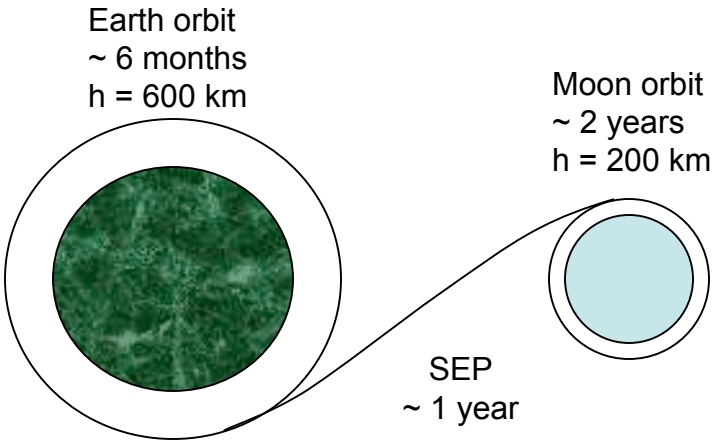


Architectures for Dual-Use Missions

Tony Freeman

JPL

Lunar Workshop

Tempe, AZ February 2007

GALILEO - A Dual-Body Mission?

Galileo - optical image gathered during Earth fly-by as part of instrument cal/val

Other Examples:

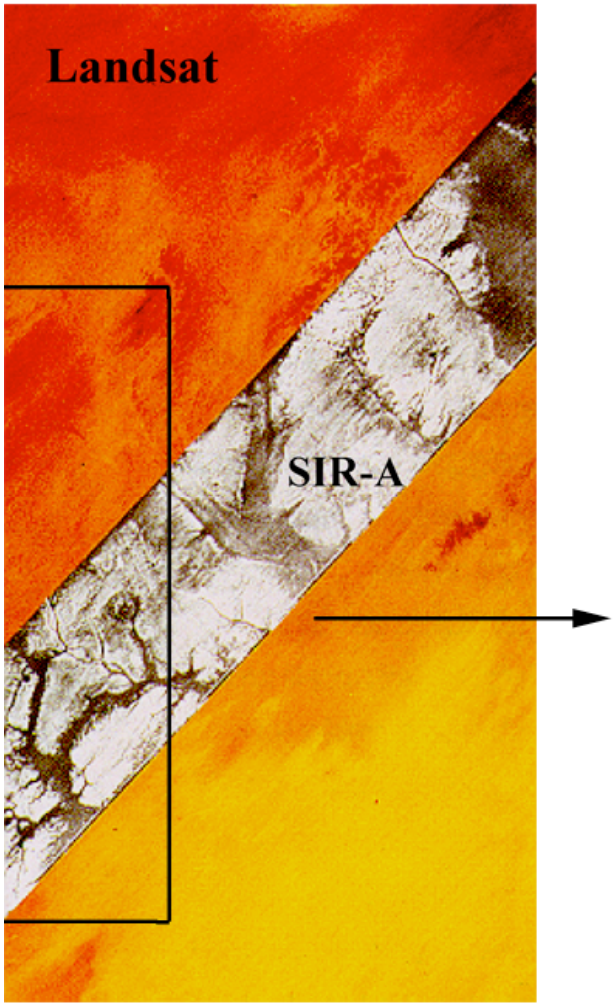
- Cassini
- Voyager
- Pioneer
- Deep Impact
- New Horizons
- Any Gravity Assist Mission

Dual-Body Missions

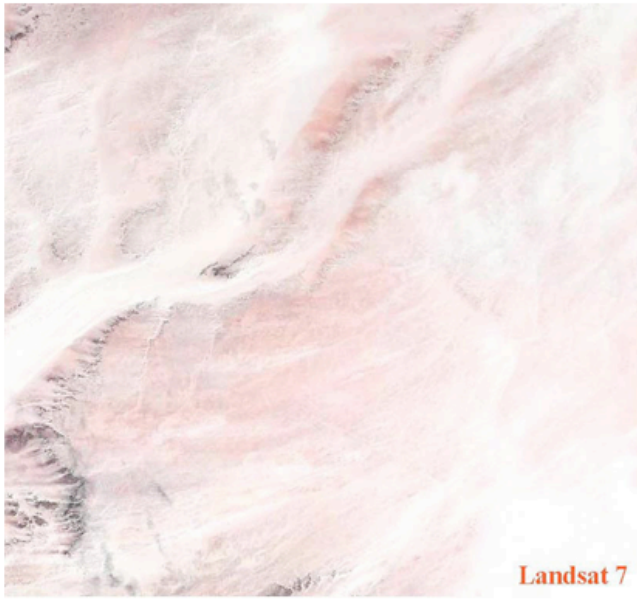
- Definition:
  - Achieve significant science return at each body (implies significant time is spent at each body - not just a fly-by)
  - Non-trivial energy is required to transfer between bodies
- Challenges:
  - Longer mission lifetimes
  - Rad-hardened electronics
  - Mission design

Uncovering the Landscape with Long-Wavelength Radar
- *Unfinished business*

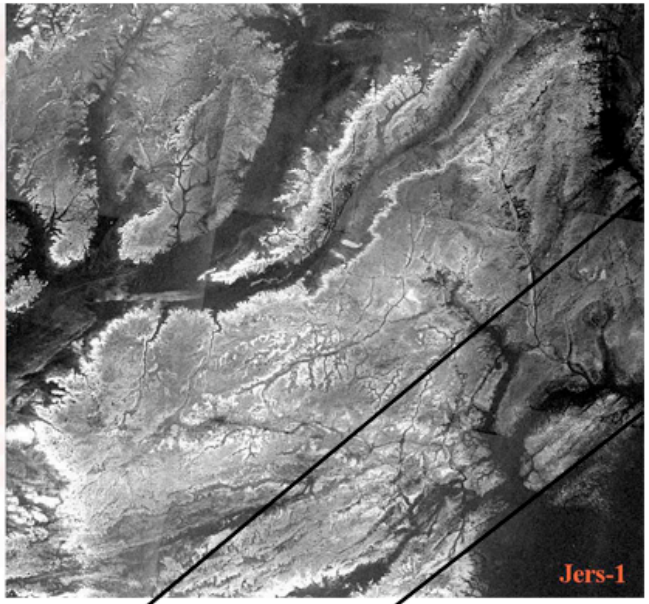
1981 Shuttle Radar



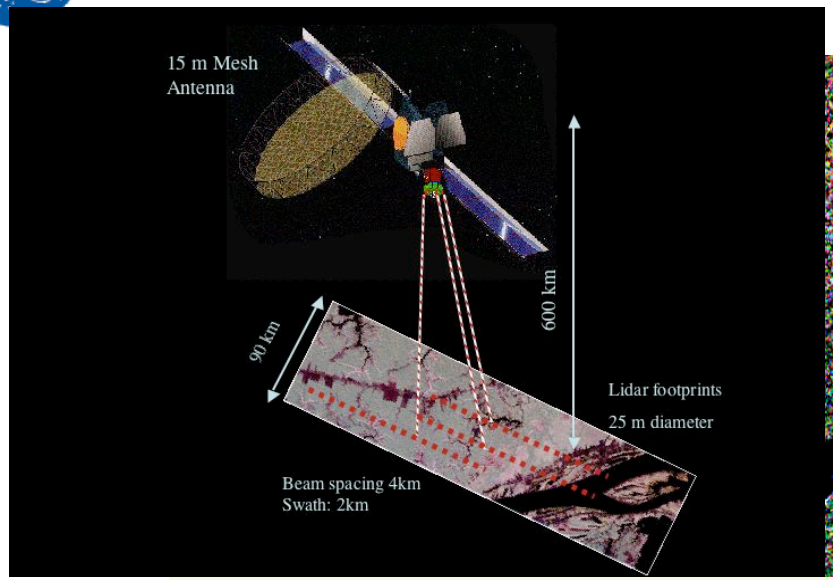
Landsat (visible)

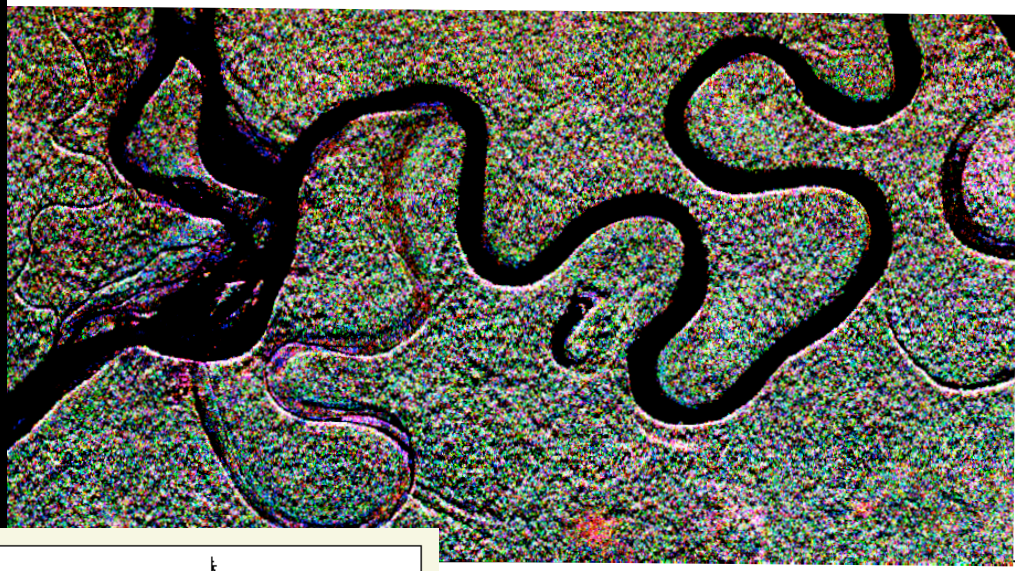


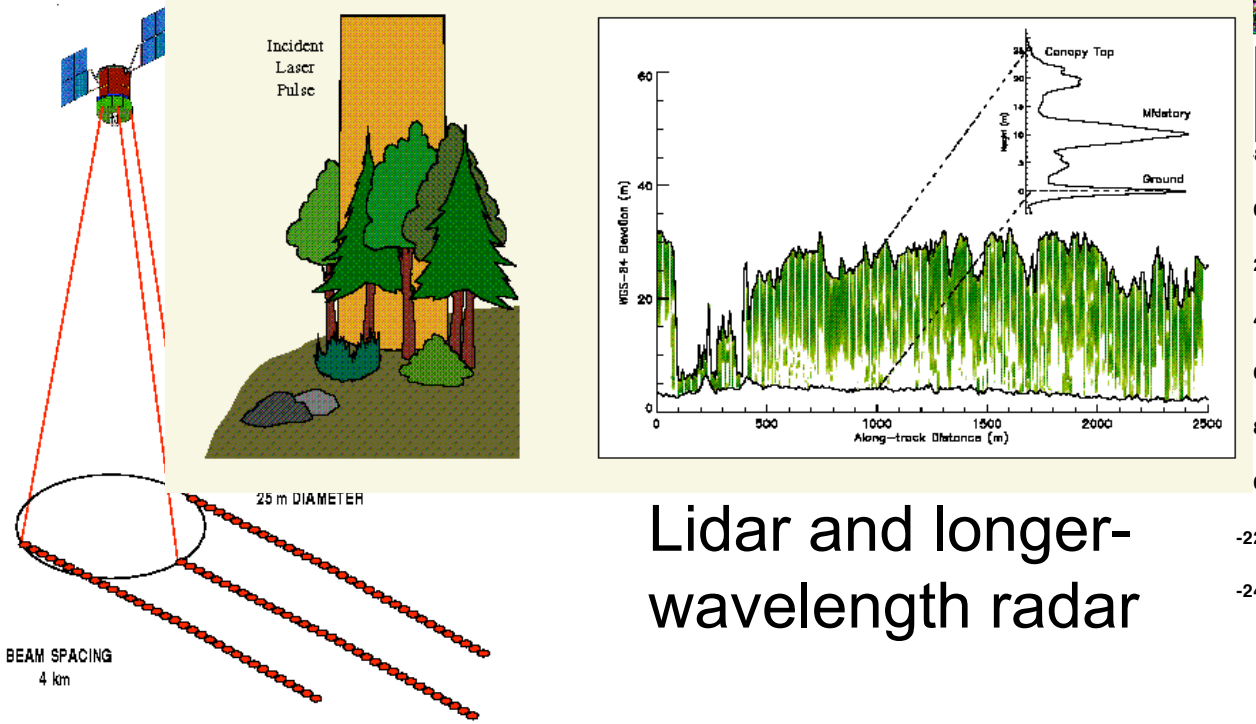
1992 Japanese Radar

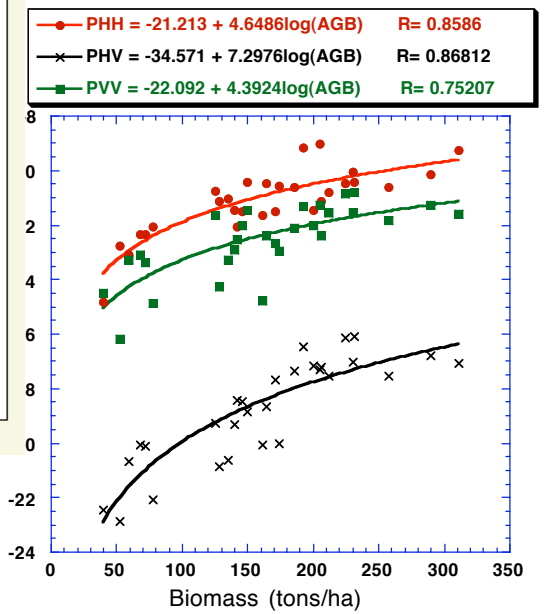


Global Vegetation Biomass



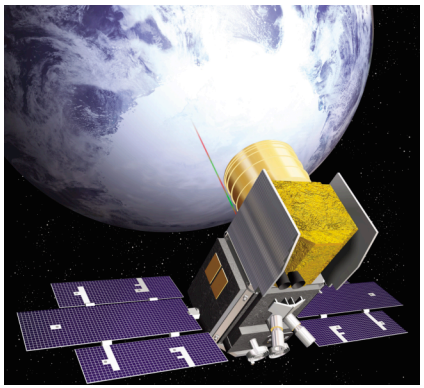


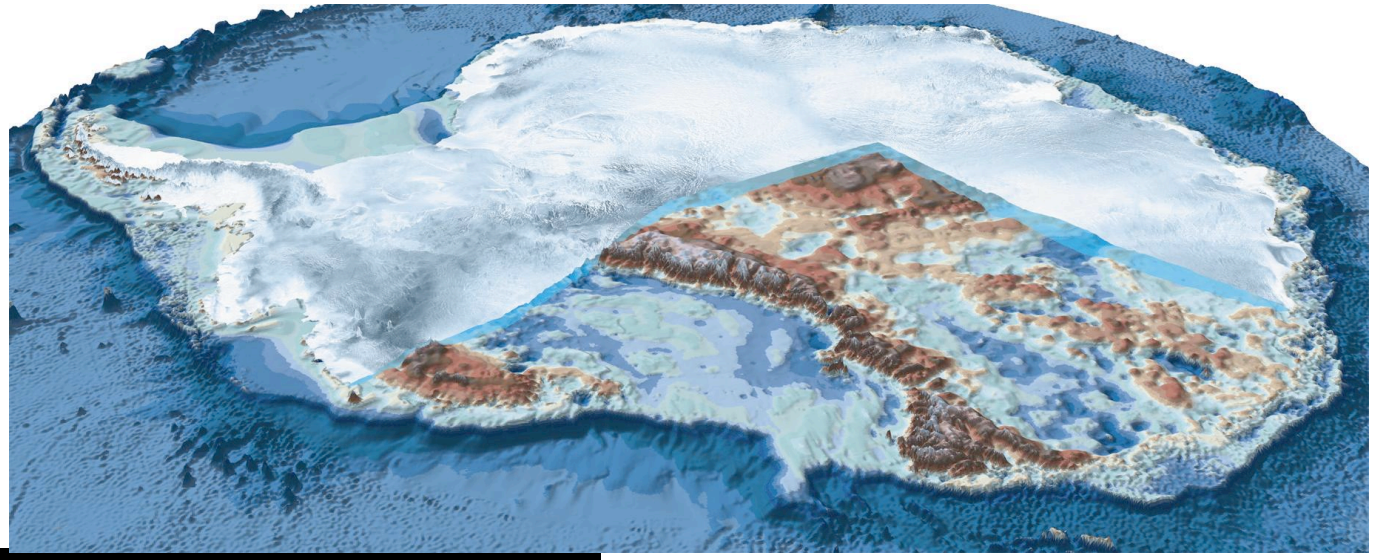


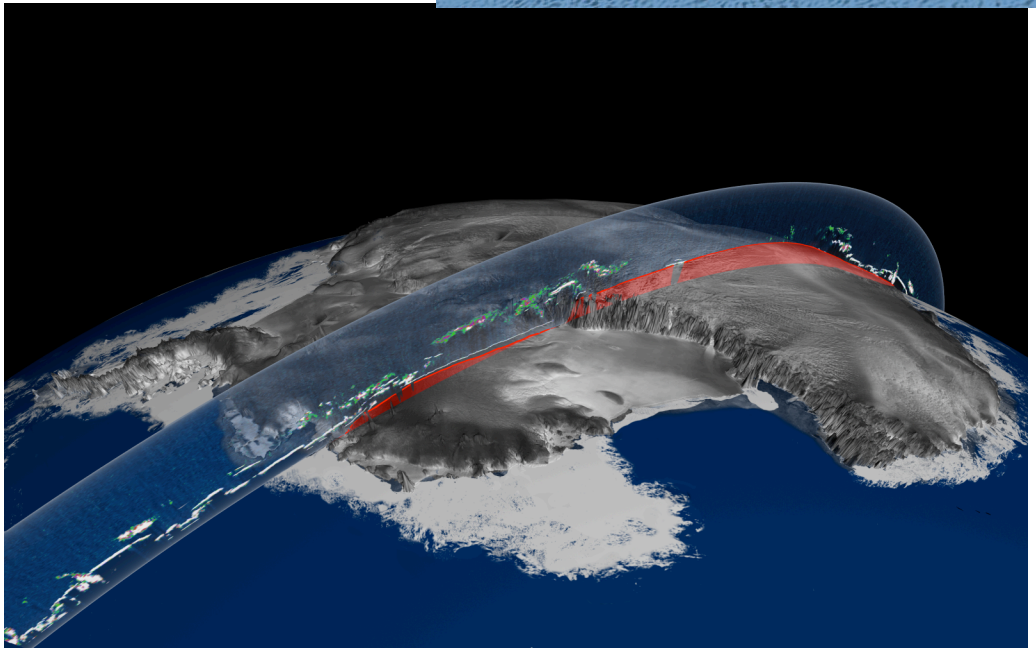


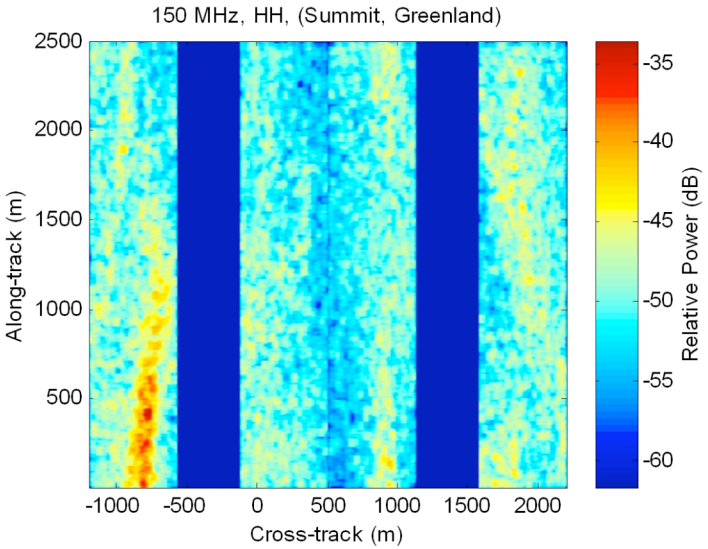
Lidar and longer-wavelength radar

Antarctica - probing the 3rd dimension with lidar and radar



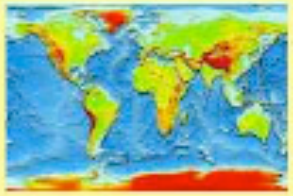






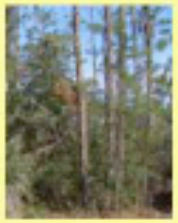
Lidar Surface Topography (LIST)

LIDAR Surface Topography (LIST)
Launch: 2016-2020
Mission Size: Medium



Global high resolution topography

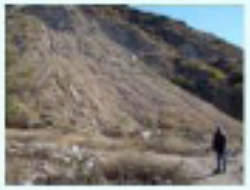
Detection of active faults



Global shifts in vegetation patterns and forest stand structure

Quantified assessment of wildfire risk

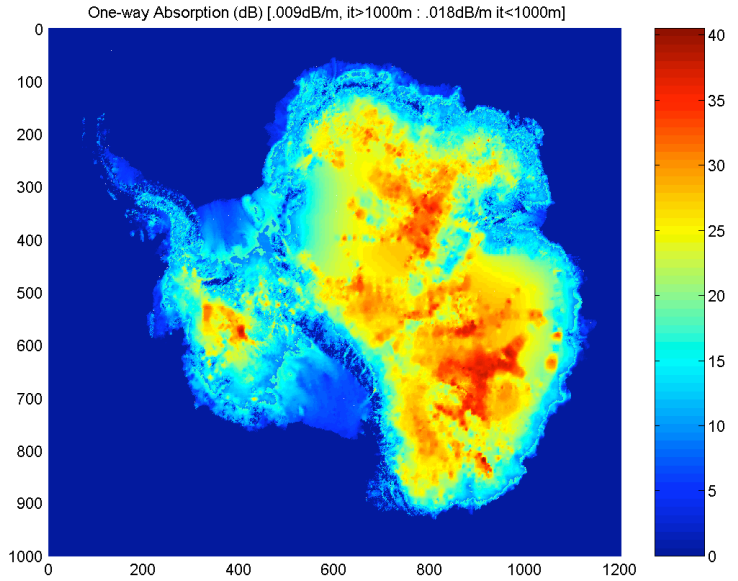
Monitoring land use change and the effects of land management



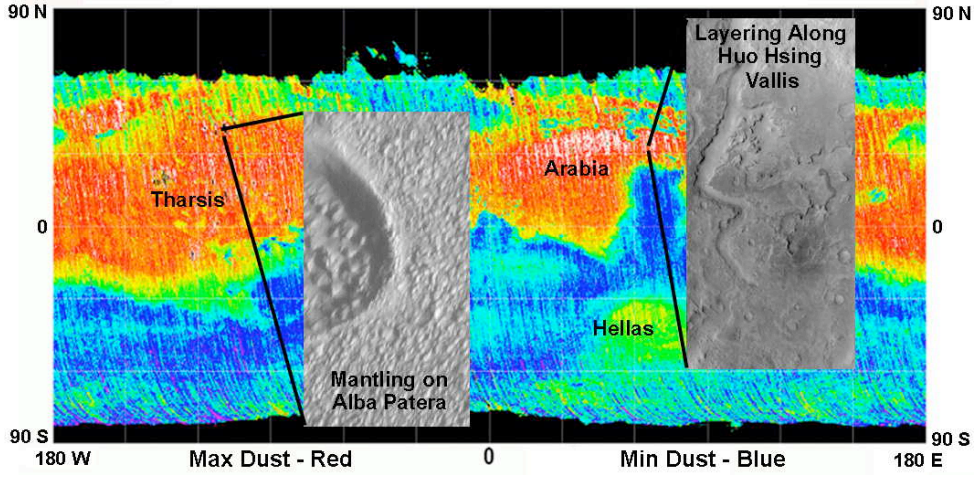
Forecast likelihood of volcanic eruptions, earthquakes, and landslides

Exploring Mars

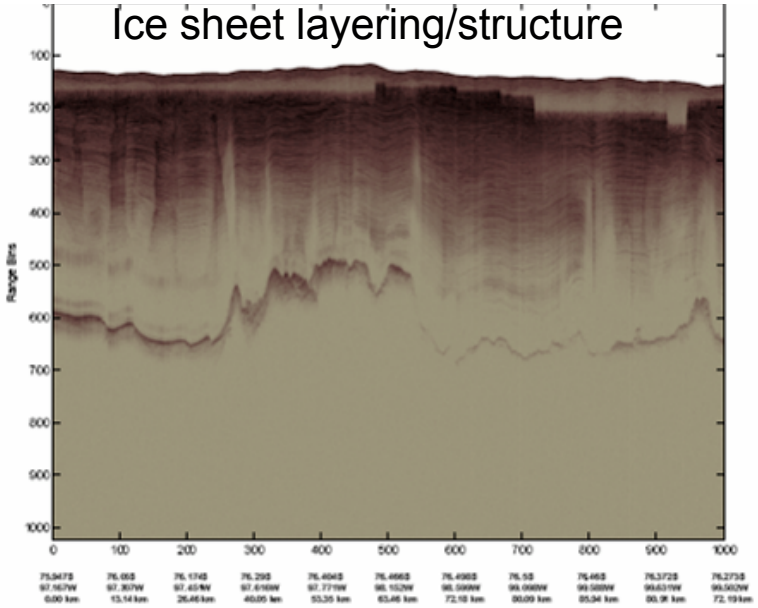
Polar ice sheet variability



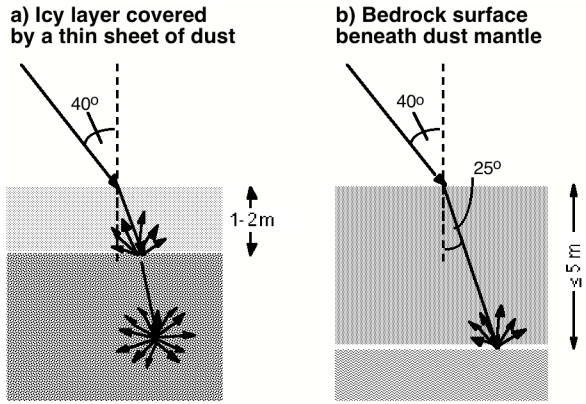
Hydrology and Geology beneath the dust layer (1/3 of the surface)



Ice sheet layering/structure



Mapping near-surface ice deposits



Exploring Earth's Moon

Topographic data to determine illumination

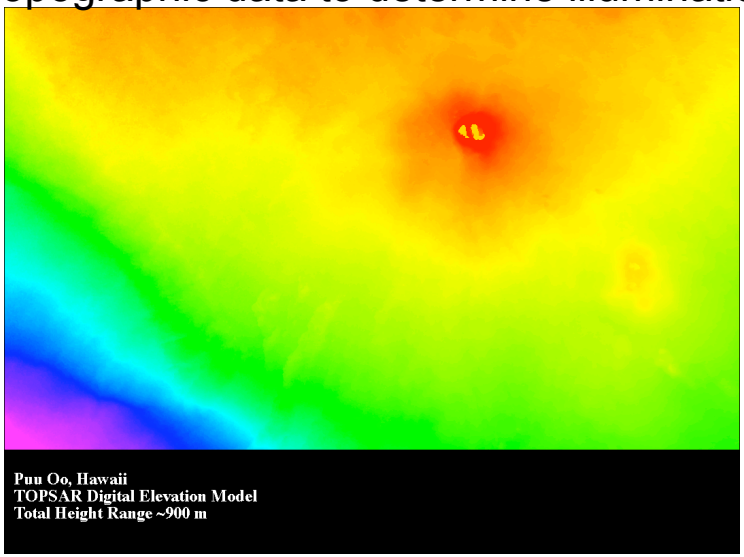
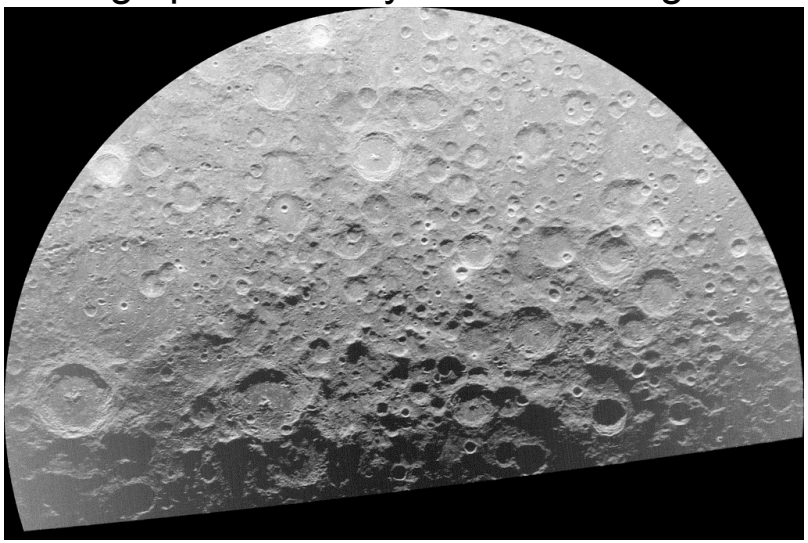
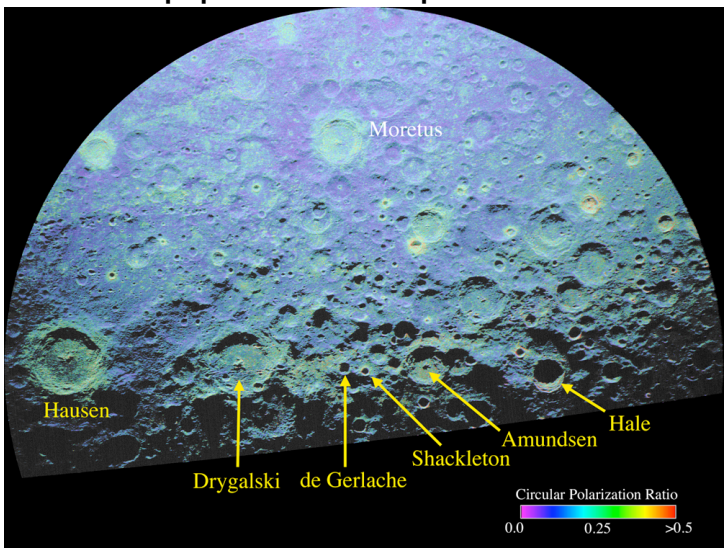


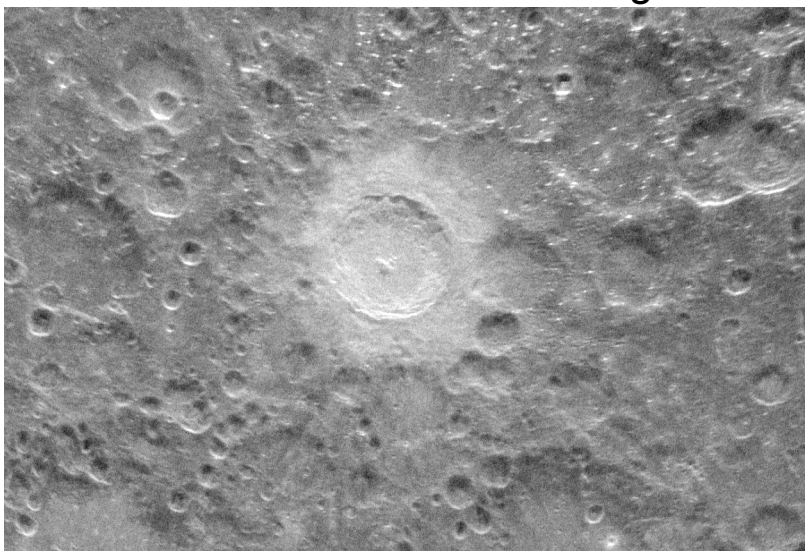
Image permanently shadowed regions



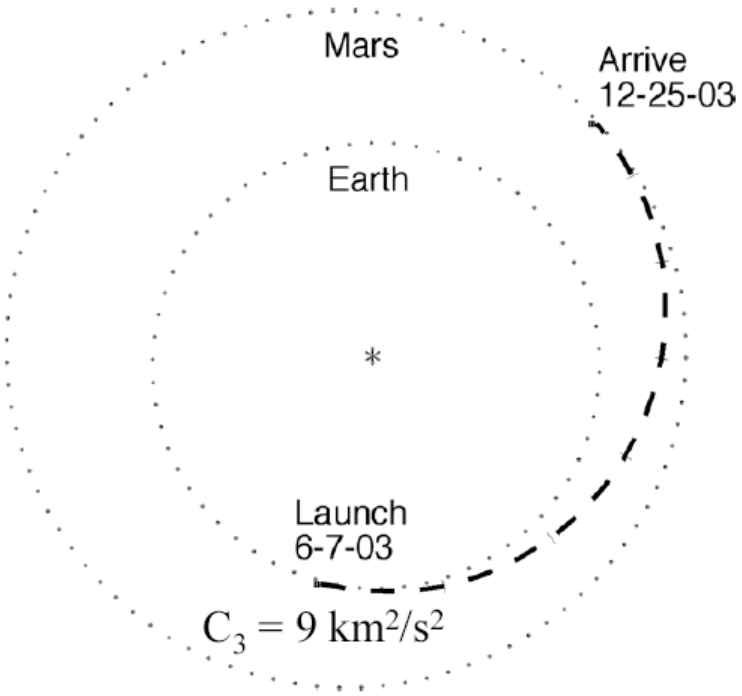
Map polar ice deposits



Characterize terrain for landing sites

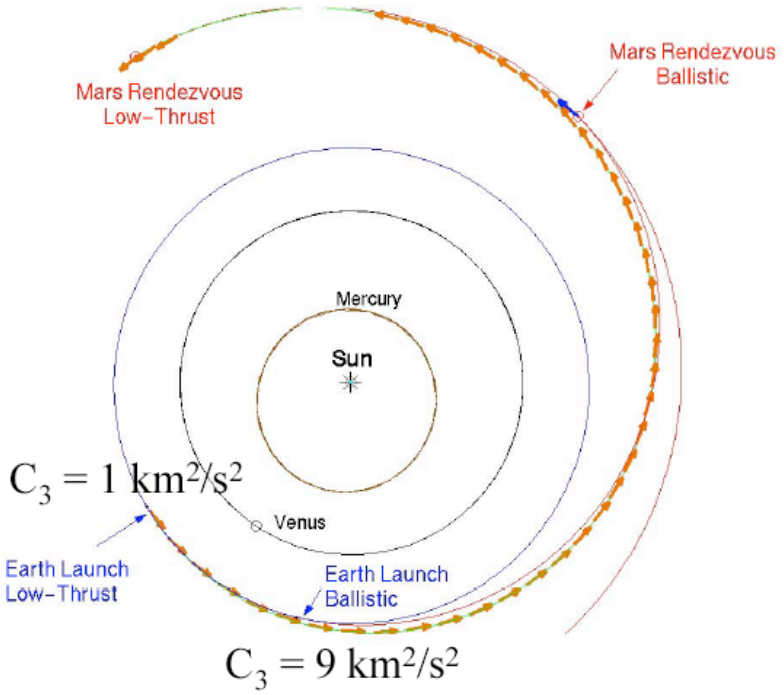


Earth to Mars Ballistic Transfer

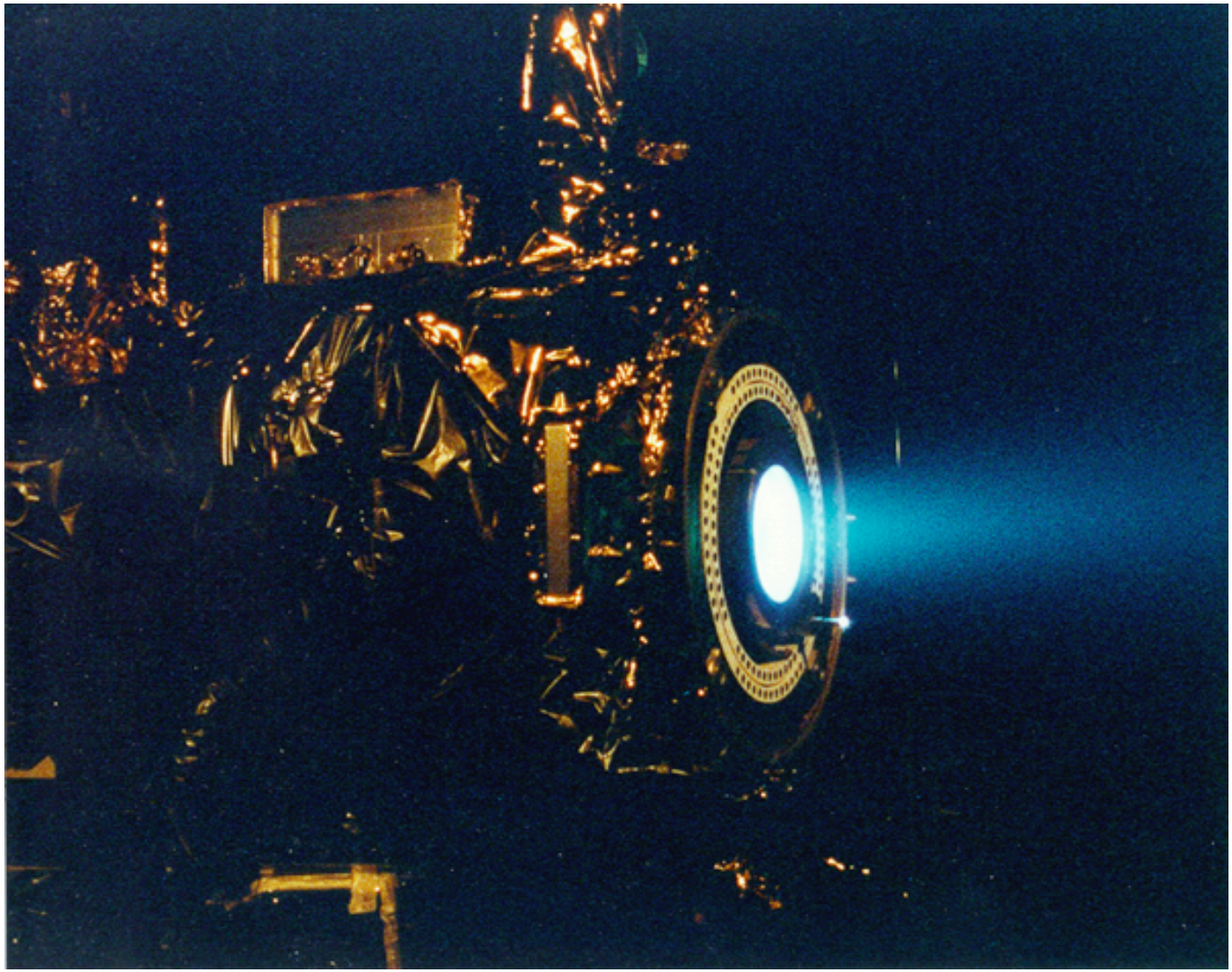


- Launch vehicle inserts to a positive C_3 (escaped from Earth)
  - No other deterministic ΔV prior to arrival at Mars
  - Orbit insertion ΔV at Mars if rendezvousing
- Trajectory can be designed without knowledge of launch vehicle, spacecraft, propulsion system
- Very few optimization variables

Example Earth to Mars Low-Thrust Transfer



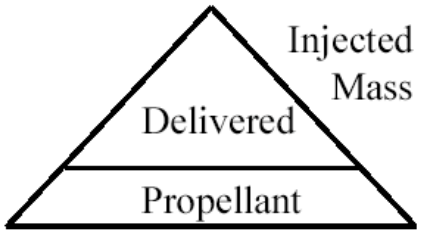
- The launch vehicle ΔV is augmented with thrusting from the more efficient (I_{sp}) electric propulsion system
- Reduce V_∞ at Mars and capture with electric propulsion system
- Thrusting is always in the same general direction as the velocity
  - Recall Hohmann transfer
  - Adding energy while thrusting
- Although ΔV increases, more mass can be delivered using low-thrust propulsion



Ion Thruster Life Test at JPL

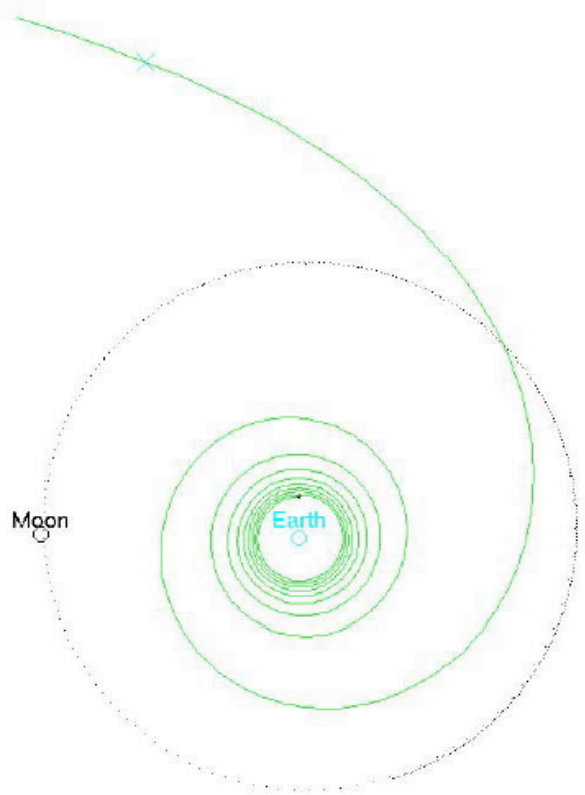
Introduction to Low-Thrust Trajectories

- (Thrust)×(I_{sp}) is proportional to Power
  - I_{sp} is a measure of the efficiency of propellant usage
    - Exhaust speed c = Thrust/(propellant mass flow rate), $I_{sp} = c/g_E$
    - Chemical: 300 s; Electrical: 3000 s (DS1) - 9000 s (advanced)
  - For a given power level, higher I_{sp} results in lower thrust
- Lower thrust levels lead to higher required ΔV
  - Thrusting must occur at less optimal locations
- Typically optimize in terms of mass: injected, propellant, and delivered
  - ΔV is less relevant



- For a given set of mission parameters, there is a trade between flight time and delivered mass

Low-Thrust Spiraling Escape from Earth



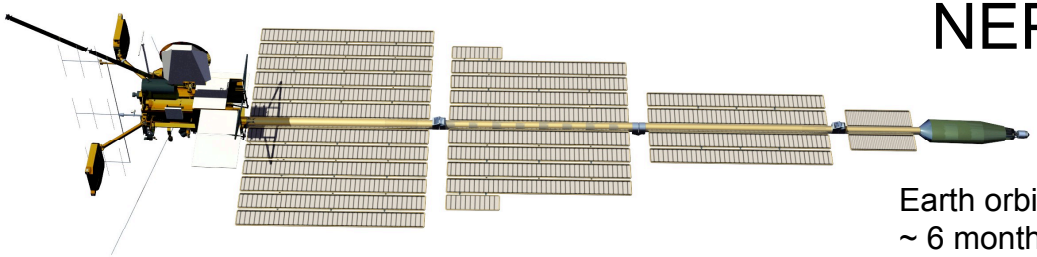
- Accomplish even more of the departure with electric propulsion system
  - Launch vehicle injects to $C_3 < 0$ (captured orbit)
  - Use electric propulsion to gain energy and escape
  - Spiraling can take many hundreds of revolutions and hundreds of days
  - Lower thrust-to-mass requires longer flight time

Earth-Moon Mission

Mission Highlights:

- Launch from Cape Kennedy on a Delta IV Heavy to a 1000 km circular 55º inclined orbit
- Conduct low thrust transfer to 1000 km circular, high inclination science orbit
- Spend six months collecting Earth science data
- Conduct low thrust transfer from Earth to 500 km polar Lunar orbit
- Conduct high power SAR demonstration at MEO/GEO altitude during Earth-Lunar transit
- Spend two years collecting Lunar science data

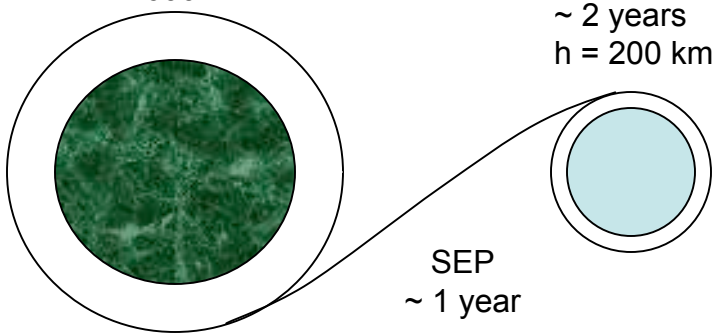
Earth-Moon Mission



NEP or SEP?

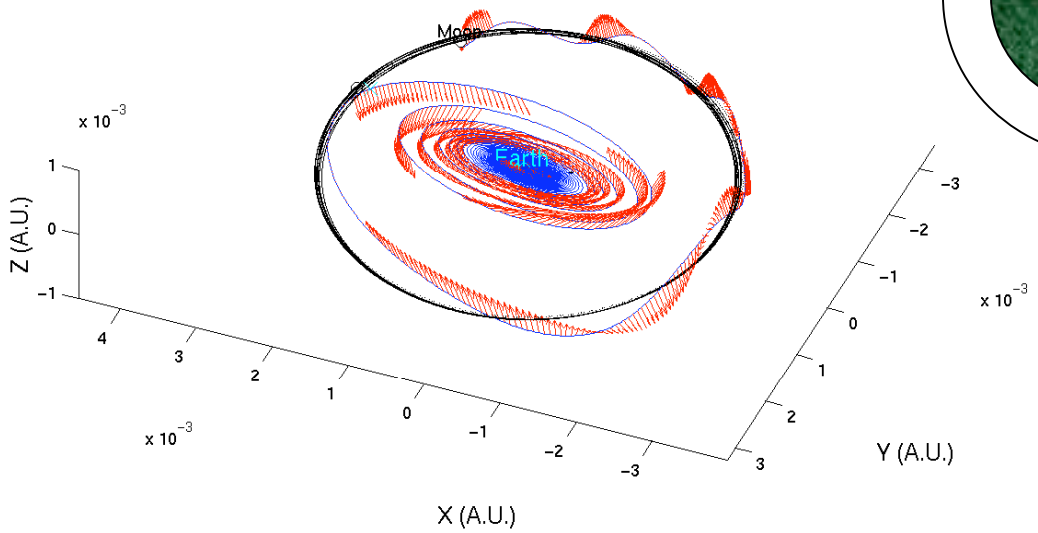
Earth orbit
~ 6 months
h = 600 km

Moon orbit
~ 2 years
h = 200 km



SEP
~ 1 year

Spiral out



Multi-use instruments

Name	Instrument	Measurement - Earth	Science applications - Earth	Measurement - Moon	Science applications - Moon
L-SAR	L-band SAR Dual-polarization	- Biomass mapping - Subsurface imaging of hyperarid regions - Pass-to-Pass Interferometry	- Near-global baseline map of boreal and tropical forest landcover and Biomass during multiple seasons - Map relict hydrological systems in N. Africa/Arabian Peninsula reflecting spatial and temporal variability of past climates - Measure vegetation canopy structure at selected sites (complementary to laser-derived measurements)	- Polar ice detection - surface mapping	- Image permanently shadowed Near-Polar terrain - Use unique polarization signature of ice to identify putative deposits in cold traps - Characterize meter and smaller-scale roughness at potential landing sites
SAR interferometer	Ku-band fixed-baseline interferometer	- Near-nadir hi-resolution sea surface height for ocean eddy fields and currents	- First synoptic measurements of global ocean eddies, coastal currents and tides, internal tides. - Verify height measurements at smallest scale of eddy fields	- hi-resolution topographic mapping	- Provide high resolution digital elevation maps geophysical studies - Characterize Polar region illumination environment at temporal scales relevant to lander operations (hours)
Scanning Laser altimeter	Scanning Laser altimeter	- topographic spot heights and transects - Vegetation canopy thickness	- global reference data set for geodetic mapping - Characterize land cover and canopy height for ecosystem aned global climate modeling	- global topography	- Improve global coverage of topographic height measurements

Instrument Specifications

		L-SAR	SAR interferometer	Laser altimeter
Instrument		L-band SAR dual-polarization	Ku-band fixed-baseline interferometer	Laser altimeter
Characteristics		24 cm. wavelength side-looking imager detecting polarized and depolarized echoes	-2 cm wavelength dual-antenna interferometer -7 meter baseline -nadir-oriented altimeter at Earth, side-looking interferometer at Moon	1064 nm laser altimeter
Mass		200 kg total (SARs share some electronics, data system elements)		50 kg
Power		420 w	200 w	45 w
Earth	**Resolution**	40 m horiz 18 looks	12 km horiz 5 cm vertical	25 m spot, 1.5 km spacing 0.5 m vert
	Incidence angle	41.5°	nadir	nadir
	Swath width	80 km	200 km	30 km
	Data rate	100 mbps	90 mbps	<10 kbps
	Duty Cycle (ave)	15%	70%	30%
Moon	**Resolution**	10 m horiz 5 looks	15 m horiz 2 m vert 10 looks	15 m spot, 0.7 km spacing 0.5 m vert
	Incidence angle	47.6°	47.6°	nadir
	Swath width	40 km	37 km	30 km
	Data rate	98 mbps	120 mbs	< 10 kbps
Hardware		Electronics package plus 3 x 10 meter flat panel antenna, oriented with long axis along velocity vector, boresight 30° off-nadir	Electronics package plus two 2.5 x 0.3 m antennae at ends of 7 m mast, oriented perpendicular to velocity vector	Electronics package plus ~1 m nadir oriented telescope and detectors
Heritage		Seasat, Shuttle Imaging Radars, JERS	WSOA, SRTM, airborne systems	IceSAT, MOLA, LRO altimeter, VCL

Earth-Moon Mission

	Option A 57 deg Earth Science Orbit	Option B 67 deg Earth Science Orbit	Option C Polar Earth Science Orbit
Launch			
Launch Vehicle	Delta-IV Heavy	Delta-IV Heavy	Delta-IV Heavy
Insertion Orbit Altitude	1000 km	1000 km	1000 km
Insertion Orbit Inclination	55 degrees	55 degrees	55 degrees
Launch Mass Capability	19700 kg	19700 kg	19700 kg
Transfer to Earth Science Orbit			
Inclination Change	2 degrees	12 degrees	33 degrees
ΔV	0.5 km/s	1.8 km/s	5 km/s
Transfer Time	0.1 yrs	0.6 yrs	2.8 yrs
Earth Science Orbit			
Inclination	57 deg	67 deg	90 deg
Altitude	1000 km	1000 km	1000 km
Data Collection Period	6 months	6 months	6 months
Earth to Moon Transfer			
ΔV	7.9 km/s	8.0 km/s	8.2 km/s
Transfer Time	1.4 years	1.6 yrs	2.9 yrs
Moon Science Orbit			
Inclination	Polar	Polar	Polar
Altitude	50 km	50 km	50 km
Data Collection Period	6 months	6 months	6 months
Other			
ΔV for Stationkeeping and Margin	0.2 km/s	0.2 km/s	0.2 km/s
Mission Total			
Total ΔV	8.6 km/s	10.0 km/s	13.4 km/s
Total Science Data Collection Time	1 yr	1 yr	1 yr
Total Mission Duration	2.5 yrs	3.2 yrs	6.7 yrs

Table 3: Outline of Mission Phases, Flight Time, and ΔV

Earth-Moon Mission

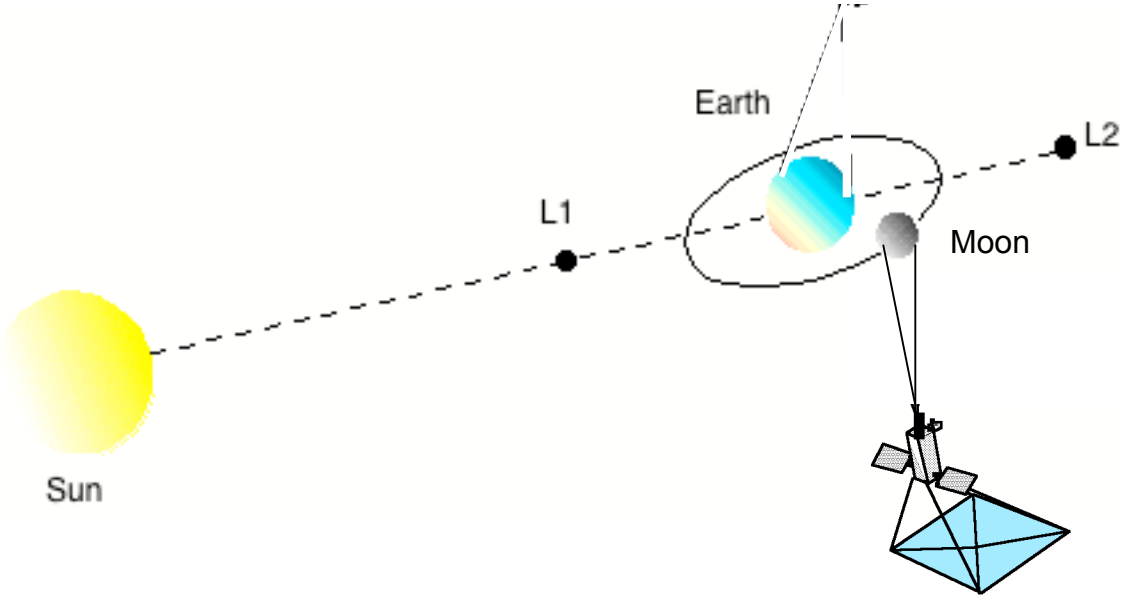
	Option A	Option B	Option C
	57 deg Earth Science Orbit	**67 deg Earth Science Orbit**	**Polar Earth Science Orbit**
Instrument Payload			
Mass of all Instruments and Antennas	300 kg		
Power	3000 W		
Data Rate (Maximum / Average)	190 Mbps / 100 Mbps		
Total Earth Science Data Collected	~1580 Terabits		
Earth Science Orbit			
Inclination	57 degrees	67 degrees	90 degrees
Altitude	1000 km	1000 km	1000 km
Spacecraft Characteristics			
Primary Power Source	Nuclear Reactor		
Primary Electric Propulsion	Ion Thrusters		
Secondary Electric Propulsion (ACS)	Hall Thrusters		
Pre-Deployment Propulsion (RCS)	Hydrazine		
Reactor Electrical Output Power	200 kW	200 kW	100 kW
Primary Engine Thrust	4.1 N	4.1 N	2.0 N
Primary Engine Specific Impulse	7000 seconds	7000 seconds	7000 seconds
Primary/Secondary Propellant	Xenon	Xenon	Xenon
Mass Breakdown (1)			
Instruments and Antennas	300 kg	300 kg	300 kg
Spacecraft Bus	16450 kg	16450 kg	14490 kg
Launch Vehicle Adapters	160 kg	160 kg	160 kg
Xenon Propellant Mass	2250 kg	2640 kg	3200 kg
Hydrazine Propellant Mass	50 kg	50 kg	50 kg
Total Launch Mass	**19210 kg**	**19600 kg**	**18200 kg**
Launch Vehicle Capability (2)	19700	19700	19700
Launch Margin	**490 kg**	**100 kg**	**1500 kg**
Launch Margin (%)	**2.5%**	**0.5%**	**7.6%**

(1) All spacecraft masses shown include 40% dry mass margin

(2) Delta IV Heavy launching from Cape to 55 degrees inclination, 1000 km x 1000 x km orbit

Pole-Sitter Mission Concept

- **Potential Applications:**
  - Communications Node (optical/IR or radio)
    - Earth-Moon
    - Deep Space Missions
  - Solar wind monitor
  - Remote sensing
  - Laser reference point for monitoring of crustal motion
  - Laser reference point to bootstrap interferometers

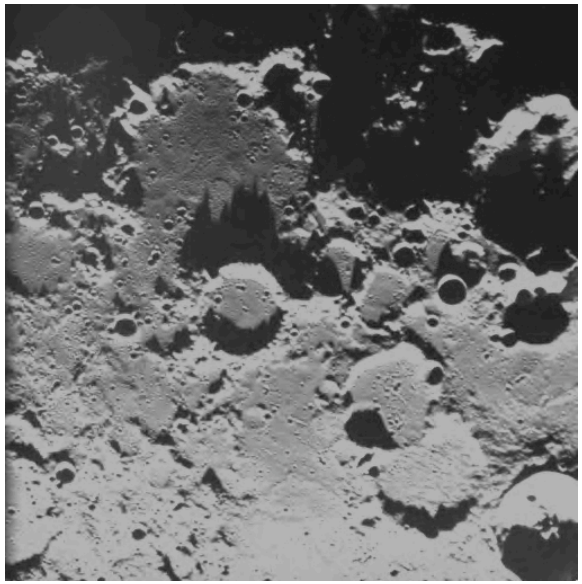


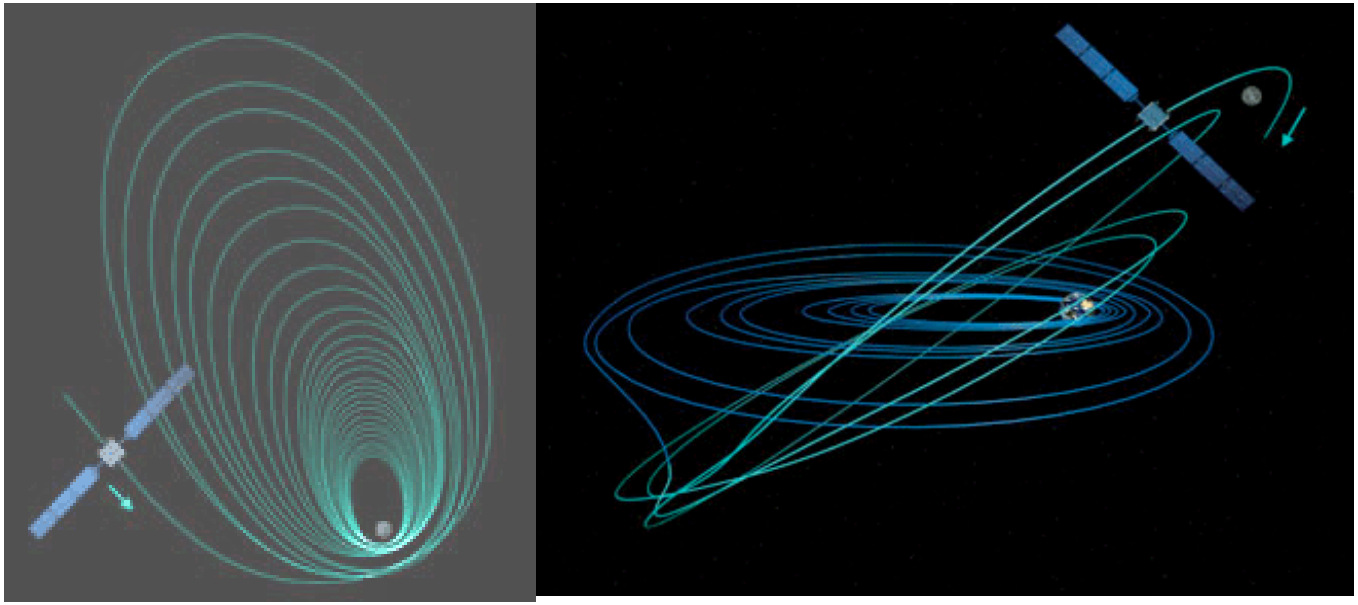
The First SEP Mission - DS-1

Encountered 2 different bodies in the solar system

ESA's SMART-1

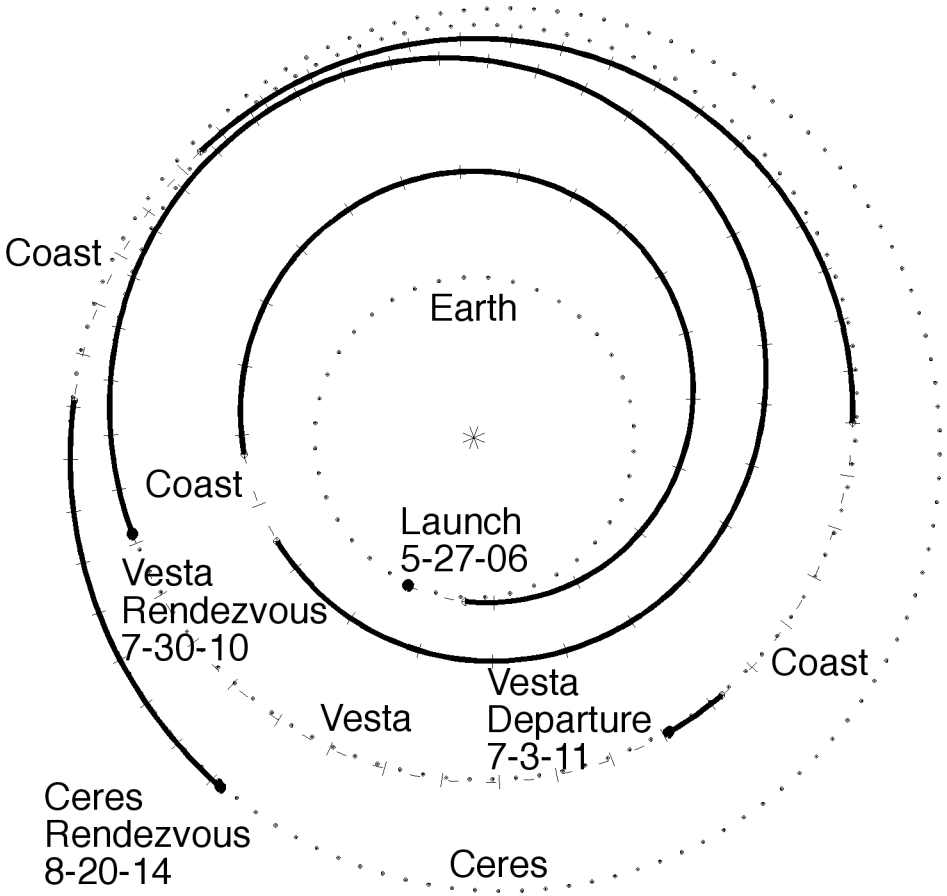
- Drawing electric power of 1350 watts from SMART-1's solar panels, the ion engine generates a thrust of 0.07 newton.
- Acceleration is 0.2 millimetre per second per second, sustained over 16 months.
- Electronics are rad-hardened to handle 2-3 months exposure to Van Allen belt radiation
- Launch mass - 379 kg, Payload 19 kg





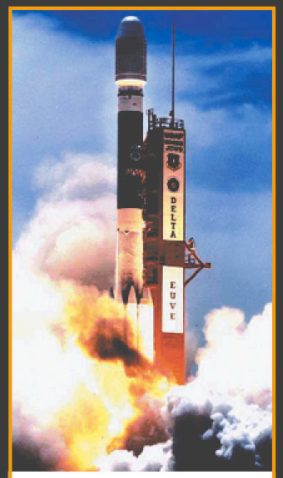
Images courtesy ESA

DAWN's trajectory



Continuous thrust models are challenging

Gradual trajectory modifications minimize risk for critical events



LAUNCH
May 27, 2006
Delta 2925H

CRUISE
4.2 Years

Survey (16 days)
r = 5000 km orbit

Global Mapping (30 days)
r = 1360 km, 11 hr orbit

Laser Altimetry (143 days)
r = 630 km, 3.3 hr orbit

High Res Imaging (25 days)
r = 529 km, 2.7 hr orbit

CERES
August 20, 2014
July 26, 2015
11 Months

CRUISE
3.1 Years

Survey (18 days)
r = 2700 km orbit

Global Mapping (15 daysx2)
r = 950 km, 12.1 hr orbit

Laser Altimetry (130 days)
r = 375 km, 3.0 hr orbit

High Res Imaging (25 days)
r ≤ 304 km, 2.2 hr orbit

VESTA
July 30, 2010 to
July 3, 2011
11 Months

Advantages of Dual-Body Missions

- Higher payload mass fraction delivered
- Calibration of instruments at Earth
- Some measurements at Earth that need only 6 months of measurements (often repeated at decadal intervals)
- Fits exploratory measurements (but not most sustained climate records)
- Current solar panel capabilities - 18 kW (on ISS)
- SEP is very efficient in the inner solar system
- NEP needed for outer solar system
- It takes more time, but one multi-body mission is definitely cheaper than several single-body missions

Challenges of Dual-Body Missions

- Stovepiped funding sources
- Different orbital altiudes:
  - Earth LEO: 600-1000 km
  - Mars: 250 - 400 km
  - Moon: 25-50 km
  - Asteroids, Comets: 0 - 25 km
- Next-generation ion engines with demonstrated thrust capability (Nm and hours)
- Refuelling?
- Captain Cook's Endeavour was a decades-old coal carrier from the East Coast of England
- Several of the ships at Trafalgar were more than 50 years old
- Challenge is to build long-lived, multi-purpose spacecraft and service them (in LEO?) with instrument upgrades