Mars: Science and Engineering

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CMU Osher
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Course Goals

- Show how robotic spacecraft work
- Show what they have found out about Mars
- Explore the iterative interplay between the science and the engineering
- Show both triumphs and failures
- Show the human side of the scientists and engineers
- Discuss possible future human missions to Mars

About me and you

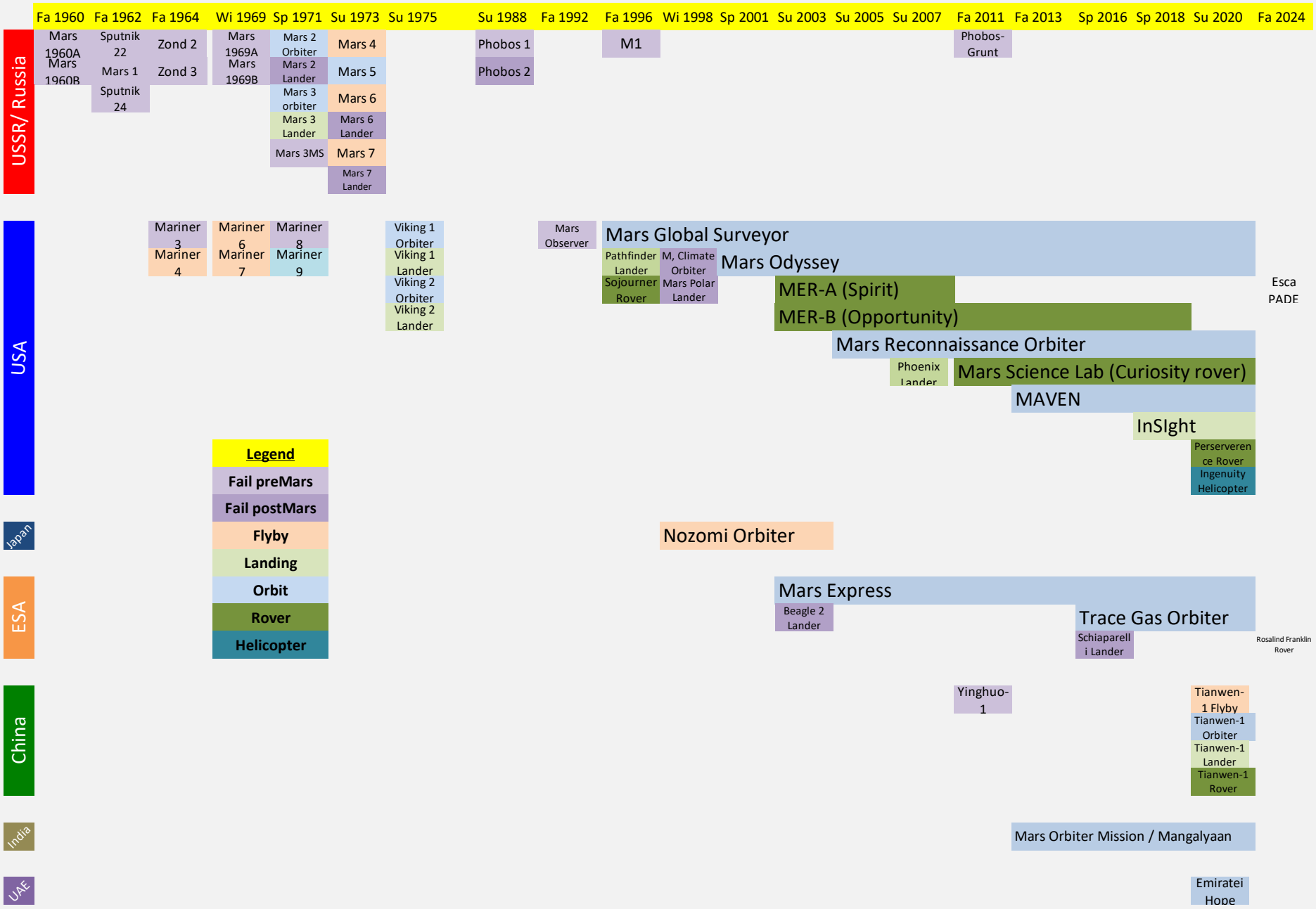
- Science Background
  - Ground a 6-inch mirror and built a telescope at age 13
  - BA in Biology from Oberlin including field geology course
  - MD from Medical College of Pennsylvania
  - Clinical Pathology including microbiology and clinical chemistry
  - PhD in Statistics
- Engineering Background
  - Devoured “The Way Things Work” at age 12
  - Repaired radios and televisions as an early teen
  - Ham radio operator with home-built equipment as a teen
  - Designed, built and programmed a system to automate radioimmunoassays
  - Extensive experience with laboratory instrumentation included gas chromatography/mass spectrometry

Course outline

- **Week 1**
  - Astronomy background
  - Early flights with no or minimal success
  - US Mariner Program (1960s)
- Week 2
  - 1970s: USSR Mars 4-7, US Viking program
  - 1990s: MGS, Pathfinder lander with Sojourner rover, Nozomi
- Week 3
  - Early 2000s: Odyssey, Spirit & Opportunity, Mars Express
  - Late 2000s: Mars Reconnaissance Orbiter, Phoenix lander
- Week 4
  - 2010s: Curiosity, MAVEN, Mangalayan, Insight
  - 2020s: Perseverance, Ingenuity, Tianwen, Emirati Hope
  - Future: EscaPADE, Exo-Mars
  - Far future: humans on Mars

Some sources

- NASA: https://www.nasa.gov
- NASA Space Science Data Coordinated Archive: http://nssdc.gsfc.nasa.gov
- JPL: https://www.jpl.nasa.gov
- European Space Agency: https://www.esa.int
- Planetary Society : https://www.planetary.org
- Wikipedia
- Marspedia: https://marspedia.org
- *The Search for Life on Mars* by Elizabeth Howell and Nicholas Booth
- *The Viking Missions to Mars* by John Hamilton
- *Managing Martians* by Donna Shirley
- *The Right Kind of Crazy* by Adam Steltzner
- *Roving Mars* by Steven Squyres
- *The Design and Engineering of Curiosity* by Emily Lackdawalla
- Beyond Earth: A Chronicle of Deep Space Exploration by Asif A Siddiqi https://www.nasa.gov/connect/ebooks/beyond_earth_detail.html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USSR/ Russia
Mars 1960A
Mars 1960B
Sputnik 22
Mars 1
Sputnik 24
Zond 2
Zond 3
Mars 1969A
Mars 1969B
Mars 2 Orbiter
Mars 2 Lander
Mars 3 orbiter
Mars 3 Lander
Mars 3MS
Mars 4
Mars 5
Mars 6
Mars 6 Lander
Mars 7
Mars 7 Lander
Phobos 1
Phobos 2
M1
Phobos-Grunt
USA
Mariner 3
Mariner 4
Mariner 6
Mariner 7
Mariner 8
Mariner 9
Viking 1 Orbiter
Viking 1 Lander
Viking 2 Orbiter
Viking 2 Lander
Mars Observer
Mars Global Surveyor
Pathfinder Lander
M, Climate Orbiter
Mars Odyssey
Sojourner Rover
Mars Polar Lander
MER-A (Spirit)
MER-B (Opportunity)
Mars Reconnaissance Orbiter
Phoenix Lander
Mars Science Lab (Curiosity rover)
MAVEN
InSIght
Perserverence Rover
Ingenuity Helicopter
Esca
PADE
Legend
Fail preMars
Fail postMars
Flyby
Landing
Orbit
Rover
Helicopter
Japan
Nozomi Orbiter
ESA
Mars Express
Beagle 2 Lander
Trace Gas Orbiter
Schiaparelli Lander
Rosalind Franklin Rover
China
Yinghuo-1
Tianwen-1 Flyby
Tianwen-1 Orbiter
Tianwen-1 Lander
Tianwen-1 Rover
India
Mars Orbiter Mission / Mangalyaan
UAE
Emiratei Hope

Knowledge of the sky before the space age

- Early humans must have recognized the movement and phases of the moon, apparent patterns in the stars (constellations), the movement of the stars through the night, the yearly star cycle, and the presence of the five naked-eye planets (Mercury, Venus, Mars, Jupiter, and Saturn) as they “wander” among the stars
- Egyptian, Babylonian and Chinese star tables go back 3000 to 4000 years

The movement of the stars

- Revolution Around the Sun (1:42) [Conceptual Academy: Observing the Night Sky]
- Rotation on Our Axis (0:23) [MissGoin4U: North Star Star Trails]

Naked eye observation of Mars

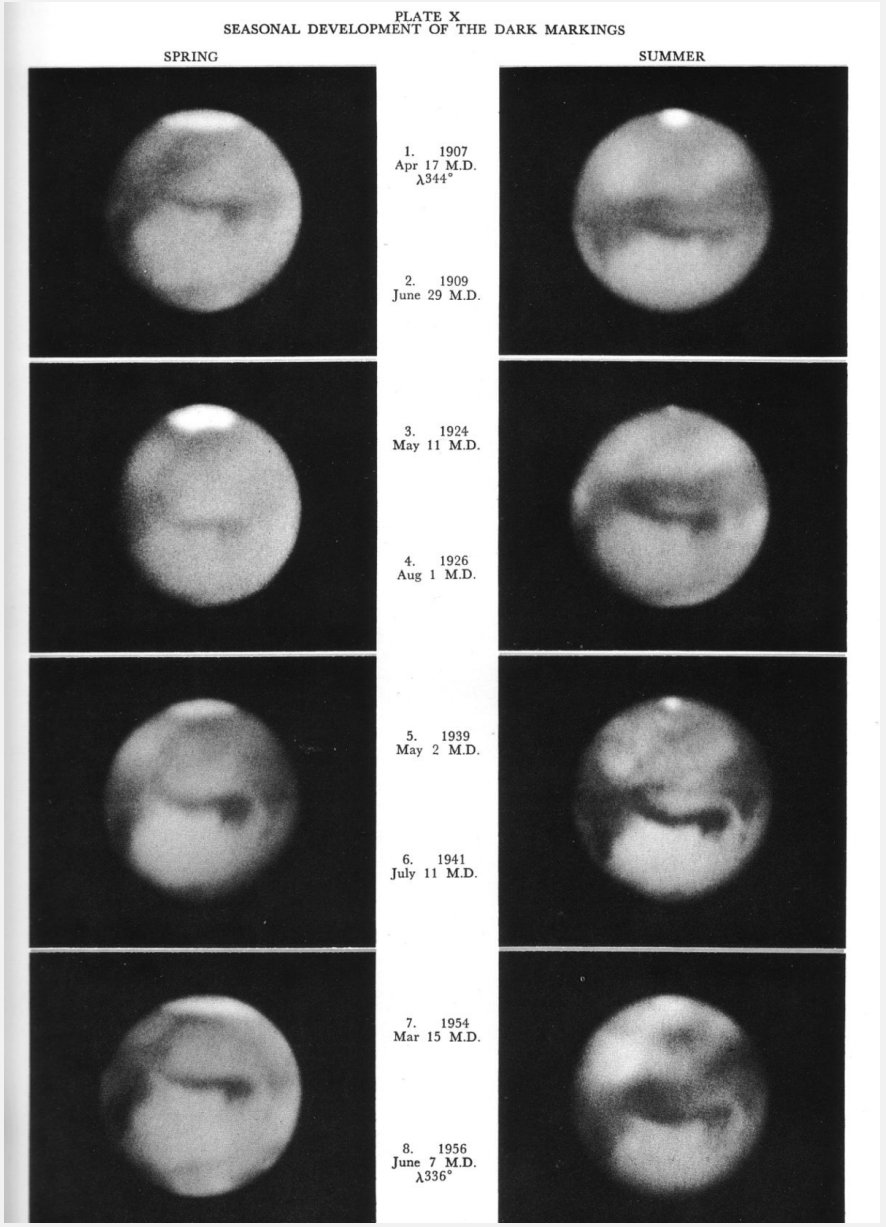
Seeing Mars (3:40) [Youtube: Learn the Sky]

Knowledge of Mars before the modern era

- Aristarchus of Samos (c. 310 – c. 230 BCE) presented the first known heliocentric model of the solar system
- The geocentric model in the *Almagest* of Ptolemy (circa 100 – circa 170 AD) dominated astronomy for over 1300 years
- Copernicus (1473 – 1543) provided convincing evidence of the heliocentric solar system
- Galileo (1564 – 1642) was the first to see Mars through a telescope
- Mars was first mapped by Christian Huygens in 1659, who saw the ice caps, and measured the diameter and day length
- In 1704 Jacques Philippe Maraldi observed periodic changes in the sizes of the ice caps
- In the 1870s Eugène M. Antoniadi saw windblown dust storms

Percival Lowell

- American businessman and amateur astronomer (1855-1916)
- Founded Lowell Observatory outside of Flagstaff, AZ
- Studied, photographed and drew Mars from 1893 to 1908
- Believed he saw canals, oases, and crop cycles
- Mostly rejected by the scientific community, but highly popular
- Stimulated science fiction!
- Work continued by Earl Slipher until 1961



Knowledge of Mars before the space age

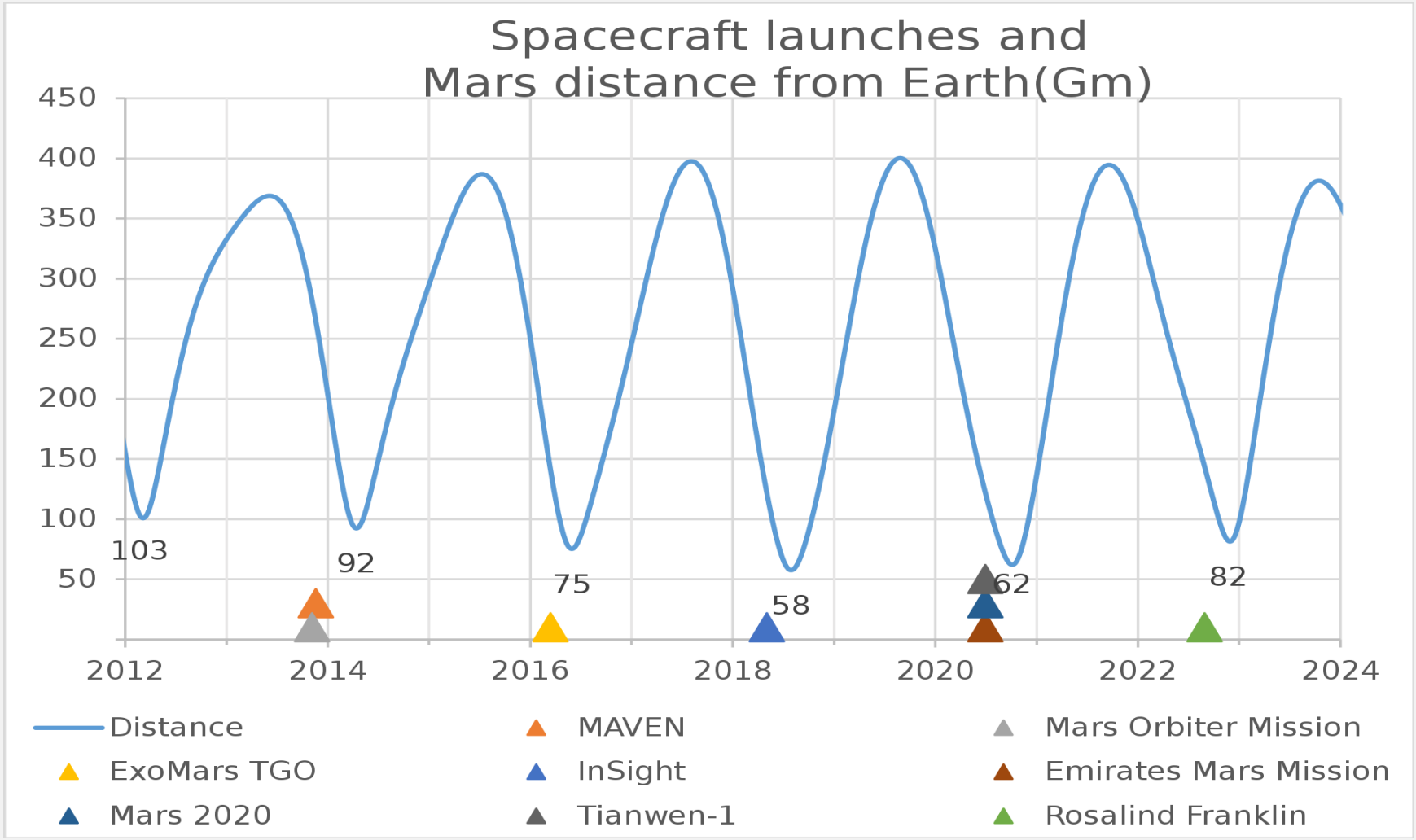
- In 1924 American astronomers Seth Nicholson and Edison Pettit, working at Mount Wilson Observatory used a vacuum **thermocouple** to estimate the temperature as −90 °F (−68 °C) at the pole and 45 °F (7 °C) at the equator. Americans William Coblentz and Carl Lampland showed that the nighttime temperature dropped to −121 °F (−85 °C)
- In 1926 Walter Adams used **spectroscopy** to measure the amount of oxygen and water vapor in the atmosphere. He determined that "extreme desert conditions" were prevalent on Mars. In 1934, Adams and Theodore Dunham Jr. found that the amount of oxygen in the atmosphere of Mars was less than one percent of the amount on Earth.

More facts about Mars

- Sun-Mars distance varies from 128 to 155 million miles
- From https://solarsystem.nasa.gov/planets/mars/in-depth/
  - “As Mars orbits the Sun, it completes one rotation every 24.6 hours. Martian days are called sols – short for ‘solar day.’ A year on Mars lasts 669.6 sols, which is the same as 687 Earth days.
  - “Mars' axis of rotation is tilted 25 degrees with respect to the plane of its orbit around the Sun. […Earth’s is 23.4 degrees]. [Mars’ seasons last longer than] seasons here on Earth since Mars takes longer to orbit the Sun, [and are uneven] … because of Mars' elliptical, egg-shaped orbit around the Sun.
  - “Spring in the northern hemisphere (autumn in the southern) is the longest season at 194 sols. Autumn in the northern hemisphere … is the shortest at 142 days. Northern winter … is 154 sols, and northern summer … is 178 sols.”

Hohmann Transfer Orbit

- Hohmann Transfer Orbit (1:00)



Some challenges for visiting Mars

- Launch periods/windows and trajectory planning
- Rockets powerful and reliable enough
- Rocket guidance
- Cost, reliability, and capability (weight) trade-offs
- Choice of scientific instruments
- Entry, descent and landing
- Effects of radiation, low temperature, temperature change, dust, and low gravity on equipment
- Known unknowns
- Unknown unknowns

Early USSR Missions

- Soviet Mars missions, based on Venera hardware, were far from successful, with nine failures from 1960 to 1969.
- November 1962: Soviet Mars 1
  - Upper stage fired out of Earth orbit towards Mars
  - An attitude control valve failed, expending all its N_2 gas
  - Backup gyro control kept solar panels pointed to the sun
  - Successfully collected interplanetary data
  - Lost antenna pointing and flew by Mars at 122,000 miles in June 1963

US Mariners and JPL

- Spacecraft built by JPL (Jet Propulsion Laboratory)
- Total Mariner 1-10 cost: $554 million ($5.4 billion today)
- JPL
  - Started as the rocket propulsion lab of Theodore Von Kármán in the 1930s at Caltech University
  - Located off-campus, in a 168-acre canyon north of the Rose Bowl
  - 1943: Hired by the US army to understand, duplicate, and improve on the German V-2 rockets. Took the name JPL.
  - Worked with Army Ballistic Missile Agency to launch the first US satellite, Explorer 1, in 1958
  - Transferred from Army to NASA in December 1958
  - Got Mariner Program contract in 1960

Mariners 1 and 2 (to Venus)

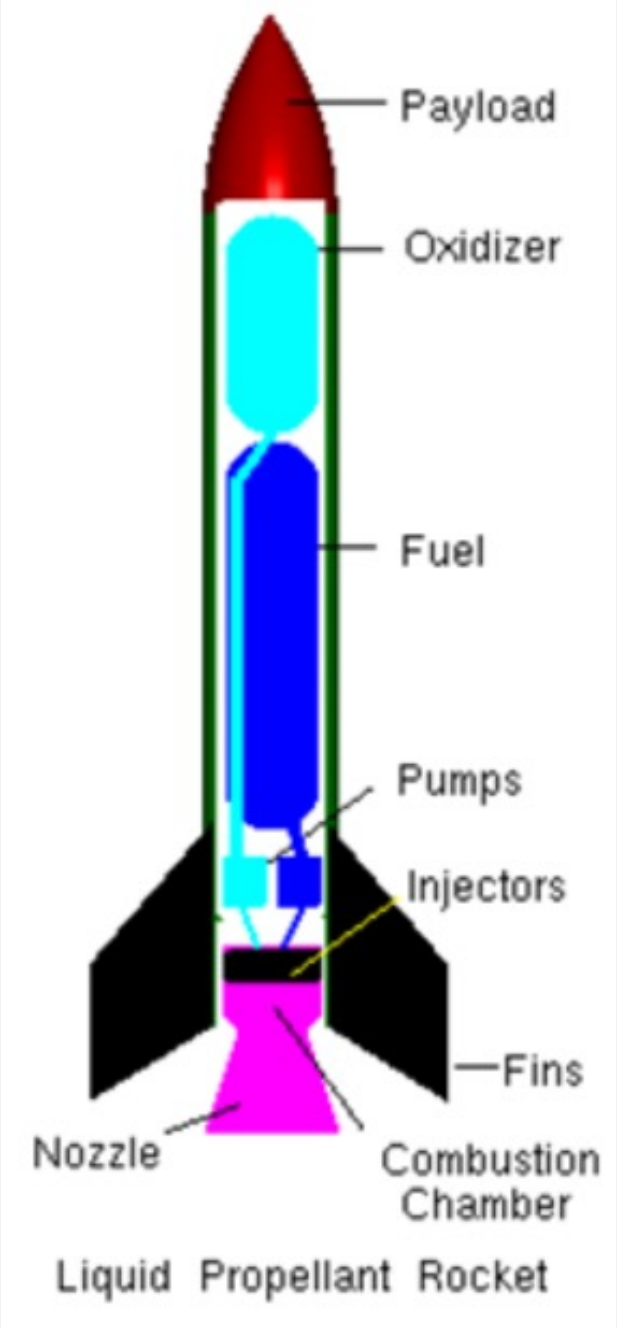
- July 1962, Mariner I was supposed to fly by Venus. It was destroyed approximately 5 minutes after liftoff by the Air Force Range Safety Officer when its malfunctioning Atlas-Agena rocket went off course.
- NASA Space Science Coordinated Archive: "[T]he Mariner 1 Post Flight Review Board determined that the omission of a superscript overbar when translating the handwritten equations into the coded computer instructions allowed transmission of incorrect guidance signals (basically instantaneous values instead of smoothed values) to the spacecraft [...] This caused the rocket to swing automatically into a series of unnecessary course corrections with erroneous steering commands which finally threw the spacecraft off course."
- Mariner 2 successfully flew by Venus in August 1962

To Mars: Mariner 3/4 construction

- Mariner 3/4 cost: $83.2 million (about $807 million today)
- Launched on a General Dynamics Atlas/Agena rocket
  - The Atlas was developed as an ICBM. It had booster engines fueled by RP-1 (highly refined kerosene) and liquid oxygen and which were discarded when empty, and a central RP-1/LO_2 engine, both with gimbaled engines and inertial guidance.
  - The Agena used a Bell Aerosystems engine using dimethylhydrazine (DMH) as the fuel, and red fuming nitric acid (RFNA) as the oxidizer, originally developed for bomber jets. It had gimbaled nozzles for steering.

Rocket primer

- Based on Newton's third law of motion: For every action there is an equal and opposite reaction
- Main types:
  - Monopropellant produces gasses when in contact with a catalyst
  - Fuel plus oxidizer: produce gasses when mixing propellant and oxidizer
    - with an igniter (non-hypergolic)
    - without an ignitor (hypergolic fuels)
- Gasses are expelled through a nozzle, causing the rocket to move in the opposite direction
- Steering is with movable fins, movable (gimbaled) engines, movable exhaust nozzles, or extra "vernier" thrusters



Inertial guidance

- Three gyroscopes at right angles measure direction
- Three accelerometers at right angles measure acceleration
- Circuits integrate acceleration to get velocity
- Integration of velocity produces position
- Feedback relative to stored desired position keeps the rocket on trajectory
- This is a form of “dead reckoning”

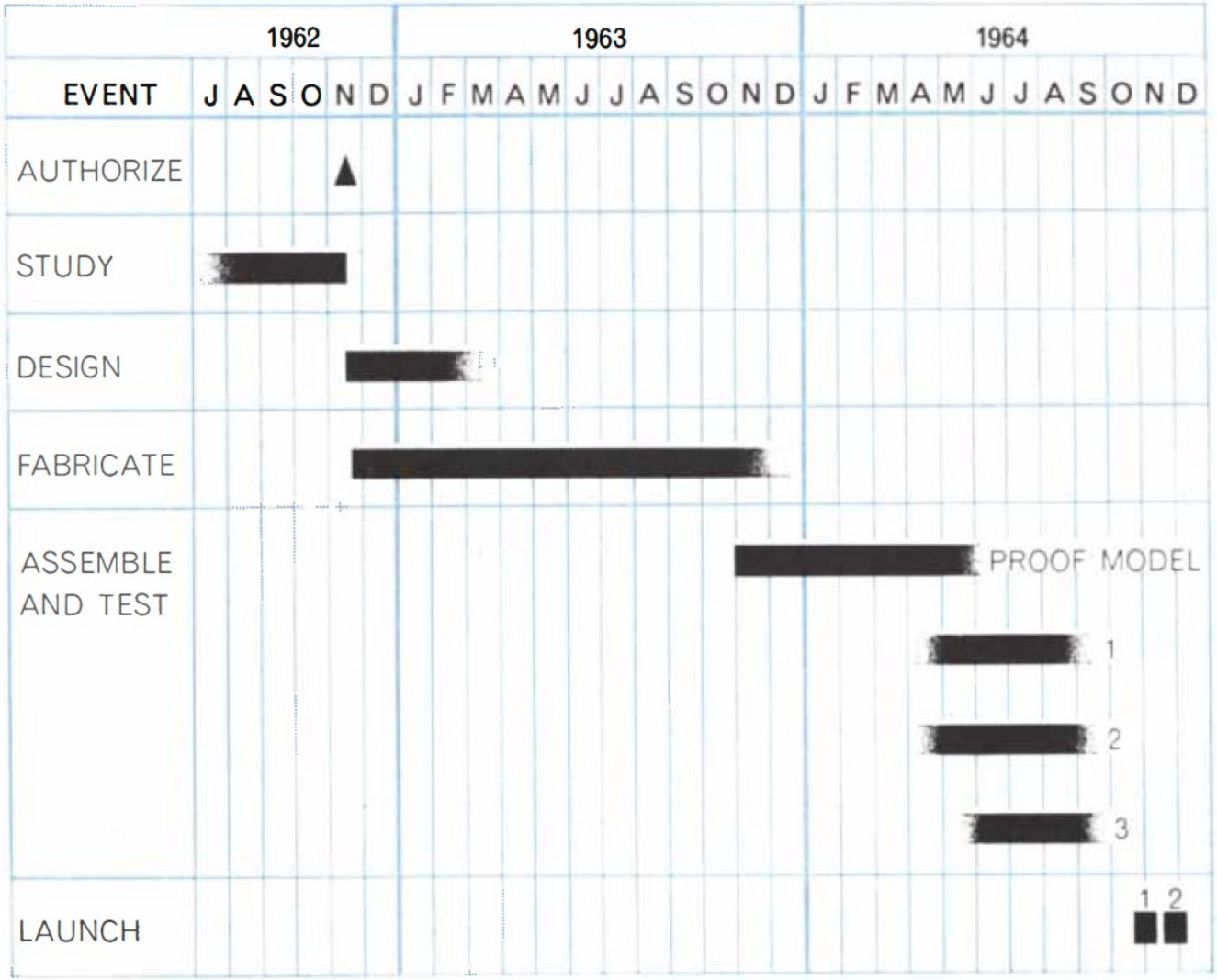
Mariner 3/4 spacecraft

- 575 pounds, 54,000 parts
- 4’4” octagonal magnesium frame 1.5 feet high
- Four solar panels: 70 square feet, 7000 cells, 300 watts
- Rechargeable silver zinc battery, 1200 watt-hours
- Two 10-watt microwave-band transmitters
- Hydrazine monopropellant course correction engine

Mariner 3/4 instrumentation

- Star tracker (locking on Canopus)
- High-gain parabolic antenna (33 bits/second) [4G=100 Mb/s]
- Omnidirectional low gain antenna (8 bits/second)
- Magnetometer
- Geiger counter (failed)
- Low energy radiation detector
- Cosmic ray detector
- Solar plasma detector
- Cosmic dust detector
- Television camera: first ever digital camera
- 5-megabit magnetic tape recorder

Mariner 3/4 schedule



MARINER SCHEDULE for the Mars mission began with authorization in November, 1962, based on prior studies. The chart shows how it was necessary to compress design, fabrication and testing to have three flight-qualified spacecraft ready for launching by November, 1964.

Mariner 3/4 testing

- Test chamber built to simulate temperature, pressure (vacuum), vibration and lighting
- Tested for 3500 hours (vs. 6000-hour trip to Mars)
- Problem types: too lightweight for vibrations experienced, deterioration with time, outgassing
- Data automation subsystem controls all other components and sends data to the transmitters. The resistors reacted with the boron coating compound used to “radiation harden” the electronics and changed resistance. A glass coating was applied before the boron coating, in a new data automation subsystem, but there was no time for re-testing.

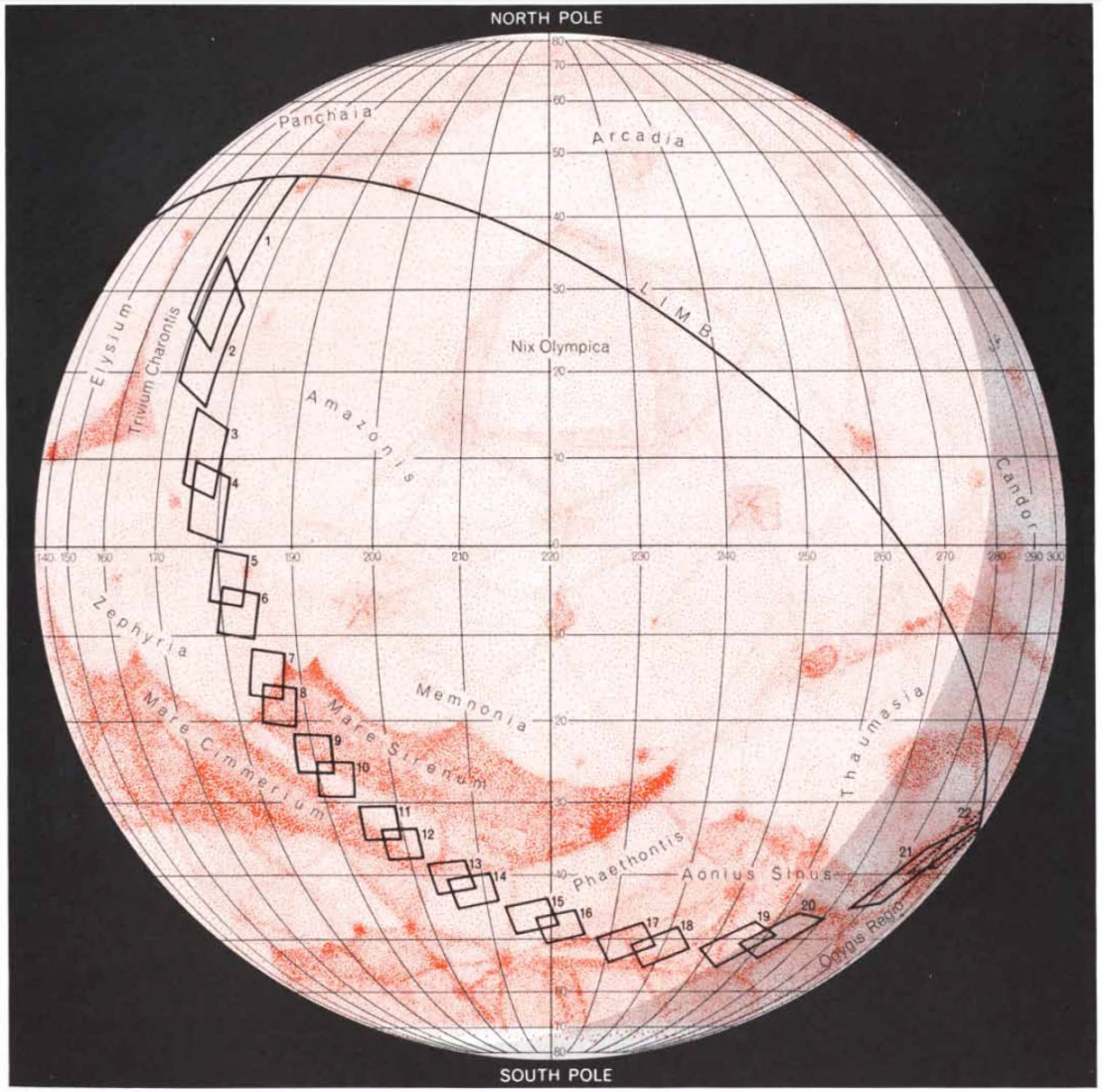
Mariner 3

- Mariner 3 attempt to fly by Mars in November 1964
  - In an attempt to reduce weight, a fiberglass shroud (fairing) was used for the first time
  - The spacecraft was found to be traveling 670 mph too slow – traced to the extra 290 pounds of the shroud still being attached
  - Battery discharge showed that the solar panels did not deploy
  - Manual command to detach the shroud failed
  - Plan to use a midcourse engine firing to shake the fairing loose failed because it was too late
  - Eight hours after launch the batteries died, and the mission ended
  - Only 27 days were left in the launch period, but a new metal shroud, only a few pounds heavier, was fabricated in 23 days

Mariner 4 operation summary

- Launch November 28, 1964 Mariner 4 Launch Movie (1:03)
- The star tracker lost Canopus multiple times, and the problem was traced to sunlight reflecting off dust coming off the vehicle
- A flight correction was successfully made December 5
- The fly-by was July 14/15, 1965, with a 6,118-mile closest approach, 134 million miles from Earth at 4.3 miles/second relative to Mars. Twenty-one pictures were taken covering 1% of the surface. Each took 8 hours to transmit.
- Interplanetary data was recorded at 10^{-18} watts until Oct. 1965

Mariner 4 regions photographed



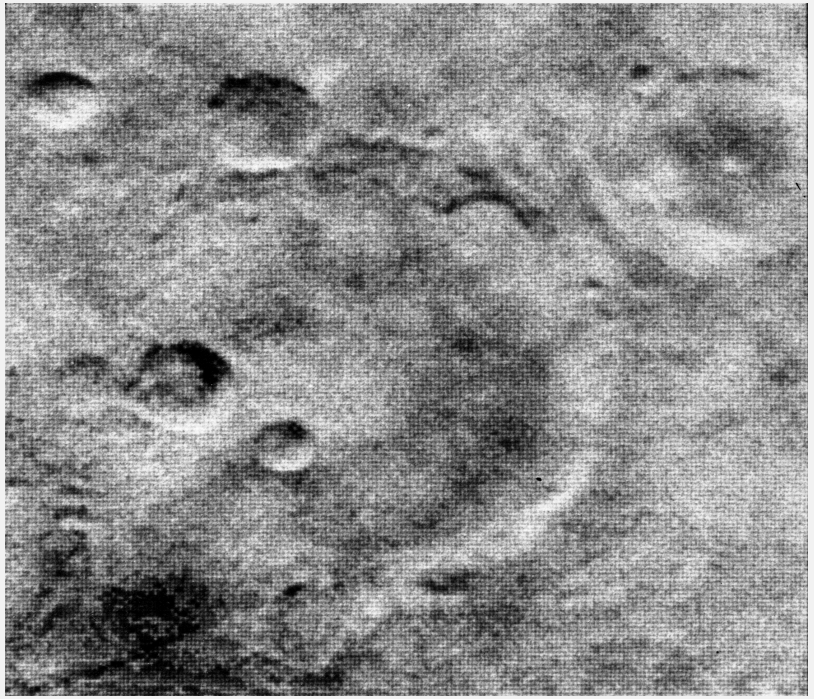
REGIONS PHOTOGRAPHED by *Mariner IV* are plotted on a pictorial representation of Mars that shows some of the prominent surface features reported by astronomers over three centuries. The map, centered on 220 degrees East longitude, is based on one prepared by the Army Map Service. Picture No. 1 caught the limb, or edge, of the planet as *Mariner IV* observed it from a position about 8,000 miles below the plane of Mars's orbit, at a slant range of 10,500 miles. As the spacecraft swept under the planet, the television scan path progressed toward the southeast and in Picture No. 19 moved across the terminator (the light-dark boundary). The last three pictures were taken in complete darkness. The coordinates of the last picture have not yet been well established.

Mariner 4 videos

- Before reaching Mars: Mariner 4 NASA Documentary Part 1 (9:09)
- At Mars: Mariner 4 NASA Documentary Part 2 (9:30)

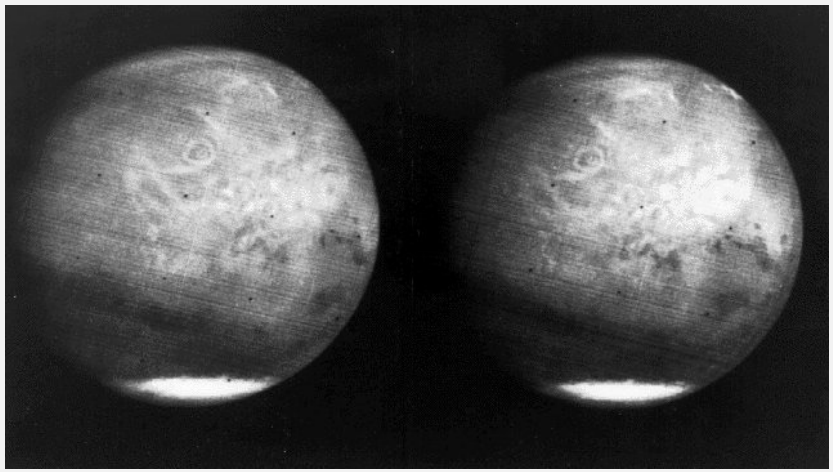
Some Mariner 4 science results

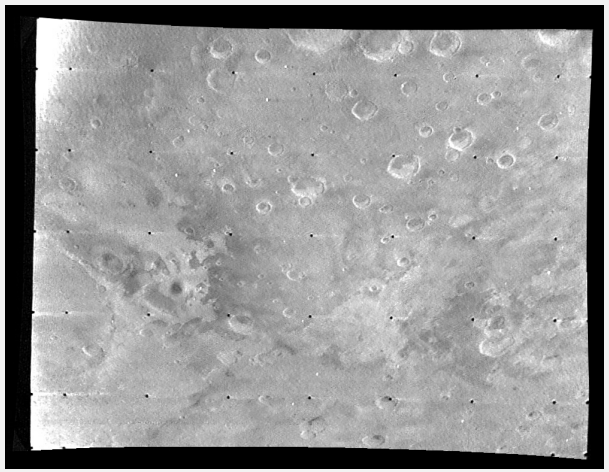
- Total data 634 kB. All instruments OK except the Geiger counter
- En route solar flares and micrometeors detected
- No magnetic field or radiation belts were detected around Mars
- Atmosphere was found to be very thin: 10 to 20 millibar
- From the (non-representative) images, it was concluded that Mars was heavily cratered, and more moon-like than Earth-like

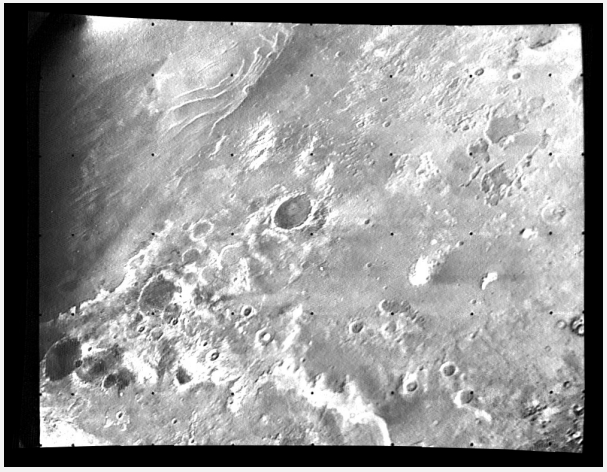


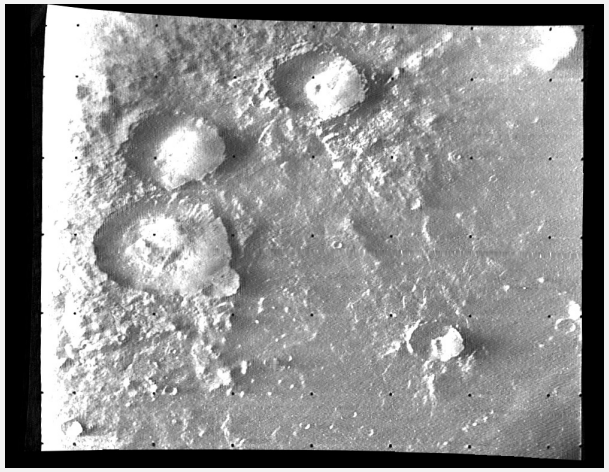
Mariner 5-7

- Mariner 5: to Venus, failure of Agena burn
- Mariner 6 and 7: Successful July 1969 Mars fly-bys
  - 201 photographs covering 20% of Mars
  - Found trace amounts of surface water by spectrometer





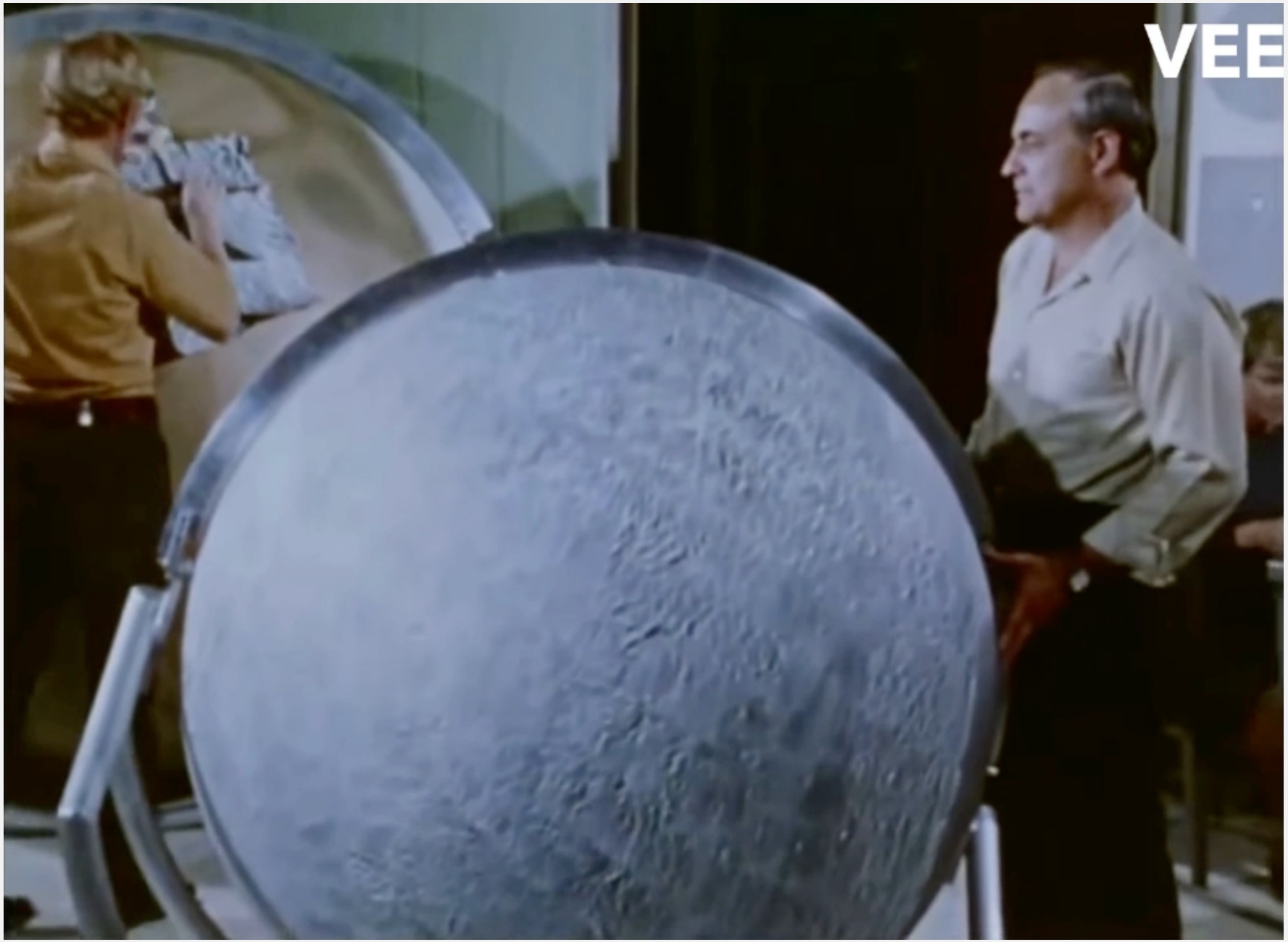




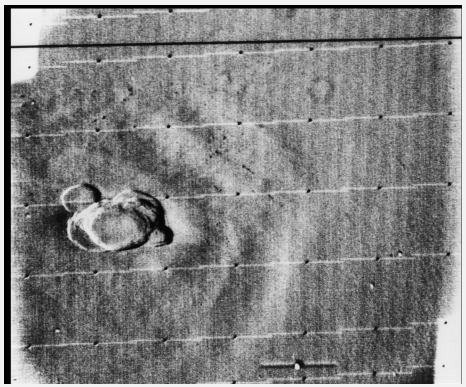
US Mariners 8-9, Soviet Mars 2+3

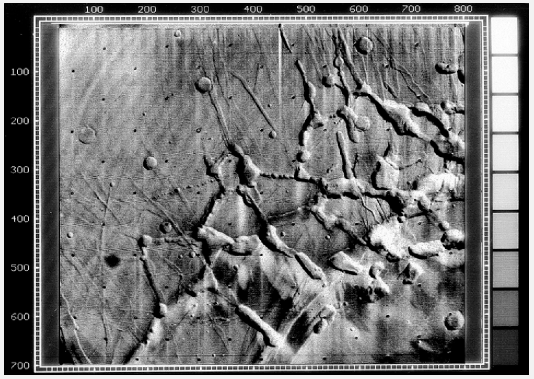
- Mariner 8: Second stage tumbled out of control (bad diode)
- Mariner 9: Launch to Mars May 30, 1971
  - First spacecraft to orbit another planet on November 19, 1971
- Soviet Mars 2 and Mars 3 launched earlier, arrived weeks later
  - Mars 2 orbited and took measurements and pictures (mostly of a huge sandstorm) and dispatched a lander that crashed
  - Mars 3 orbited and successfully dispatched a lander which lasted 110 seconds and took a bland, partial picture
- Mariner 9 waited till after the dust storm and took 7,329 images through October 1972, covering 85% of Mars. Resolution improved from 2,660 to 320 ft per pixel
- Introduced error correcting code for data transmission
- Identified extinct volcanoes, riverbeds, craters, canyons, evidence of wind and water erosion and deposition, weather fronts

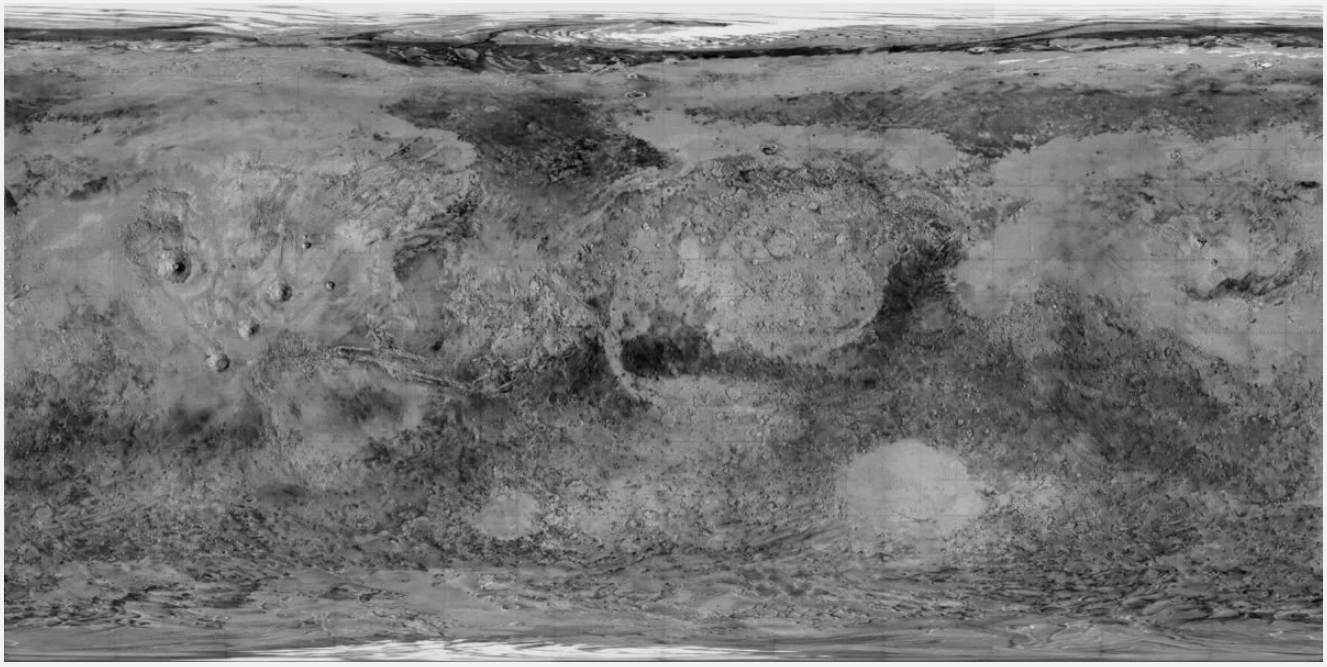
Mariner 9: Globe Construction



Mariner 9 images







Perspective after the Mariners

2016 NASA Symposium “Viking at 40” at the Langley Research Center

Ellen Stofan has a PhD in Geology and was NASA Chief Scientist from 2013 to 2016

Ellen Stofan (2:27)

Summary and next class

- The US eventually was able to send spacecraft to fly by and orbit Mars
- We found a planet seemingly hostile to life with very little water and a very thin atmosphere
- But there was tantalizing evidence of past water
- Next: 1970's, especially US Viking landers and 1990's, especially US Pathfinder/Sojourner

An early time line

- First German V2 ballistic missile: October 1942
- Russian R1 ballistic missile: November 1950
- US Redstone ballistic missile: August 1953
- USSR Sputnik 1: October 1957
- USSR Sputnik 2: flies Laika the dog in November 1957
- US Explorer 1: February 1958
- USSR Luna 1: flies by the moon in January 1959
- USSR Luna 2: crashes on the moon in September 1959
- Yuri Gagarin's flight: April 1961 (Q1?)
- Alan Shepard's flight: May 1961 (Q2?)
- USSR Venera 1: flies by Venus in May 1961 (no data at Venus)
- US Mariner 2: flies by Venus in August 1962
- US Ranger 7: returns moon pictures before crashing in August 1964
- US Mariner 4: Mars flyby in July 1965
- USSR Luna 9: first successful lunar lander in January 1966
- USSR Venera 3: crashes on Venus (communication failure) in March 1966
- USSR Venera 4: descends in Venusian atmosphere in June 1967
- Apollo 11: July 1969
- USSR Venera 7: lands on Venus in December 1970
- USSR Mars 3: briefly lands on Mars in May 1971
- US Pioneer 1: orbits Venus in May 1978