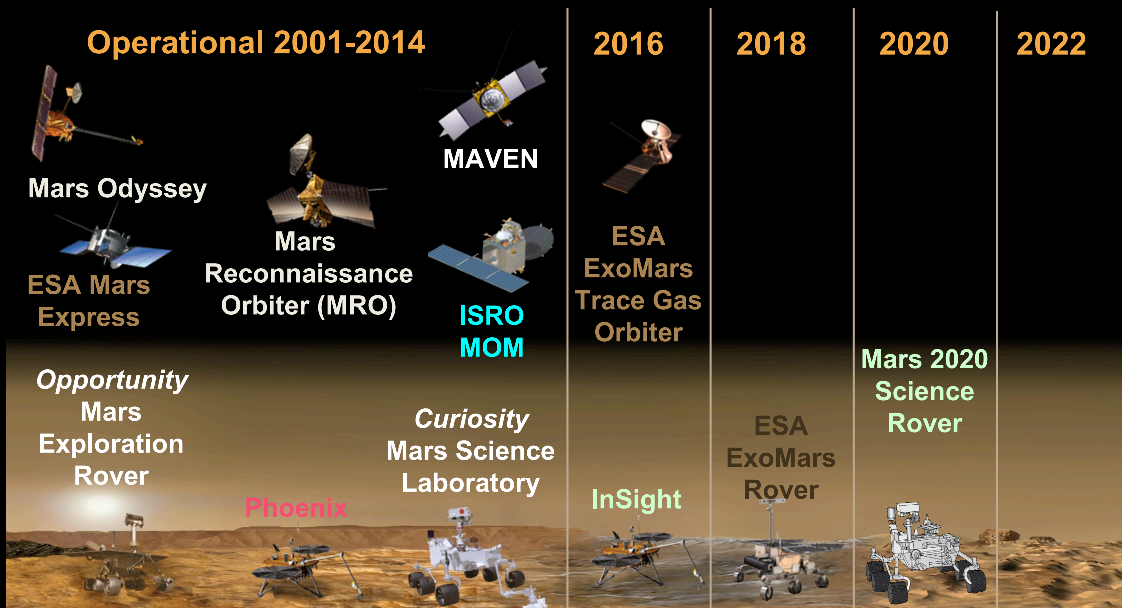
NAIF

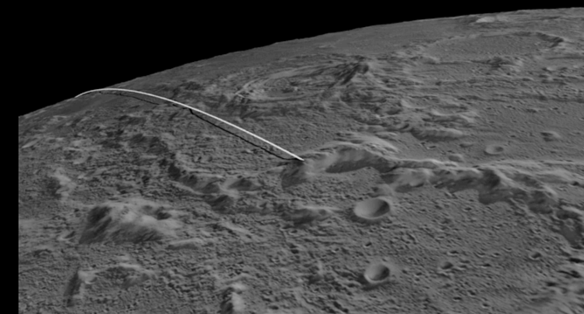
New Horizons Pluto



Galileo Jovian Tour

Mars, Lunar and Small Body Experience





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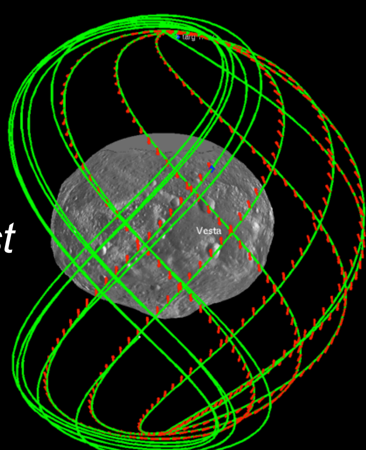

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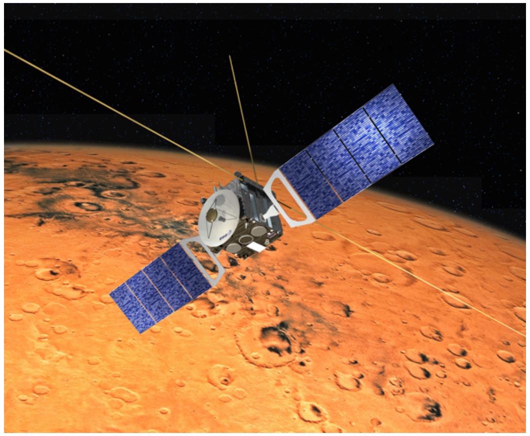
Stardust: Comet Coma Sample Return

Earth Return (2006)

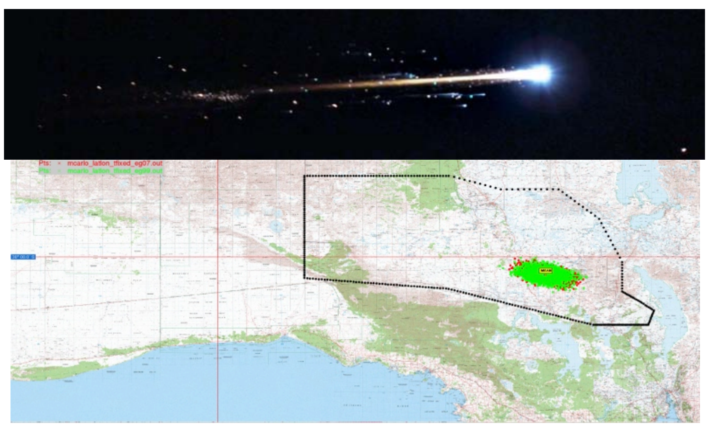
International Partnerships



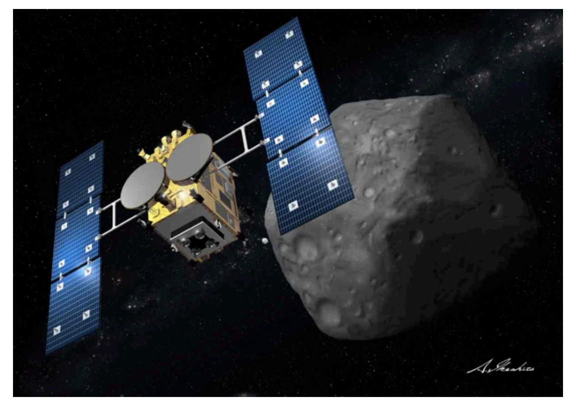
ESA Mars Express (2003)
Mars Orbit Insertion

ISRO Mars Orbiter
(Ongoing)

ESA Rosetta
Comet Rendezvous/Landing (2014)



JAXA Hayabusa-1 Comet Sample Return
(2010) Earth Return



JAXA Hayabusa-2 Asteroid
Sample Return (2014-2020)

Deep Space Navigation

Four Things Needed Beyond Low Earth Orbit:

1. **Positions and Physical Models of Celestial Bodies**

2. **“Flyable” Trajectories** (accounts for high fidelity perturbations)

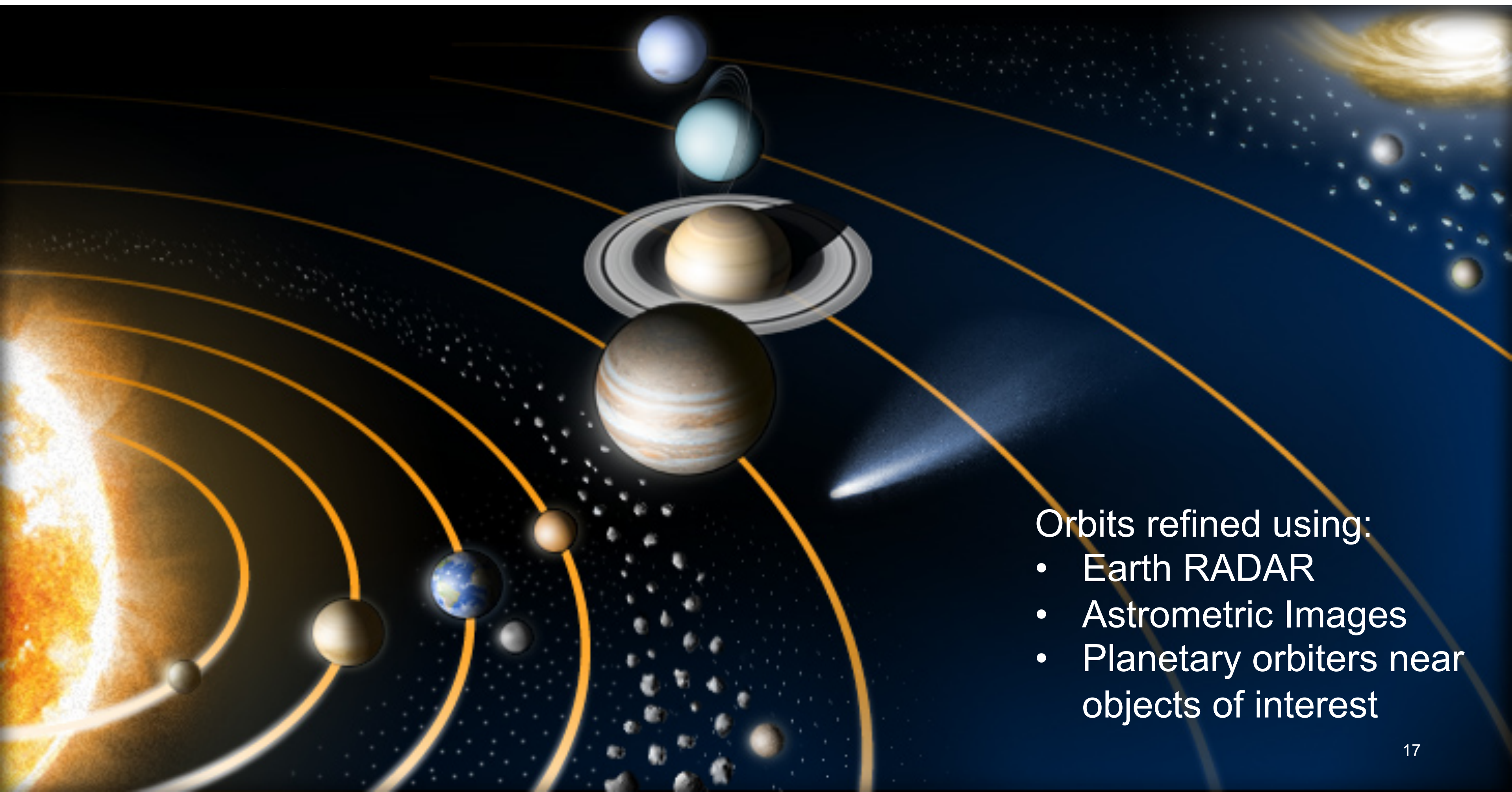
3. **Deep Space Network Tracking** (including interferometric, optical)

4. **High precision dynamic and measurement models**
   - Relativity – lots of gravity and high speeds tweak onboard clocks
   - Non-gravitational – spacecraft attitude control, venting, leaking and outgassing perturb trajectories
   - Maneuvers – chemical and electric to setup EDL, Orbit Insertions, Flybys

Celestial Body Positions – Past, Present and Future

Locations & Uncertainties of Planets, Natural Satellites and Small Bodies

NASA/JPL Maintains Horizons Database (Google Maps of the Solar System)
Currently Contains ~650,000 Objects

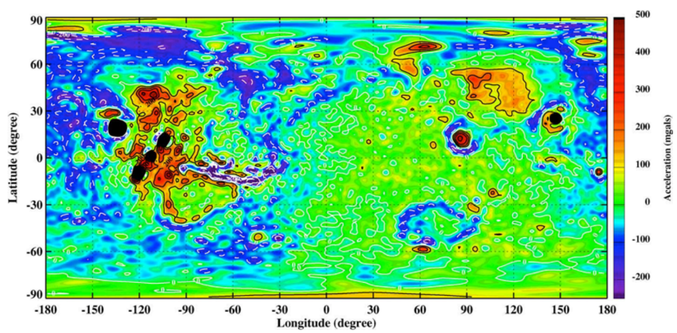


Determine Natural Body Physical Models

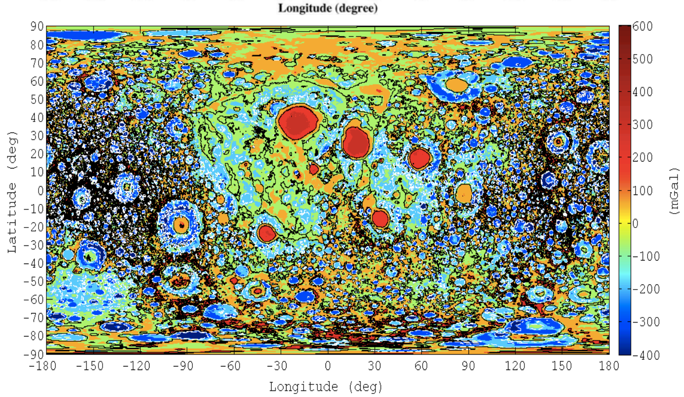
Often needed for flight operations prior to availability from science team

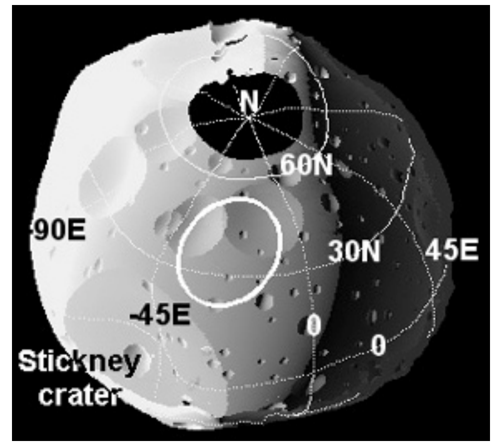
- *Pole Orientations*
- *Spin Rates*
- *Shape Models*
- *Gravity Fields*

Mars Gravity Map

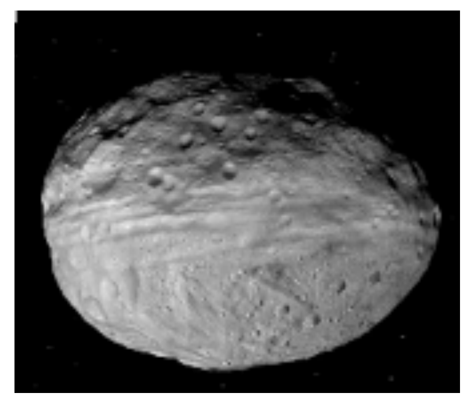


Lunar Gravity Map





Phobos Orientation

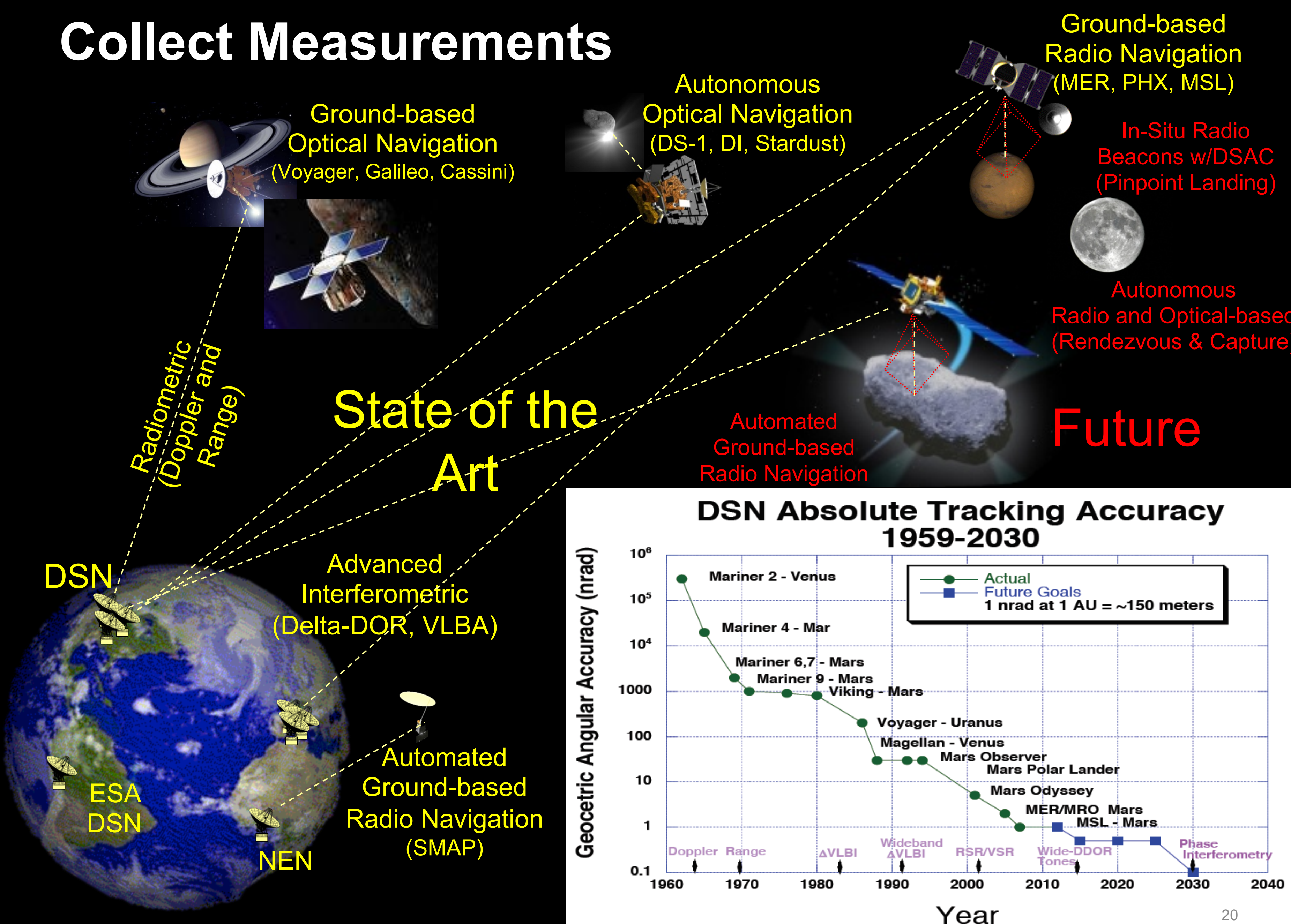


Vesta Shape Model

Develop "Flyable" Travel Plan

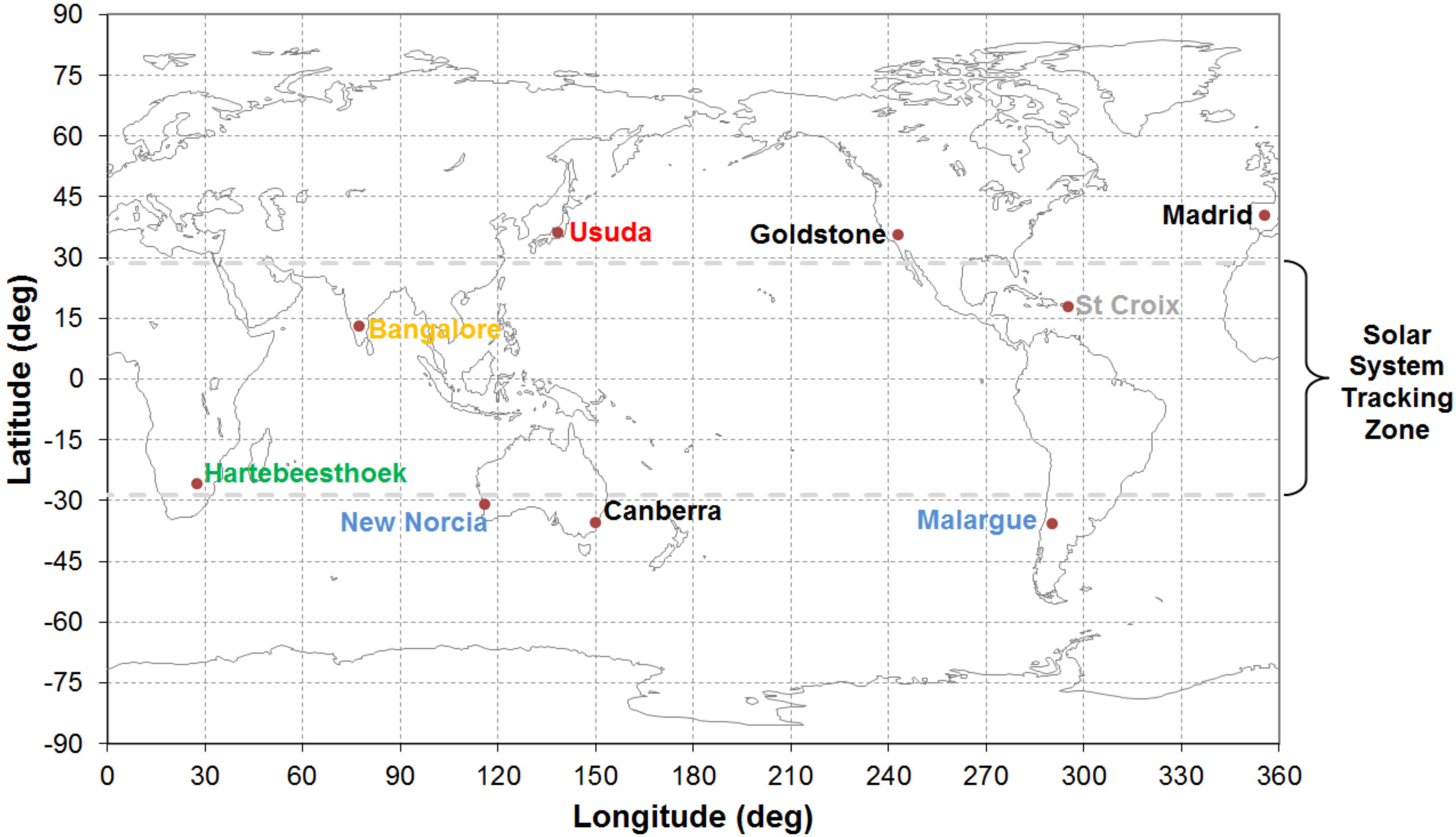
Optimal Trajectory Design

Collect Measurements

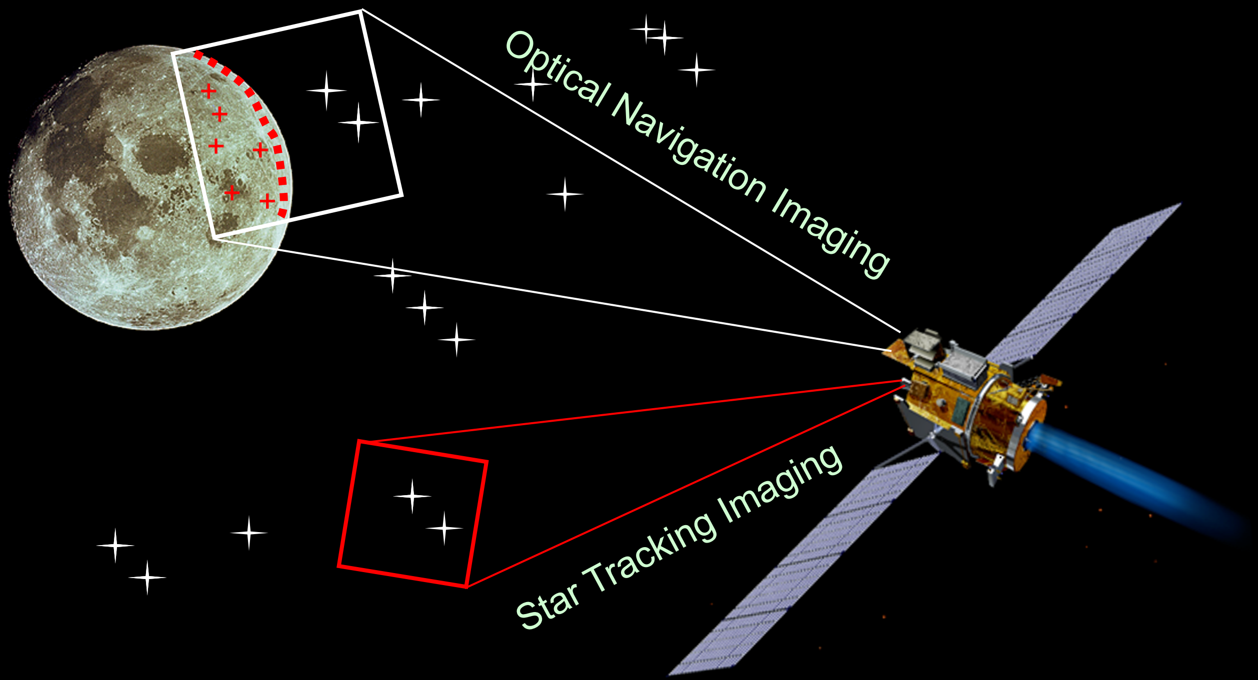


Deep Space Tracking Stations

NASA and non-NASA



What is Optical Navigation?



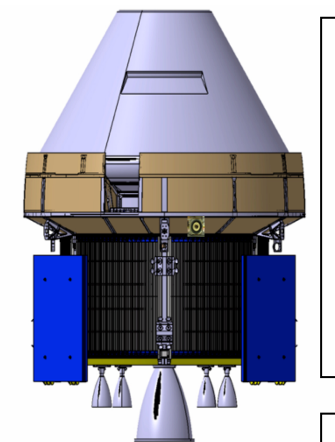
Optical Navigation:
The location of a near-field object (e.g. the Moon) relative to a well-known far-field object (e.g. the background starfield) or relative to well known camera attitude. (However, with a sufficiently wide-field imager, pointing knowledge can be obtained simultaneous to position knowledge)

Optical Navigation variously requires:

- Accurate star catalogs, and physical body models, including landmarks.
- Accurate camera calibrations including geometric distortions and photometric modeling.
- Astrometric-quality imaging systems (often) with high-dynamic range.
- Filtering and estimation of optical-relevant parameters with s/c position and attitude.
- Ground-based Optical Navigation processing is very similar to radiometric ground processing - with the addition of (sometimes difficult and labor-intensive) image processing.

X/Ka Band Telecom Package for Orion/SM

Improvements for Navigation and Data Return for Human Exploration

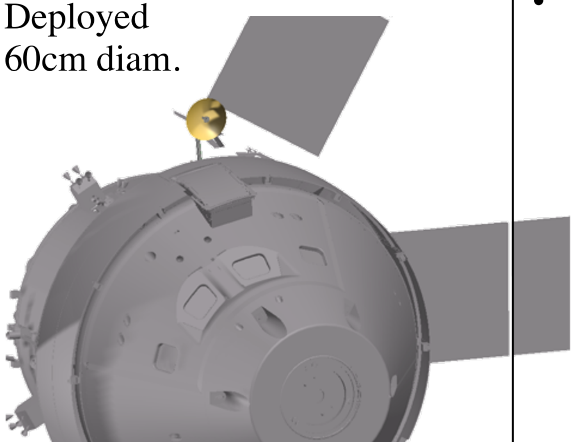


- Capability
  - X-band uplink, X- or Ka-band Downlink, with higher rates suitable (e.g.) for video conferencing
  - Deployed starting with EM-2
  - Primarily used above GEO

- Mounted on the CMA, with minimal interfaces
  - Power (120 V DC)
  - RS422 for control
  - Ethernet (for data)
  - Mechanical fastening
- No/minimal change to Orion contract

- Self-contained package
  - Electronics, Antenna/deployment, Power conversion, Controller, Thermal
- Fully CCSDS compliant

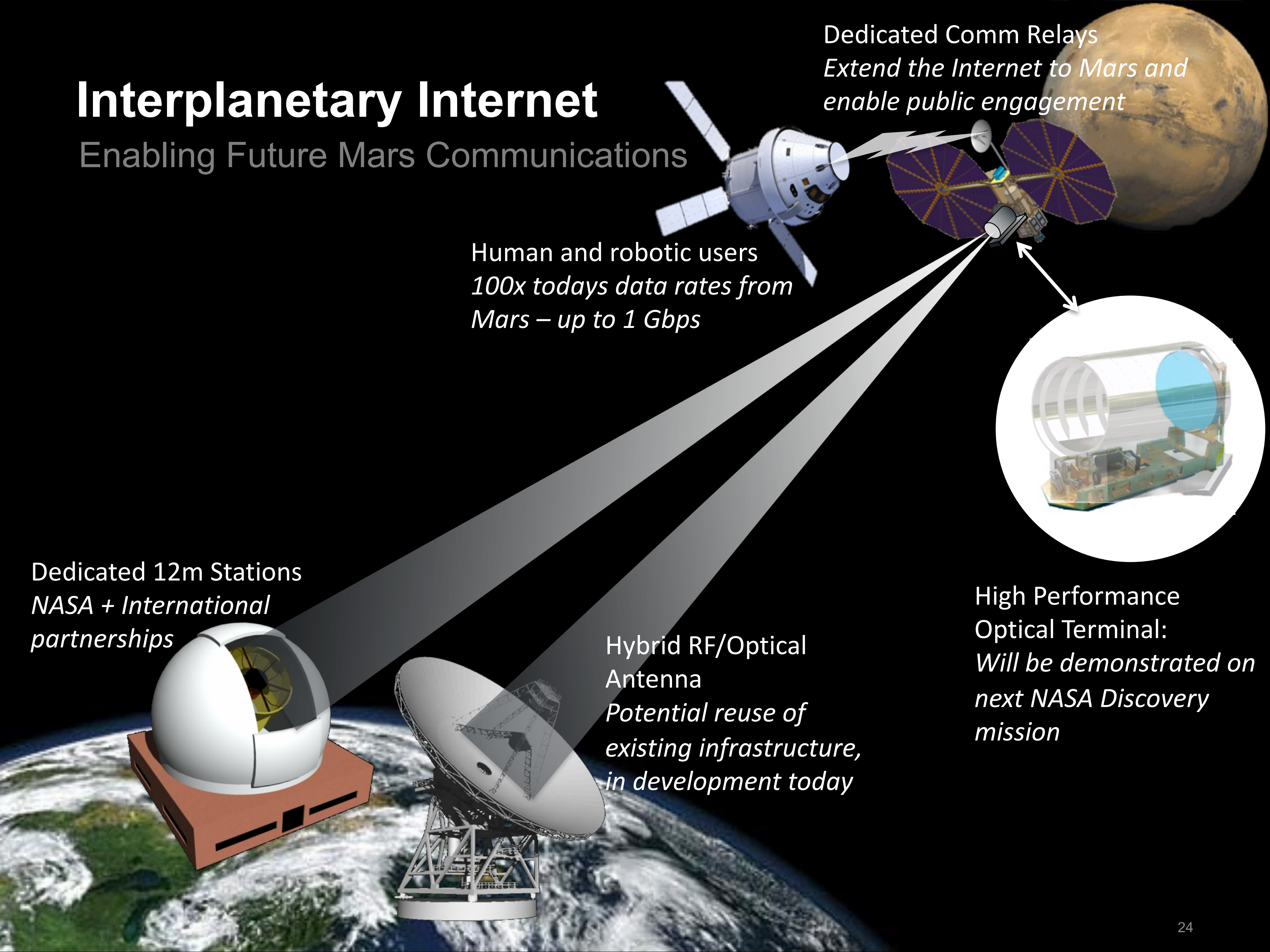
Deployed
60cm diam.



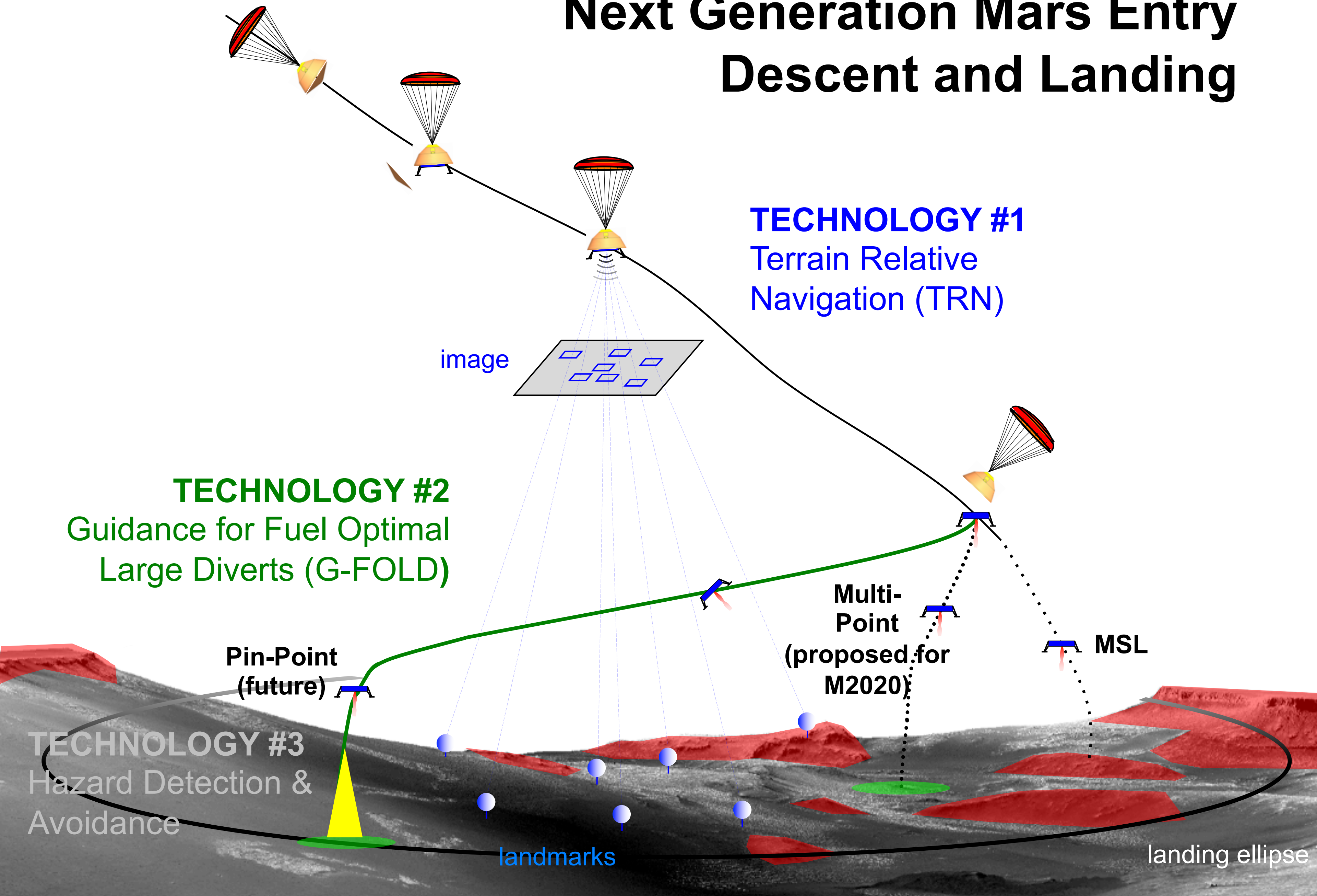
- Benefits
  - Provides higher-data rates, relative to current S-band capability
  - Improves navigation performance (higher frequency, greater ground station availability) for smaller delivery error ellipses
  - Increases support from international assets for uplink, downlink and Nav (using international/CCSDS standards)
  - Leverages NASA's existing investment in DSN systems
  - Enables missions beyond Lunar distances
  - Consistent with NASA's spectrum plan

Interplanetary Internet

Enabling Future Mars Communications

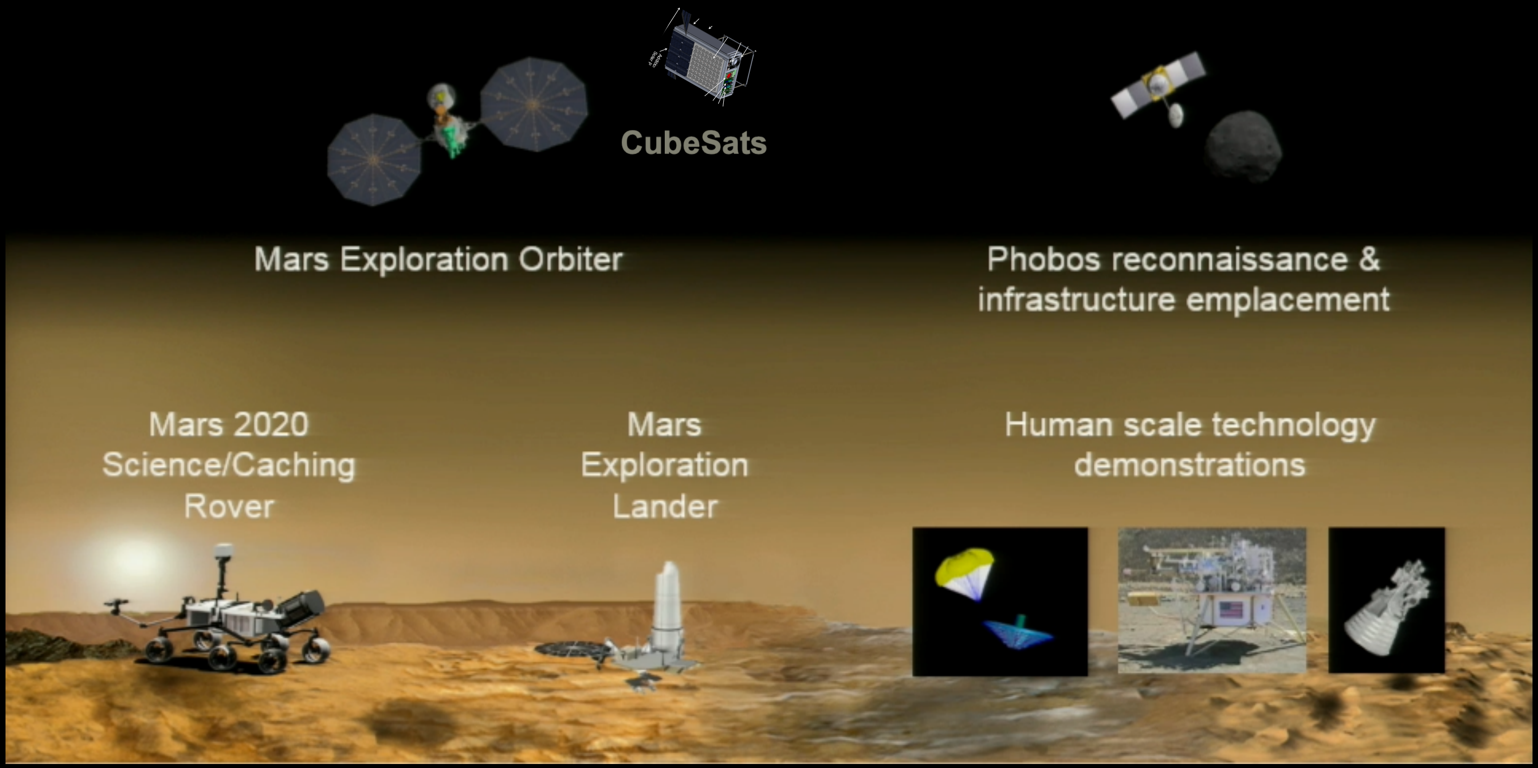


Next Generation Mars Entry Descent and Landing



Looking Ahead – Mission Concepts

***Pre-Decisional Information -- For Planning and Discussion Purposes* only**



Technology Infusion:

- Deep Space Atomic Clock – to reduce DSN tracking needs
- Low-Thrust / Low-Energy Trajectories – to increase mass delivery
- Onboard Optical and Radio Navigation - to enable pinpoint landing and autonomous operations

Collaboration with NASA/JPL MD/Nav

Five Benefits:

1. **Leverage decades of Deep Space development and operations experience**

2. **Deep bench of JPL personnel available to address surge needs and convey lessons learned**

3. **Mature tools and techniques:**
   - For design and flight of various mission types (landers, orbiters, impactors and flyby vehicles)
   - For incorporating DSN and onboard measurements (Doppler, Ranging, ∆DOR, OpNav, AutoNav, GPS)
   - For high precision trajectory reconstruction, prediction and targeting

4. **Significant automation built into JPL tools enabling efficient use of workforce and cost competitive services**

5. **Future Robotic/Human mission interoperability**

NASA Deep Space Entry/Re-Entry Experiences

Entry Point Targeting

Earth:

- Genesis (2004 direct entry)
- Stardust (2006 direct entry)

Mars:

- Viking 1,2 (1976 from orbit)
- Mars Pathfinder (1997 direct entry)
- Mars Exploration Rovers (2004 direct entry)
- Phoenix Mars Lander (2008 direct entry)
- Mars Science Laboratory (2012 direct entry)

Jupiter:

- Galileo (2003 from orbit)

Titan:

- Cassini-ESA/Huygens (2005 from Saturn orbit)

Deep Space Navigation Components

- **Deep Space Navigation refers to orbit determination & prediction, and maneuver design to reach desired target at desired time.**
  - Target orbit/position is usually estimated in advance separately, but sometimes improved with navigation data.
- **Tracking data used from Earth observatories.**
  - Primarily done with antennas of the Deep Space Network (DSN) located in Goldstone (CA), Madrid (Spain), and Canberra (Australia).
  - Occasionally augmented by stations in Japan (ISAS), Australia, and Argentina (ESA).
- **Navigation phases include; cruise, planetary orbit, satellite tour.**
  - Cruise generally has weakest observation geometry.
    - Most demanding performance to date is direct landing on Mars (MSL).
  - Planetary orbiters generally have larger dynamical signature.
  - Satellite tour (e.g. Galileo, Cassini) geometrically in-between
    - Satellite orbit determination often requires spacecraft-based imaging

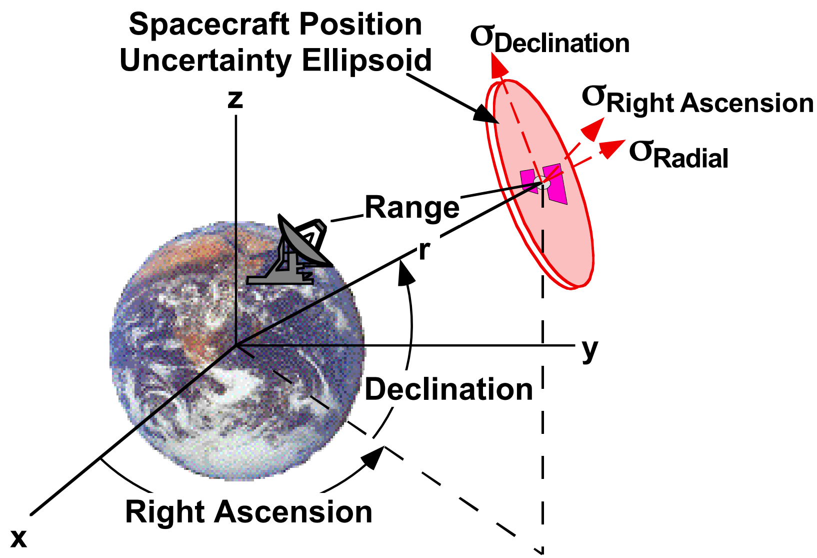
Current Deep Space Navigation Data Types

- **Radio metric observations are based on light-time.**
  - Usually multiplied by speed to light to express as distance.
  - Accuracy of clocks at stations often limit accuracy.
- **Doppler measures rate of change of light time (velocity).**
  - Measurement precision is ~(λ/1000)/100 s ~ 3μm/100s ~ 0.3μm/s ~ c/10^{15}.
  - Accuracy is usually limited by solar plasma, ionosphere, or troposphere.
  - High accuracy of Doppler is essential for estimation of force models.
- **Range measures absolute light time (1-way or 2-way).**
  - Radio uses group delay of modulation with accuracy of ~ 1 m.
    - 2-way range usually used; 1-way range requires much better clock accuracy.
    - Better accuracy not helpful, since transverse components much less well known.
- **VLBI or ΔDOR (delta-differenced one-way range).**
  - Measure difference of arrival time of signal from spacecraft at two stations.
    - Δt/c divided by distance between stations, gives angular measure.
    - Quasars (natural radio sources) used to calibrate difference in station clocks.

Orbit Error Components for Cruise

- **For cruise, we need to estimate the spacecraft position and velocity as a function of time.**

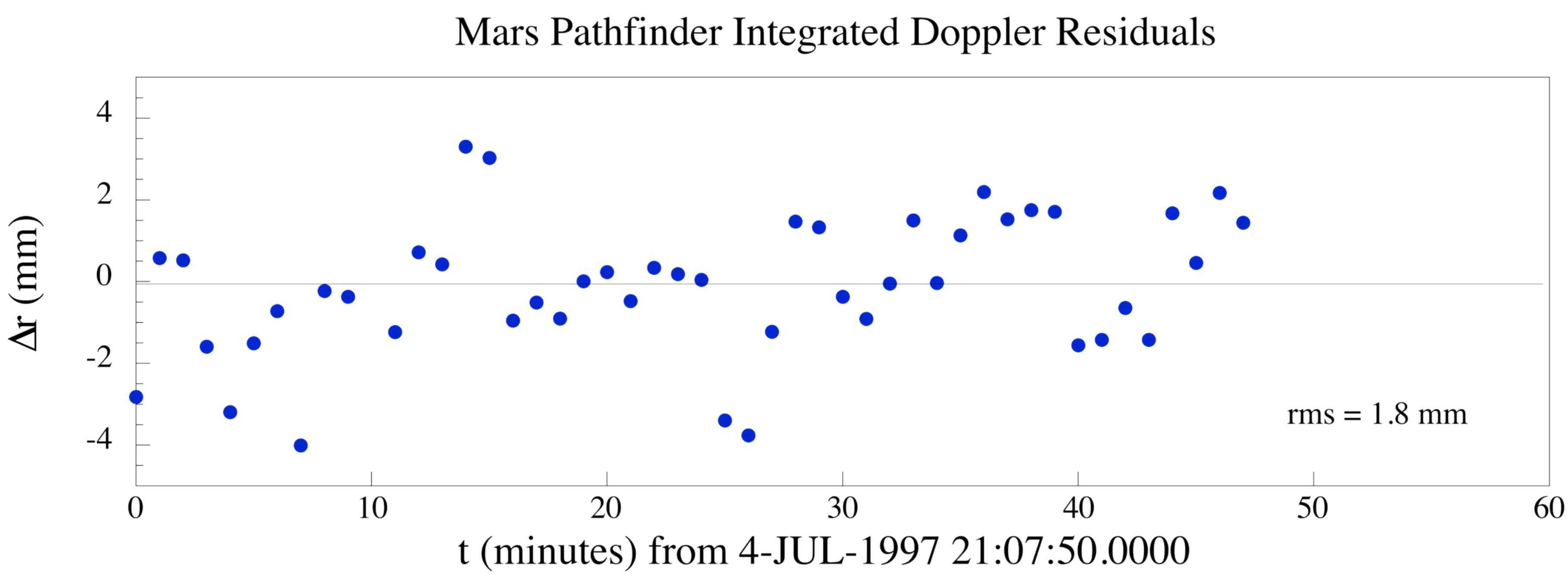
- **The radial (to Earth) position and velocity are directly measured by range and Doppler.**



- **Transverse position and velocity can be inferred from;**
  - Time history of Doppler (signature from Earth rotation).
    - Singular for zero declination.
  - Difference in range measurements.
    - Limited by station clock calibration to ~ 30 nanoradian.
- **VLBI/ΔDOR measures transverse position directly.**
  - Use of natural radio source as a timing calibration signal enables accuracy of <1 nanoradian.

Sample X-band Doppler Residuals

- **DSN Doppler files can be integrated to show actual measured changes in range.**
  - Unknown constant bias must be estimated.
- **Missing or deleted points complicate the integration.**
  - Require either correction for missing cycles or estimation of additional bias.
- **Sample shown is at SEP ~ 90°, so limited by wet troposphere noise.**



AutoNav

On July 4, 2005, AutoNav enabled the third of NASA's first three comet nuclei missions (at left); the other two being:

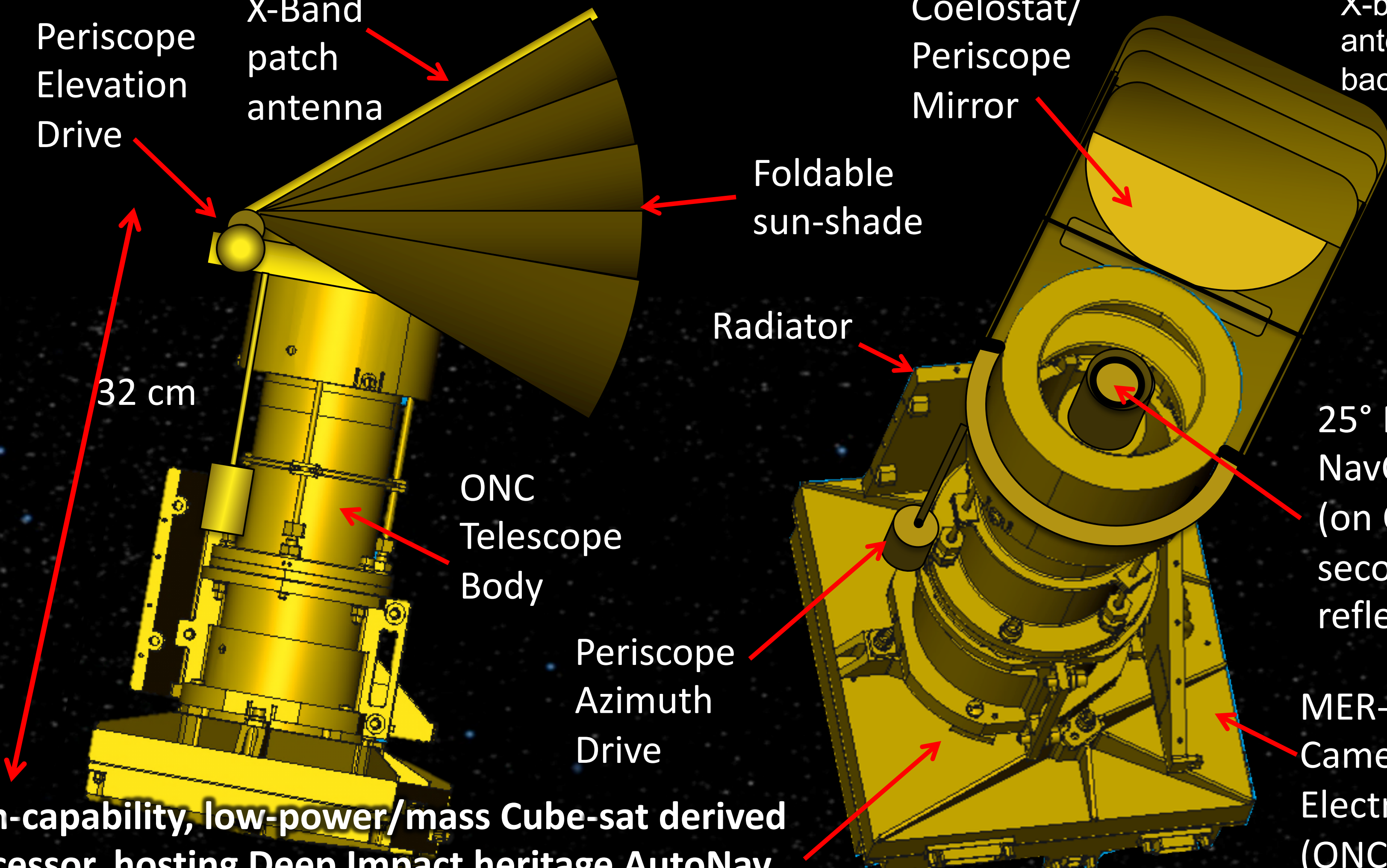
Borrelly, Sept 2001,
Wild 2, Nov. 2002, both also captured with AutoNav. These were followed by Hartley2 in 2010, and a Tempel 1 revisit in 2011.

AutoNav placed optical navigation elements onboard for otherwise impossible speedy turn-around of navigation operations.

Deep-space Positioning System (DPS)

Integrated Camera, Radio, Computer, FSW and optional Atomic Clock

Spacecraft position and control anywhere in the solar system, at any time. ™



High-capability, low-power/mass Cube-sat derived processor, hosting Deep Impact heritage AutoNav

Jet Propulsion Laboratory
California Institute of Technology