Seminar 7

Early Apollo Program
Lunar Transfer Trajectories

FRS 148, Princeton University

Robert Stengel

"Fire in the Cockpit"
The Office
First Around the Moon
Lunar Transfer Trajectories

NASA SP-4503, Apollo: A Retrospective Analysis
A Man on the Moon, Ch 1 to 3
Understanding Space, Sec 7.2, 7.3
Modern Spacecraft Dynamics and Control, Sec 3.5

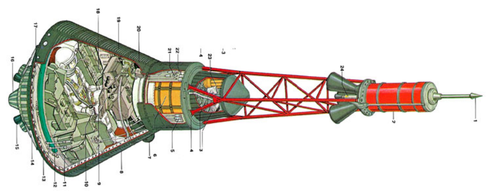
1

Buildup to Apollo

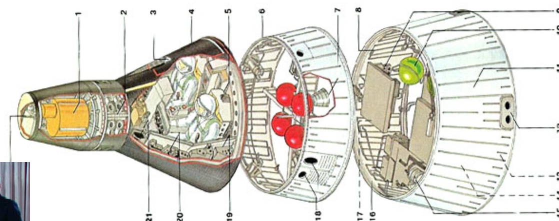
2

Early US Manned Spacecraft

Mercury
(1959-63)



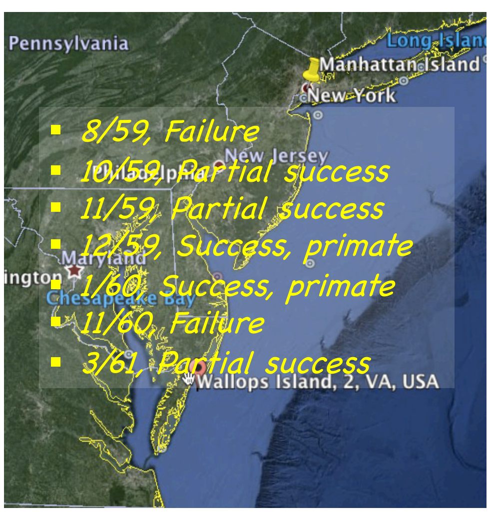
Gemini
(1965-6)



"Pete" Conrad, '53, two Gemini missions, 1965 and 1966

3

Project Mercury Flights
Little Joe (unmanned)



- 8/59, Failure
- 10/59, Partial success
- 11/59, Partial success
- 12/59, Success, primate
- 1/60, Success, primate
- 11/60, Failure
- 3/61, Partial success

4

Project Mercury Flights
Redstone & Atlas (unmanned)

Atlas
- 9/59, Failure
- 7/60, Failure
- 2/61, Success

Redstone
- 11/60, Failure
- 12/60, Success
- 1/61, Success
- 3/61, Success


5

Project Mercury Flights
Little Joe & Atlas (unmanned)

Little Joe
- 4/61, Success

Atlas
- 9/59, Failure
- 7/60, Failure
- 2/61, Success
- 9/61, Success
- 11/61, Success, primate, orbit


6

February 20, 1962

THE PLAIN DEALER

YOUR BEST NEWSPAPER—ALL DAY

GREATER CLEVELAND EDITION

CLEVELAND, WEDNESDAY MORNING, FEBRUARY 21, 1962

52 PAGES

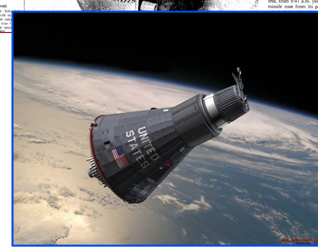
TEN CENTS

GLENN SAFE AFTER 3 ORBITS, OPENS SPACE FUTURE FOR U.S.

Glenn's Parents Never Doubted Shot's Success

Further Feats Already Being Talked at Cape

British Map Evacuation in A-Attack



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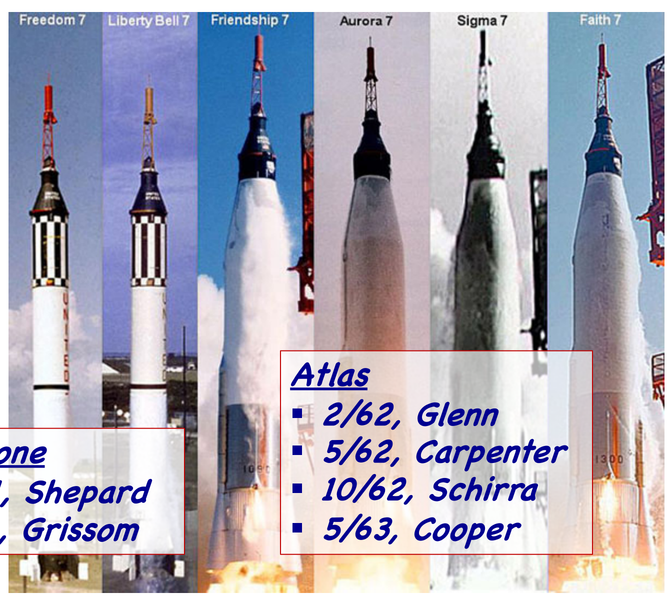
Project Mercury Flights (manned)



Redstone

- 5/61, Shepard
- 7/61, Grissom

Atlas

- 2/62, Glenn
- 5/62, Carpenter
- 10/62, Schirra
- 5/63, Cooper

8

Project Gemini [1965-66]

9

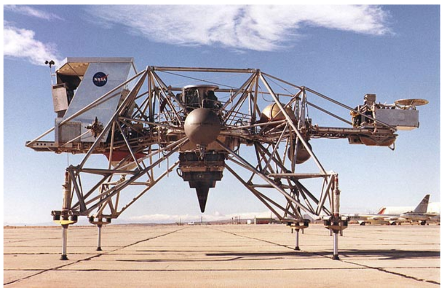
Project Gemini Flights

2/64 1/65 3/65 6/65 8/65 12/65 12/65 3/66 6/66 7/66 9/66 11/66

Unmanned | Manned

10

Lunar Landing Research/Training Vehicles (LLRV, LLTV)




https://www.youtube.com/watch?v=-3wkhywEAxA

Neil Armstrong Ejection
https://www.youtube.com/watch?v=xJa4yQ0AIbU

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Project Apollo

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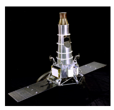
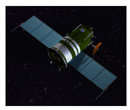
Robotic Lunar Probes

- *1958-1960*

	Success	Failure
US	1 partial	8
USSR	2, 1 partial	6

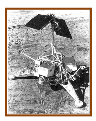
- *1962-1965*

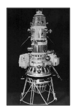




	Success	Failure
US	3, 1 partial	3
USSR	1	9

- *1966-1967*





	Success	Failure
US	11	2
USSR	5	4

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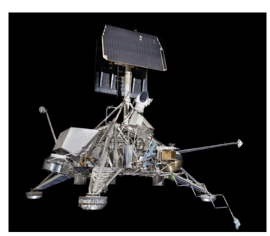
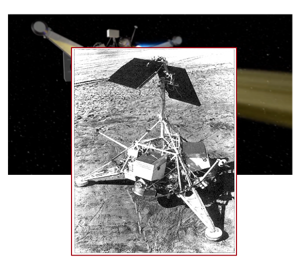
Precursors to Apollo

Rangers 7, 8, & 9
Hard Landing
[Impact], 1964-5

Surveyor 3
Soft Landing, 1967





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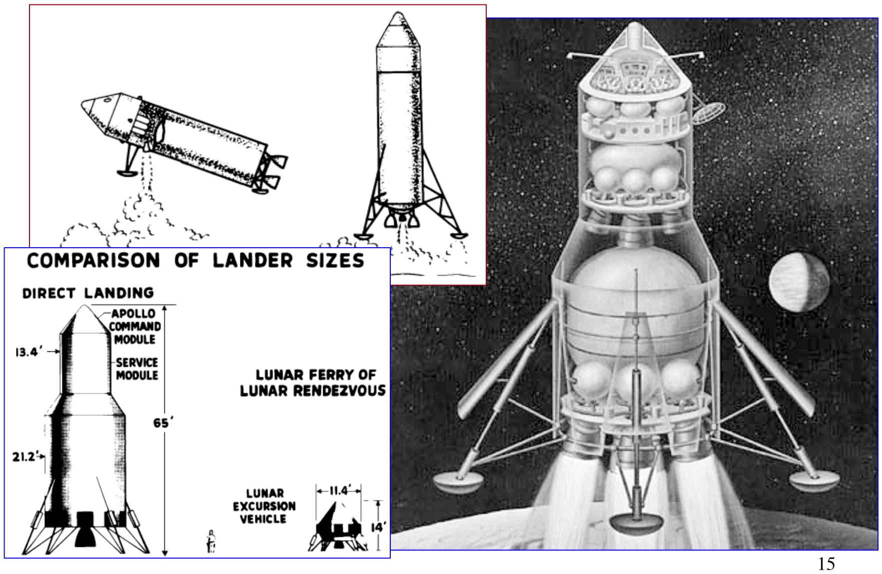
Pre-Lunar Module Lander Concepts



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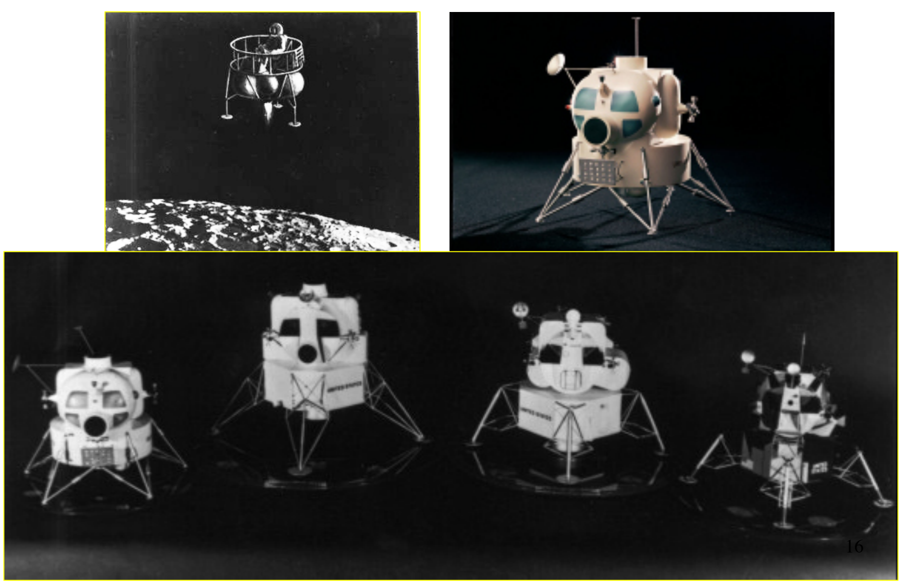
Evolution of the Lunar Module



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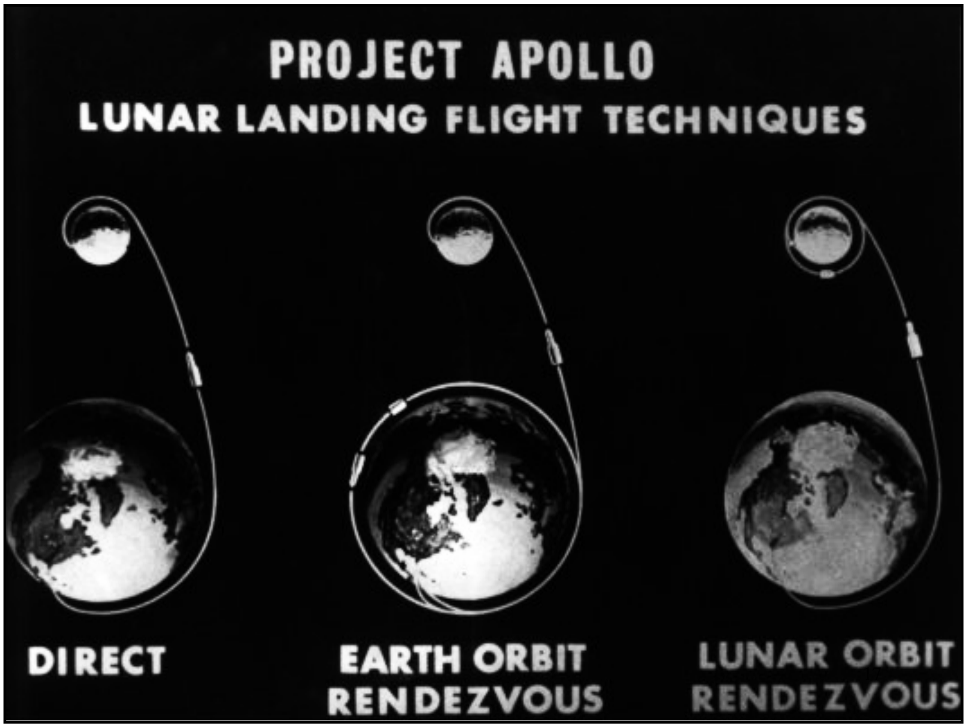
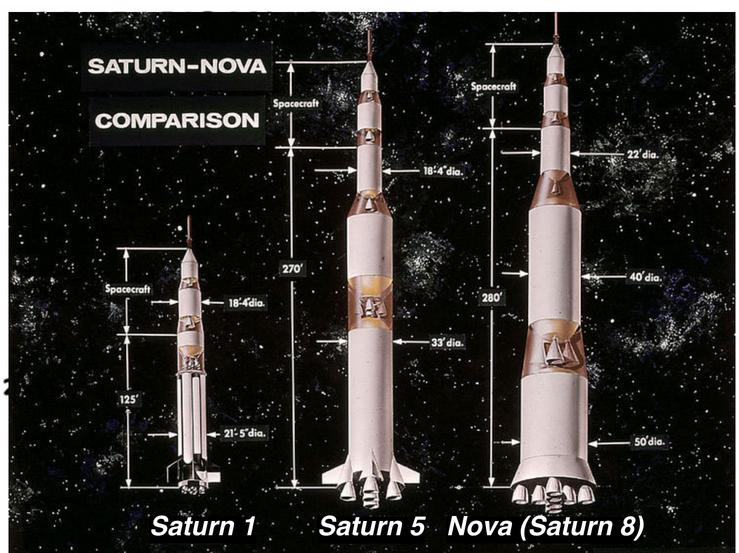


Alternative Landers and Launch Vehicles



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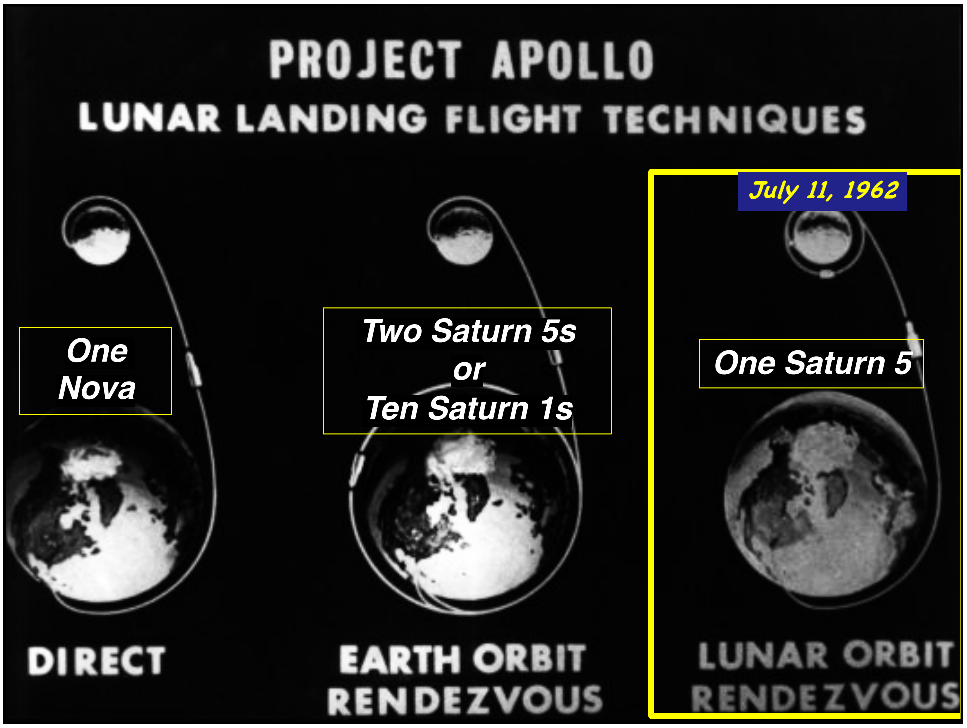

Enchanted Rendezvous*

- Lunar Exploration Working Group
- Bill Michael's ('48) paper on parking orbit
- Rendezvous committees
- Houbolt's 1st crusade
- Anti-lunar-rendezvous sentiment
- Space Task Group's skepticism
- Mounting frustration
- Kennedy's commitment
- 1st letter to Seamans
- A voice in the wilderness
- Decision to use LOR

* NASA Monographs in Aerospace History Series #4, 1999

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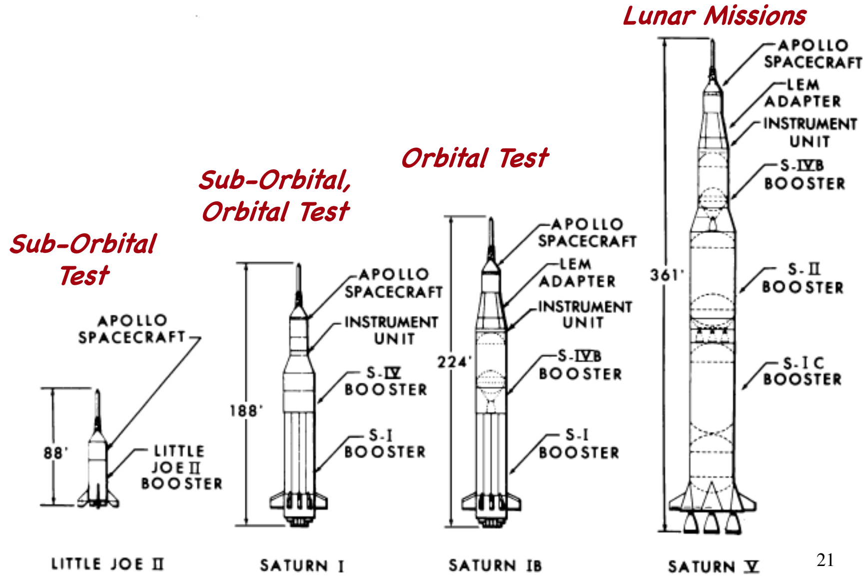
Apollo Launch Vehicles



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Little Joe II, 1963-1966

- *Unmanned test of abort escape system*
- *5 flights*
- *9 solid-rocket motors*
  - *Recruit Boosters (0-5)*
  - *Algol Sustainers (1-6)*
- *Sub-orbital, 120,000-ft apogee*
- *One unplanned low-altitude abort when rocket disintegrated*
- *All abort tests successful*

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Saturn I, 1961-1965

- Unmanned test of the launcher
- 10 flights
  - 4 with live S-I 1st stage + ballast, sub-orbital
  - 6 with S-I and S-IV 2nd stage, to orbit
- 8 Redstone tanks clustered around a Jupiter tank in S-I (V-2 heritage)
- 5 CSM "boilerplates" orbited
- 3 Pegasus satellites orbited

Saturn IB, 1966-1975

- 9 launches
  - Uprated S-I and S-IV stages
- AS-201, -202: sub-orbital
- AS-203: orbital
- AS-204: Apollo 1: Block 1, Jan 1967, no launch, loss of crew (Grissom, White, Chaffee)
- No Apollo 2 or 3
- Apollo 5: Jan 1968, LM test (unmanned)
- Apollo 7: Block 2, Oct 1968, 1st manned flight, (Schirra, Eisele, Cunningham)
- 3 flights to SkyLab, 1973
- Docking with Soyuz, 1975

Saturn V, 1968-1975

- New 1st and 2nd stages
- S-IVB became 3rd stage
- Apollo 4, 6: Unmanned
- Apollo 8: 1st to the Moon
- Apollo 9: orbital
- Apollo 10: 2nd to the Moon
- Apollo 11: 1st lunar landing
- Apollo 12: 2nd lunar landing
- Apollo 13: aborted lunar mission
- Apollo 14-17: successful lunar landings
- Skylab launch (2 stages)

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Saturn V in Princeton Stadium

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Launch Complex 34

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Apollo 1 (AS-204) Fire, January 27, 1967

- Low-risk, "Plugs Out" test
- Pressurized pure oxygen
- Electric arc
- Combustible materials
- Hatch opened inward
- Lack of preparedness

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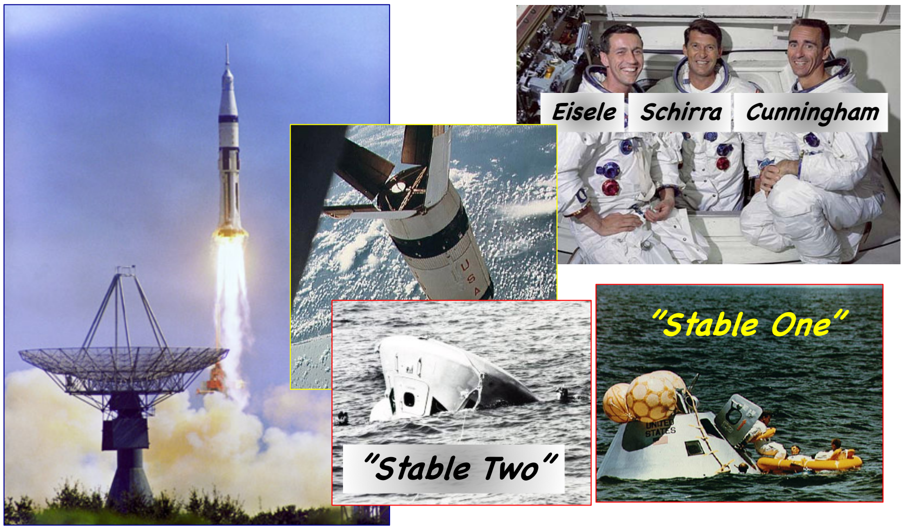
First Manned Flight, Apollo 7
October 11, 1968



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Launch Complex 39

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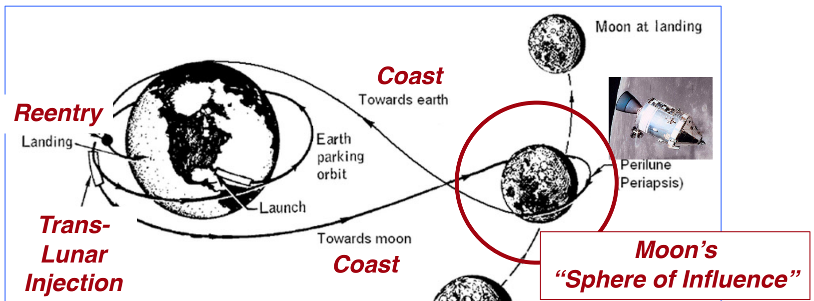
Apollo 8, December 21-27, 1968

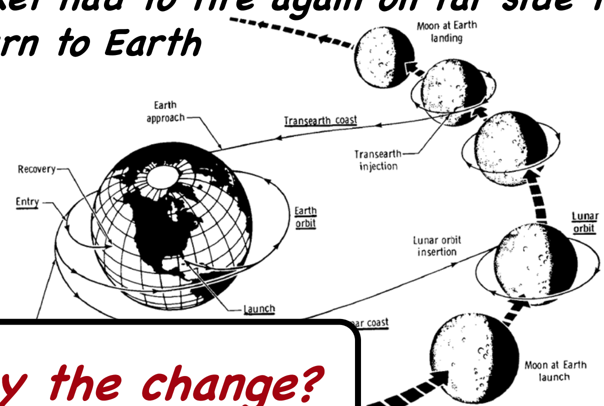
- Planned to be an Earth-orbit mission
- A more ambitious mission was pursued
- Repurposed to 1st manned flight to the Moon
- 6-day mission duration



Free-return trajectory
No further propulsion after Trans-Lunar Injection

Apollo 8 Entered Lunar Orbit

- More daring alternative was pursued
- <u>Rocket fired</u> on far side for Lunar-Orbit Insertion; no free return
- Rocket had to fire again on far side to return to Earth



Why the change?

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August 1968, CIA KH-8 GAMBIT Reconnaissance Satellite

N-1 Rocket: Russia was indeed racing for the Moon

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Racing Apollo: The Russian Perspective

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Soviet Lunar Program

- *Intense secrecy*
- *Decision to build a manned Moon rocket, N-1*
- *Insufficient investment*
- *Disarray in central planning*
- *Competing design bureaus wasted resources*
  - *Korolev*
  - *Glushko*
  - *Chelomei*
- *Gave away their lead in rocket technology*
- *Inadequate testing of the N-1 launcher*
- *The down side of autocratic technocracy*

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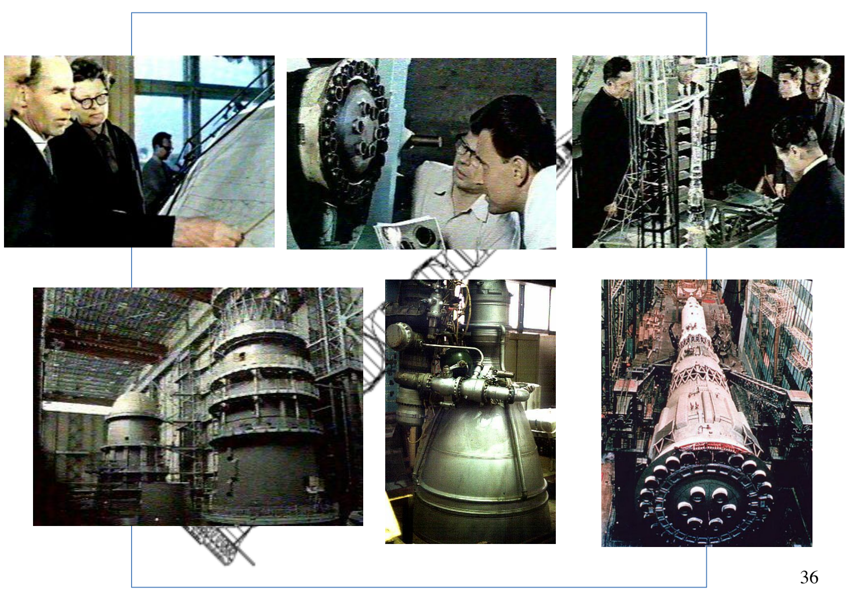
Developing the N-1 Rocket



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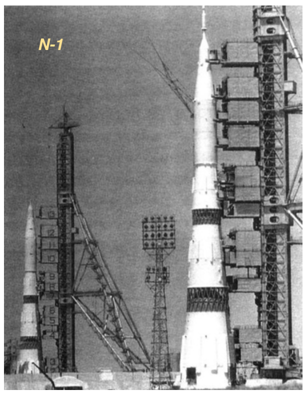
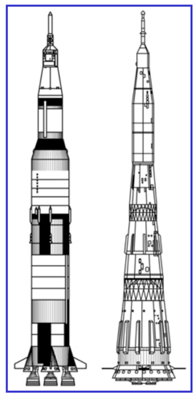
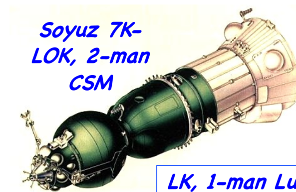
Soviet Manned Lunar Flight Program (1961-1972)

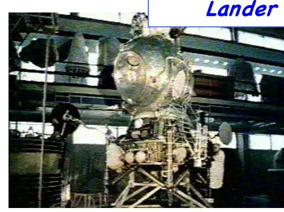
- N-1 Rocket, designed by Sergei Korolev
  - 4 launches (unmanned), none successful







LK, 1-man Lunar Lander



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Lunar Transfer Trajectories

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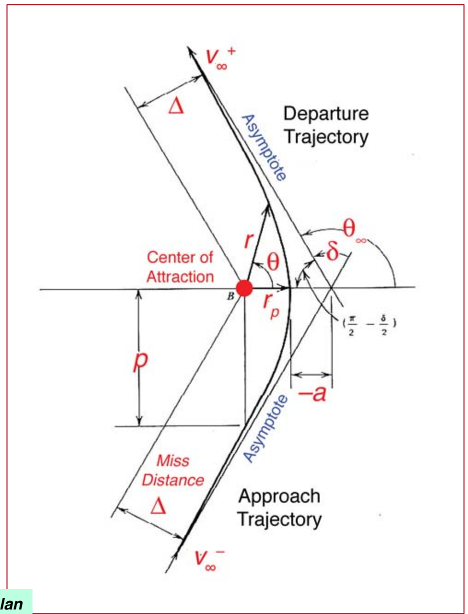

Hyperbolic Encounter with a Planet (or the Moon)

- Trajectory is deflected by target planet's gravitational field
- Velocity w.r.t. Sun is increased or decreased

Δ : Miss Distance, km
δ : Deflection Angle, deg or rad

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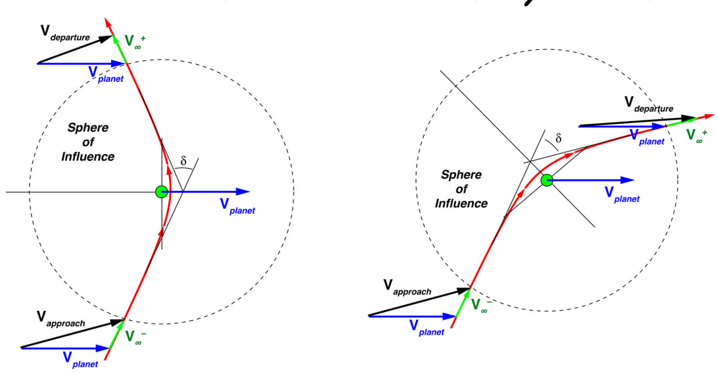
Effect of Target Planet's Gravity on Probe's Sun-Relative Velocity

Deflection – Velocity Reduction

Deflection – Velocity Addition



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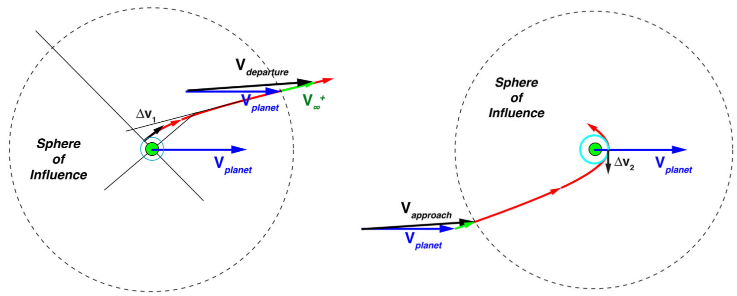
Planet Escape/Capture Trajectories

Hyperbolic trajectories within spheres of influence



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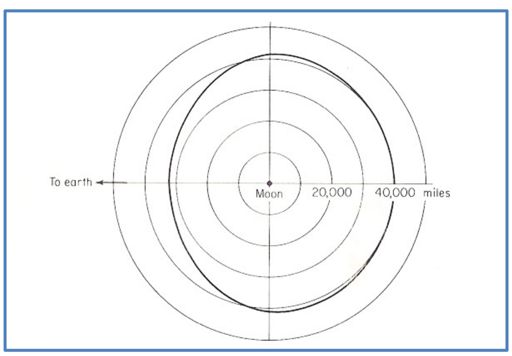
Earth-Moon Sphere of Influence

$$r_{SI} \simeq r_{Earth-Moon}\left(\frac{m_{Moon}}{m_{Earth}}\right)^{2/5} \simeq 66{,}100\ km \simeq \frac{1}{4} r_{Earth-Moon}$$

Actual "sphere" of influence is not a sphere (Battin, 1964)



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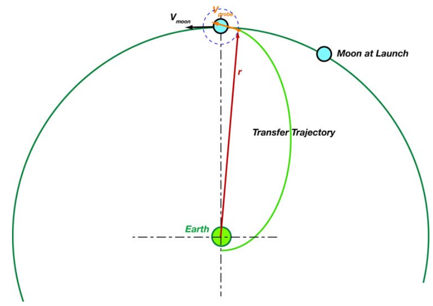
Lunar Trajectory



- *Two conic sections in patched conic approximation*
  - *Earth-relative*
  - *Moon-relative*
- *Earth-relative segment can be ellipse, parabola, or hyperbola*
- *Travel time reduced for parabolic or hyperbolic transfer*

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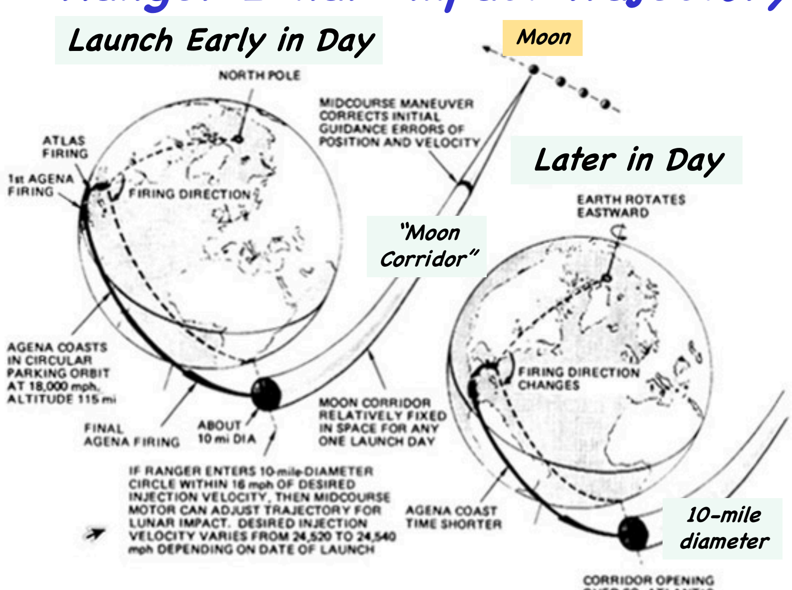
Ranger Lunar Impact Trajectory



http://en.wikipedia.org/wiki/Ranger_program

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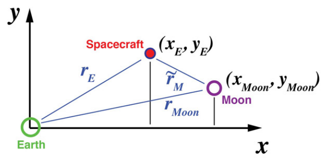
Earth-Moon-Spacecraft Dynamics



Equations of motion include inverse-square gravitational equations for both Earth and Moon

Fixed-Earth Co-planar (2-D) Model

$$\dot{v}_x(t) = -\mu_E\, x_E(t)/r_E^{\,3}(t) - \mu_M\, \tilde{x}_M(t)/\tilde{r}_M^{\,3}(t)$$
$$\dot{v}_y(t) = -\mu_E\, y_E(t)/r_E^{\,3}(t) - \mu_M\, \tilde{y}_M(t)/\tilde{r}_M^{\,3}(t)$$
$$\dot{x}_E(t) = v_x(t)$$
$$\dot{y}_E(t) = v_y(t)$$

$$\tilde{x}_M = x_E - x_{Moon}$$
$$\tilde{y}_M = y_E - y_{Moon}$$
$$\tilde{r}_M = \sqrt{\tilde{x}_M^2 + \tilde{y}_M^2}$$

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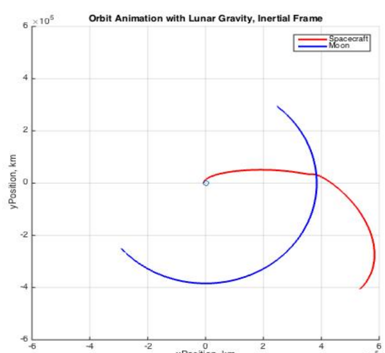
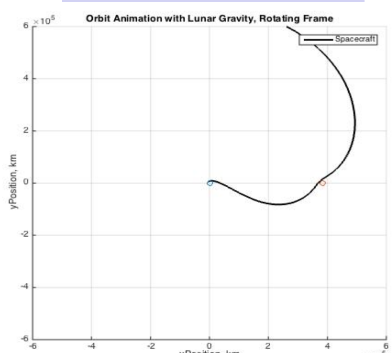
Lunar Fly-By Trajectory to New Elliptic Orbit

(from CoPlanarTraj.m)

Inertial Reference Frame



Reference Frame Rotating with the Moon



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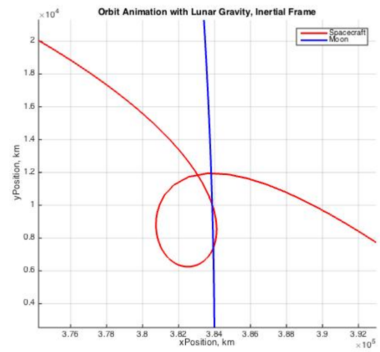
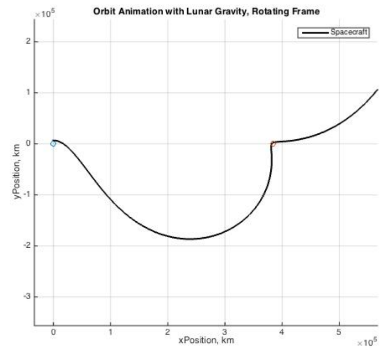
Lunar Fly-By Trajectory to Escape
(from CoPlanarTraj.m)

Inertial Reference Frame

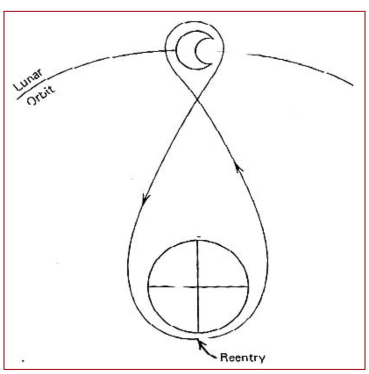
Reference Frame Rotating with the Moon

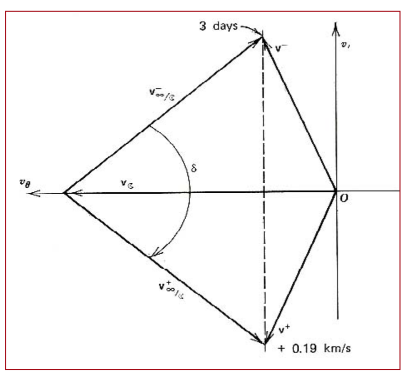




Apollo Free-Return Trajectory

With proper approach velocity, trajectory is deflected to "Figure 8" pattern for "free return"



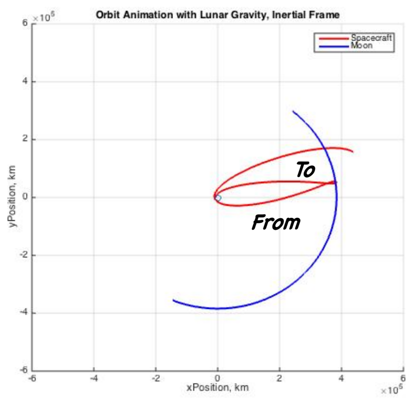


Kaplan

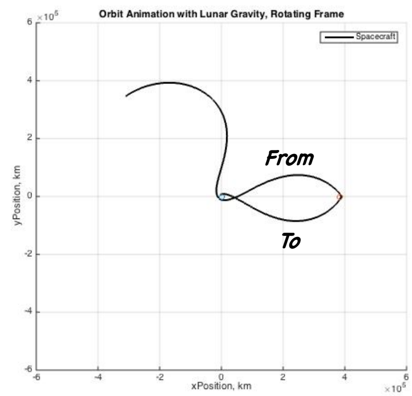
Lunar Free-Return Trajectory

(from CoPlanarTraj.m)

Inertial Reference Frame



Reference Frame Rotating with the Moon

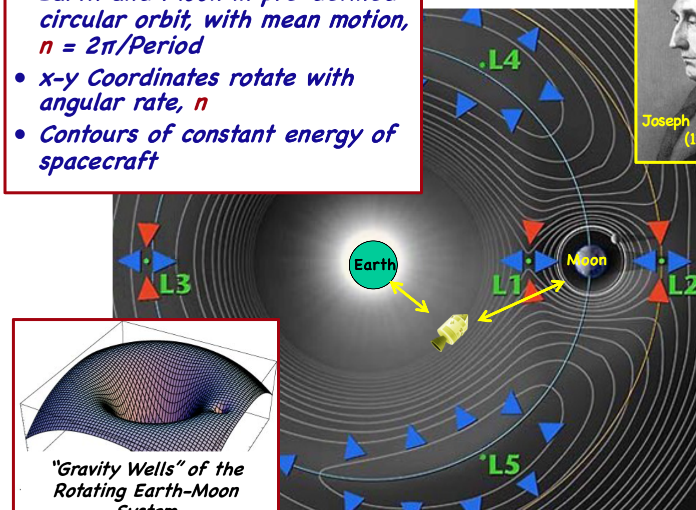


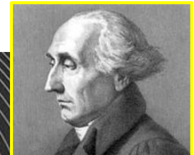
Re-Entry not simulated

Restricted 3-Body Problem

Lagrange (or Libration) Points

- Earth and Moon in pre-defined circular orbit, with mean motion, $n = 2\pi/\text{Period}$
- x-y Coordinates rotate with angular rate, n
- Contours of constant energy of spacecraft




Joseph –Louis Lagrange (1736-1813)

"Gravity Wells" of the Rotating Earth-Moon System

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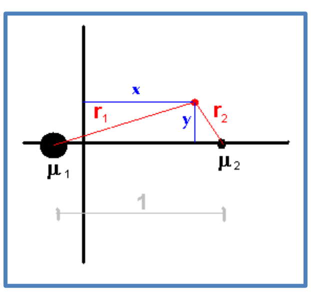
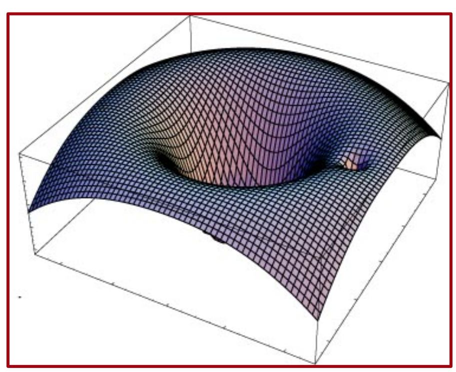
Expression of Energy in a Rotating 2-Body Gravitational Field

Jacobi Constant

$$C_J = n^2(x^2 + y^2) + 2\left(\frac{\mu_1}{r_1} + \frac{\mu_2}{r_2}\right) - \left(\dot{x}^2 + \dot{y}^2 + \dot{z}^2\right)$$





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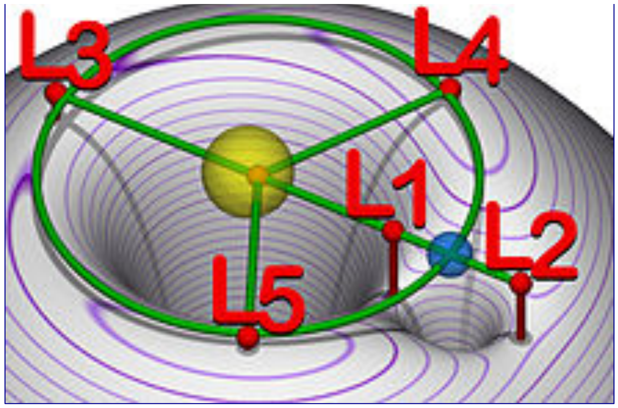
Lagrange (or Libration) Points

- *Lagrange Points are fixed in rotating coordinate frame*
- *Spacecraft can orbit about a Lagrange Point*
- *Orbits about L_1, L_2, and L_3 are unstable*
- *Orbits about L_4 and L_5 are stable*



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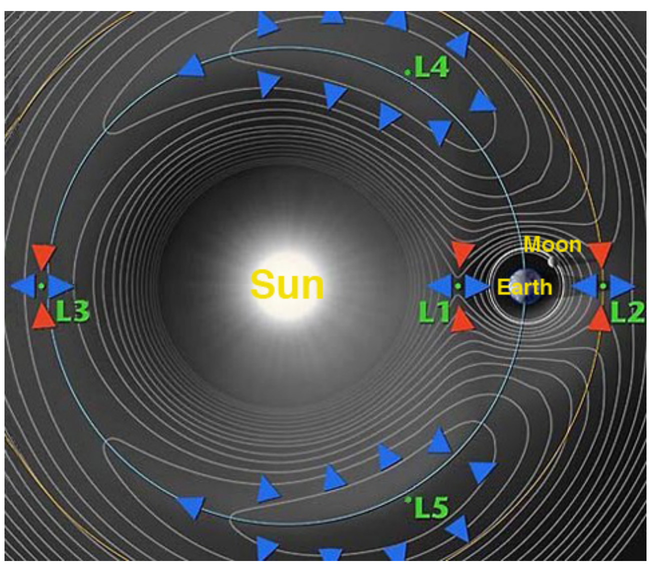
Sun-Earth Lagrange Points



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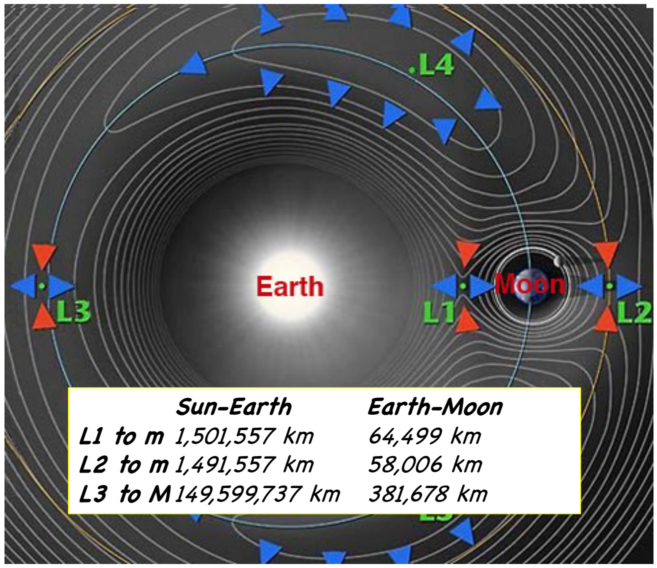
Earth-Moon Lagrange Points



	Sun-Earth	Earth-Moon
L1 to m	1,501,557 km	64,499 km
L2 to m	1,491,557 km	58,006 km
L3 to M	149,599,737 km	381,678 km

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Low-Thrust/Energy Transfers

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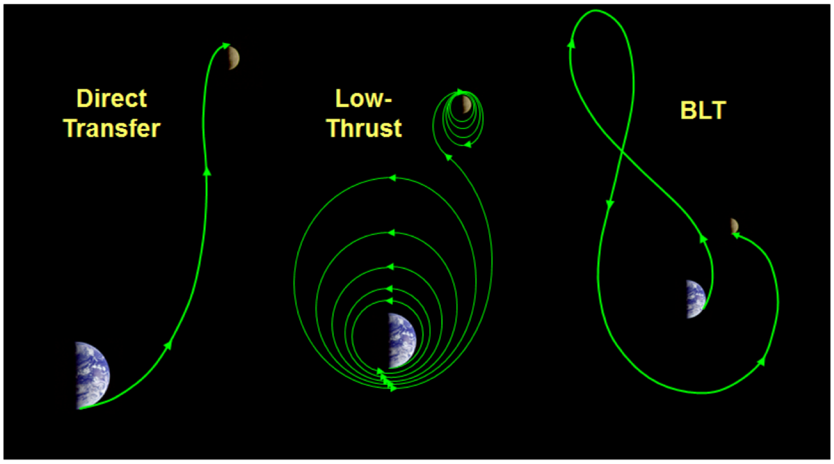
Unmanned Lunar Flight Revisited



Fast, high-thrust (~impulsive) trajectory

Slow, low-thrust trajectory

Slow, high-thrust (~impulsive) trajectory

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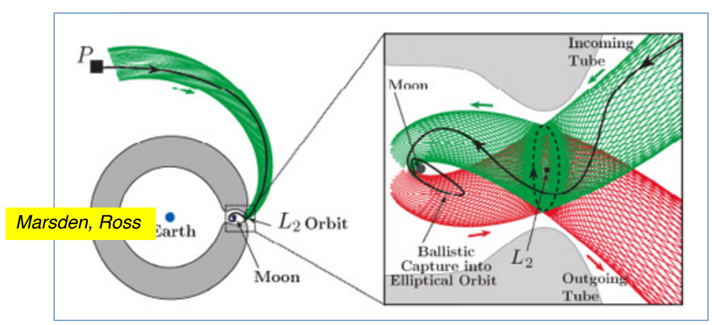
Weak Stability Region Trajectories

- Use of Earth, Moon, and Sun gravitational effects to produce low-energy maneuvers
- Very long transfer times
- Ballistic lunar transfer (BLT)



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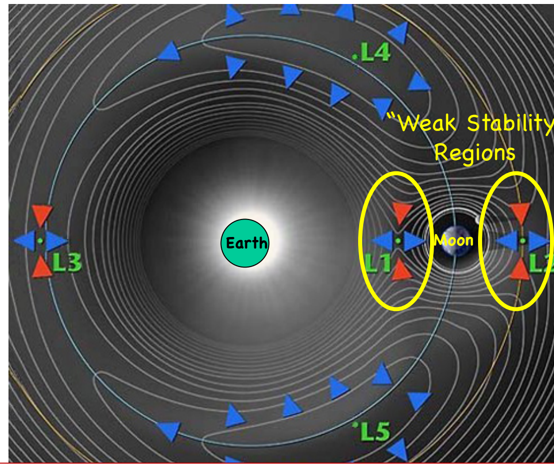
Unmanned Lunar Flight Revisited



- Space probe orbits affected by subtle gravitational effects
- Propellant savings (Belbruno et al, 1990)
- Missions salvaged or re-purposed (Hiten, HGS-1, ARTEMIS)
- Long-duration maneuvers

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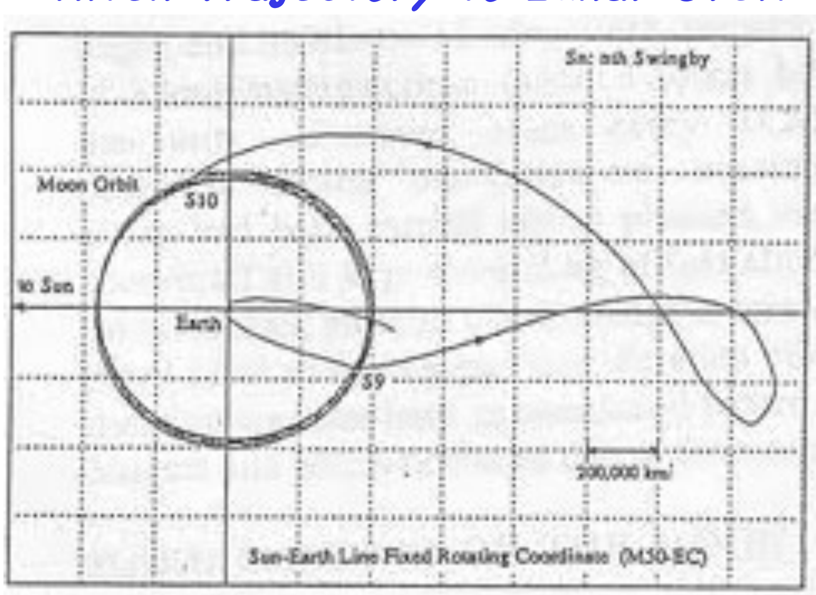
Hiten Trajectory to Lunar Orbit



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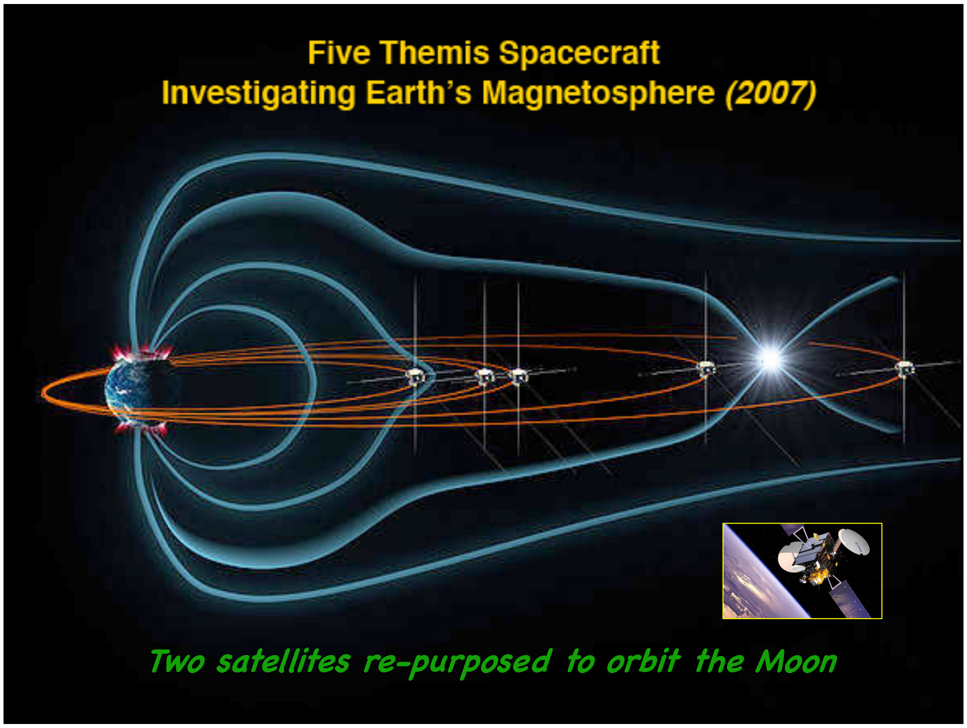
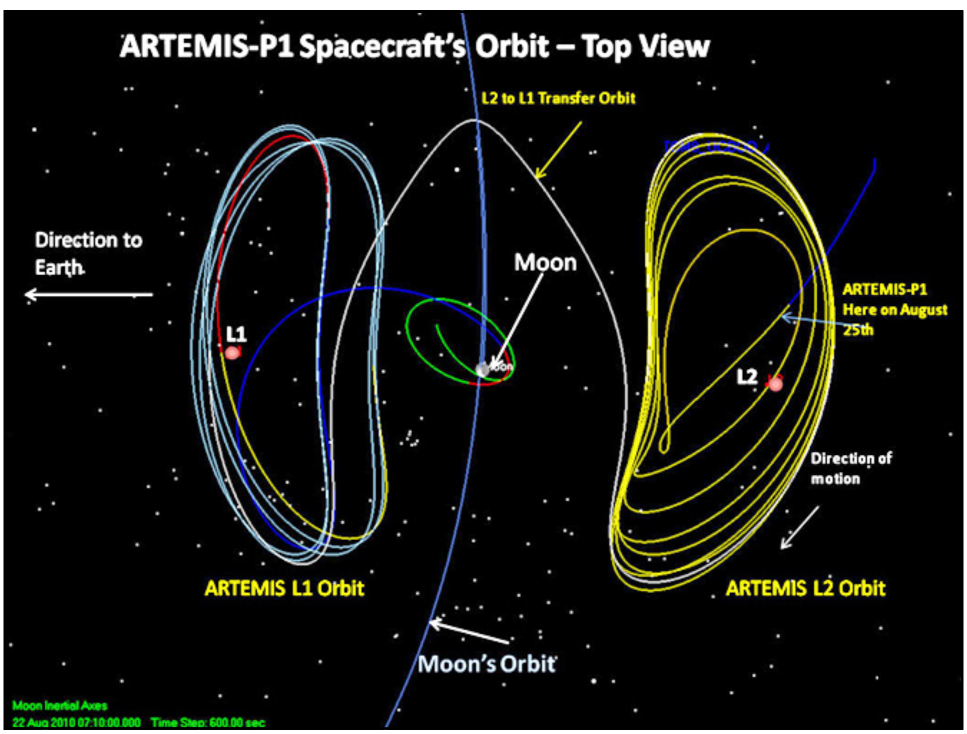
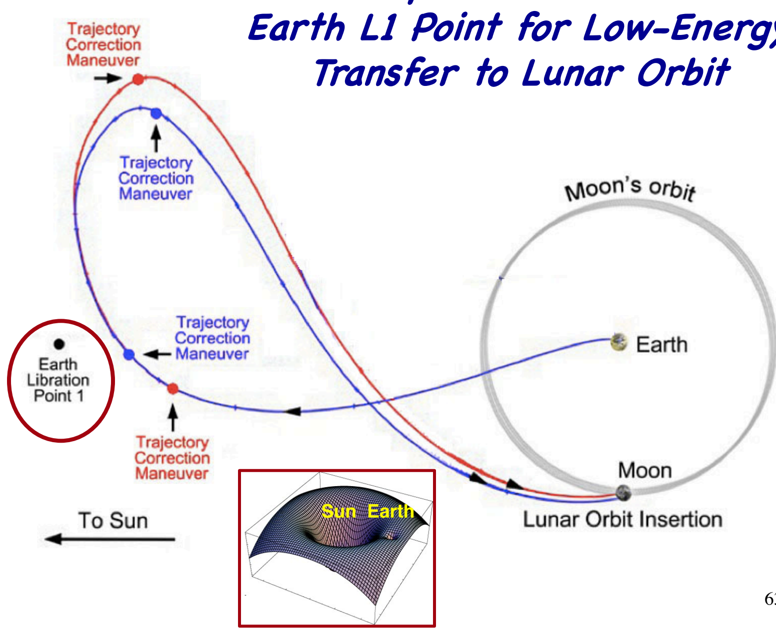

Five Themis Spacecraft
Investigating Earth's Magnetosphere (2007)
Two satellites re-purposed to orbit the Moon


ARTEMIS-P1 Spacecraft's Orbit – Top View
L2 to L1 Transfer Orbit
Direction to Earth
Moon
L1
L2
ARTEMIS-P1 Here on August 25th
Direction of motion
ARTEMIS L1 Orbit
ARTEMIS L2 Orbit
Moon's Orbit
Moon Inertial Axes
22 Aug 2010 07:10:00.000 Time Step: 600.00 sec

GRAIL Spacecraft Used Sun-Earth L1 Point for Low-Energy Transfer to Lunar Orbit



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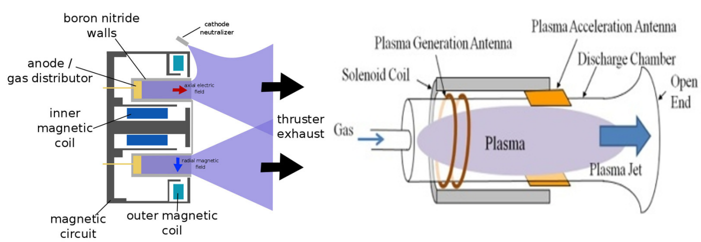
Ion/Plasma Thrusters
Low Thrust, High Specific Impulse



Engine	Propellant	Required power	Specific impulse	Thrust
		kW	s	mN
NSTAR	Xenon	2.3	3,300 to 1,700	92 max
NEXT	Xenon	6.9	4,300	236 max
HiPEP	Xenon	20–50	6,000–9,000	460–670
Hall effect	Xenon	25	3,250	950
FEEP	Liquid Cesium	6 x 10–5–0.06	6,000–10,000	0.001–1
VASIMR	Argon	200	3,000–12,000	~5,000
DS4G	Xenon	250	19,300	2,500 max

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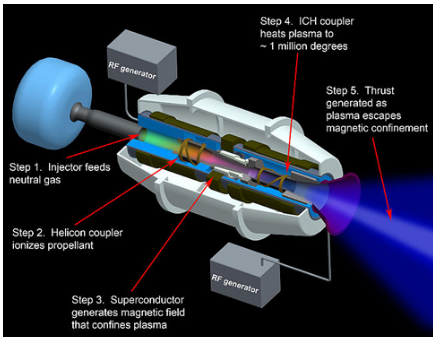
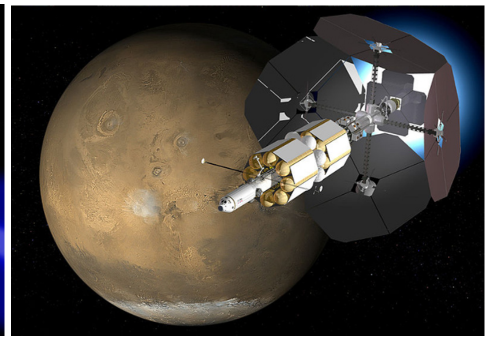
Variable Specific Impulse Magnetoplasma Rocket (VASIMR)

Propellant	Required power	Specific impulse	Thrust
	kW	s	mN
Argon	200	3,000–12,000	~5,000





Unproven concept

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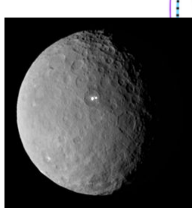
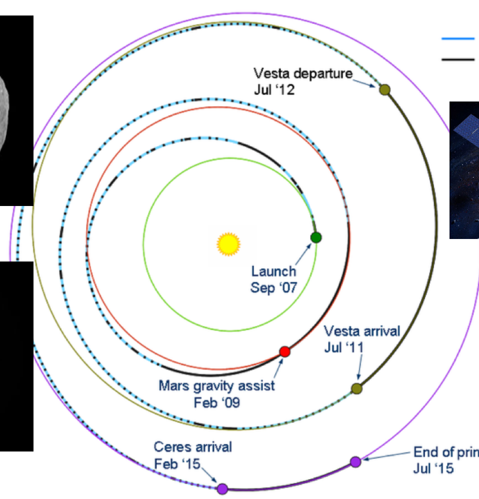
DAWN Spacecraft





Engine	Propellant	Required power	Specific impulse	Thrust
		kW	s	mN
NSTAR	Xenon	2.3	3,300 to 1,700	92 max

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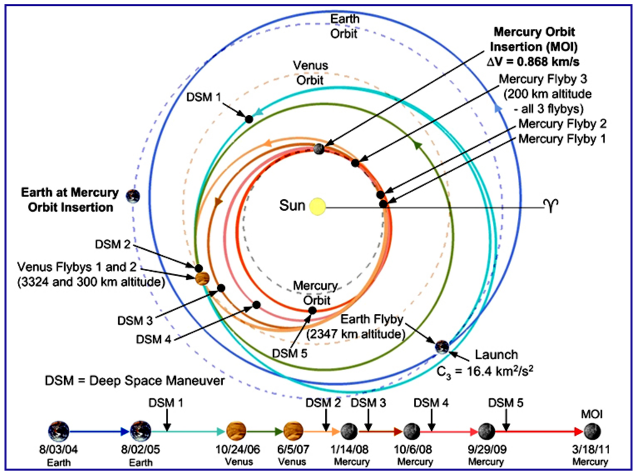
Mercury MESSENGER Fly-By Trajectories



Mercury MESSENGER Mission
https://www.youtube.com/watch?v=otF2FjpCyZk

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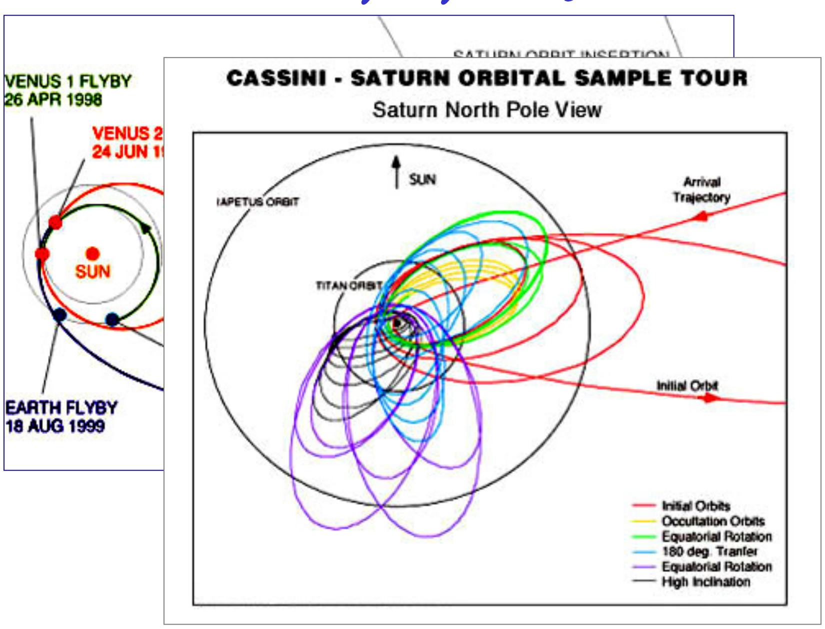
Cassini Fly-by Trajectories



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Next Time:

- ***Countdown to Landing***
- ***Attitude Dynamics & Control***

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