Space Flight Software

Jane Oh, PhD

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[CL#23-6454]

[Credit: NASA/JPL-Caltech]

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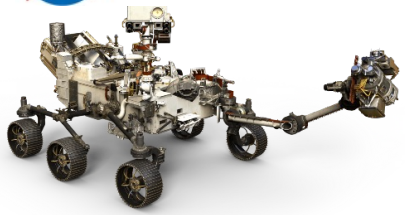

Today's Agenda

Part 1: Mars Helicopter Project Flight Software

- Mars Helicopter Project
- Conditions at Mars & Helicopter Capability
- Mars Helicopter Hardware
- Mars Helicopter FSW Architecture & Description
- Concept of Operations

Part 2: Mars Rover Project Flight Software

- Mars Rover Family Portrait
- Growth of FSW Complexity & Size
- Mars2020 Rover Project
- Mars2020 FSW Architecture
- Mars2020 FSW Modules
- Mars2020 Surface Operations FSW

Part 3: Dare Might Things in Past, Present, and Future

- NASA's Three Balanced Pillars
- Flight Project Funding Strategy
- NASA's Ten Centers
- NASA/JPL-Caltech Beginnings
- NASA JPL's 160 Flight Projects [1958-2027]

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[Credit: NASA/JPL-Caltech]

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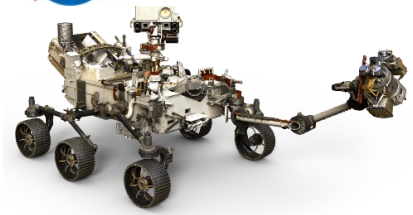
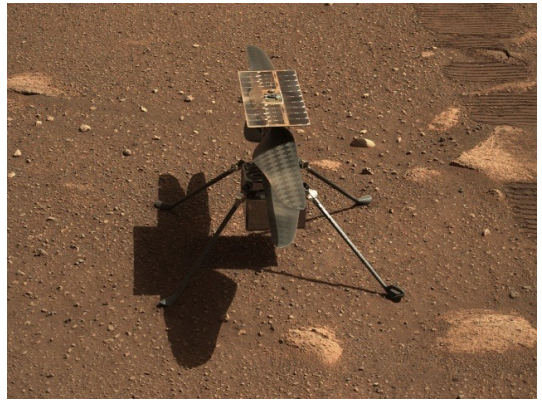
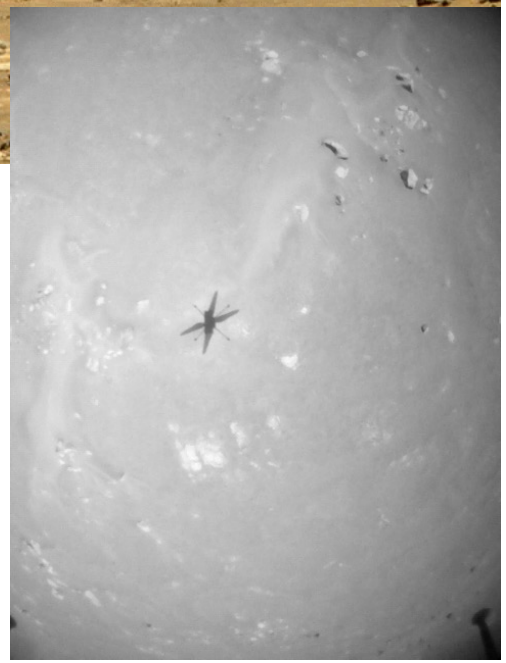


Mars Helicopter Project

- NASA technology demonstration
- Landed with Perseverance rover in Feb 2021
- Originally slated for 30 Mars Sol (Note: A Sol is a Martian day, 24 hours 37 minutes long) in April 2021
- Because of great success, is still on ongoing extended mission (as of Nov 2023)
- Purpose is to gather detailed flight performance data to inform future rotorcraft
- Extended mission is to explore scouting concept for Perseverance Rover





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[Credit: NASA/JPL-Caltech]

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Conditions at Mars & Helicopter Capability

- Long distance from Earth (average distance: ~ 140 million miles, ~ 225 million km)
  - Autonomous flight and landing
- Thin atmosphere (<1% of Earth's)
  - Large blades; light-weight vehicle; high RPMs
- Cold Martian nights (~ –90° C)
  - Active temperature control where needed; External parts which can survive cold
- Need self-sufficient solar power system
  - Solar powered with batteries

[Credit: Canham/CL#19-7128 /CL#22-0146]

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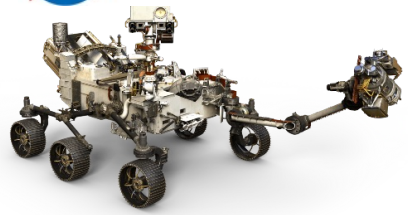
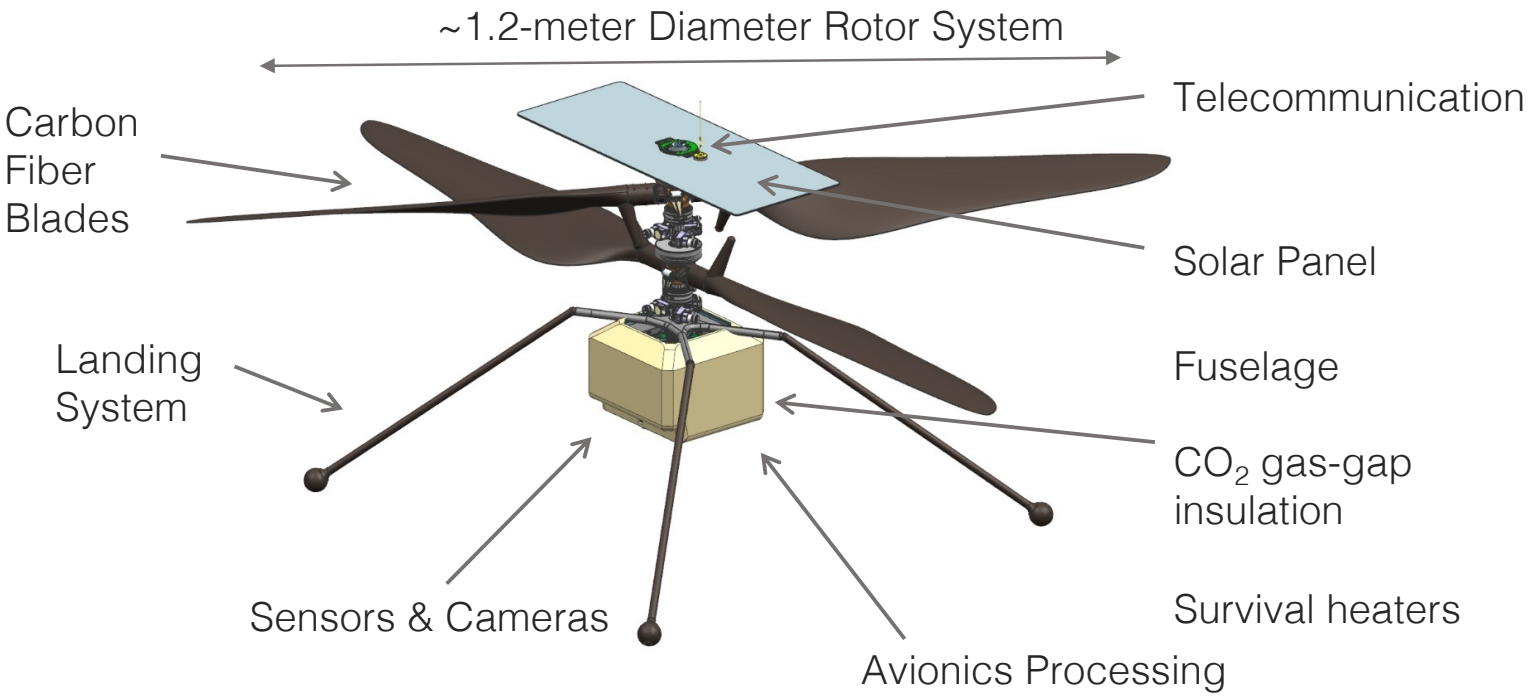


Anatomy of Mars Helicopter



- ✓ Total Mass < 1.8 Kg
- ✓ Rotor Speed: 1900-2800 RPM
- ✓ Blade Tip Mach Number: < 0.7

[Credit: Canham/CL#19-7128 /CL#22-0146]

[Credit: NASA/JPL-Caltech]

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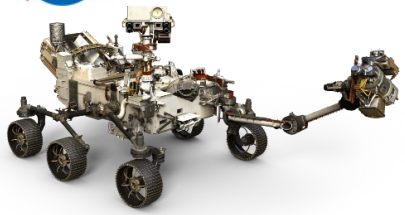

Helicopter Avionics Block Diagram

Sony IMX214 13MP Color

MIPI

Omnivision OV7251 B&W

Qualcomm Snapdragon 801
4 core, 2.2GHz
2GB RAM,
32 GB eMMC
(Linux)

SPI

5MHz

GPIOs

MicroSemi ProASIC 3L FPGA

Motors

I2C

Garmin Lidar Lite LRF

SPI

8MHz

Bosch BMI-160 IMU

SPI

8MHz

GPIOs

SPI

500 KHz

muRata SCA100T inclinometer

Zigbee Radio

UART

460Kb

UART

920Kb

TI TMS570LC4357 MCU
350MHz, 4MB flash,
512KB RAM
(Bare Metal)

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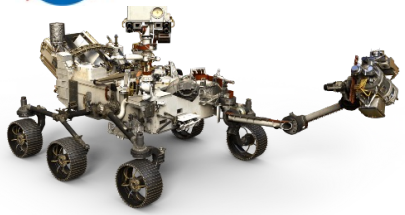

Helicopter FSW Architecture

- Chose F Prime flight software framework
  - JPL developed, but open sourced on NASA GitHub https://github.com/nasa/fprime
  - Component architecture
  - The use of F Prime allowed us to leverage work done by other projects to mature the core components of the system
  - The flexibility of F Prime allowed us support a number of venues and functions
  - Component architecture allowed combinations for different testing, Ground Support Equipment (GSE), flight deployments
  - Helicopter reused many infrastructure components from previous projects
- Used on previous projects
  - RapidScat, Asteria, NeaScout, Lunar Flashlight, University CubeSat projects

[Credit: Canham/CL#19-7128 /CL#22-0146]

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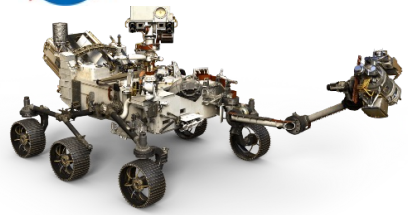
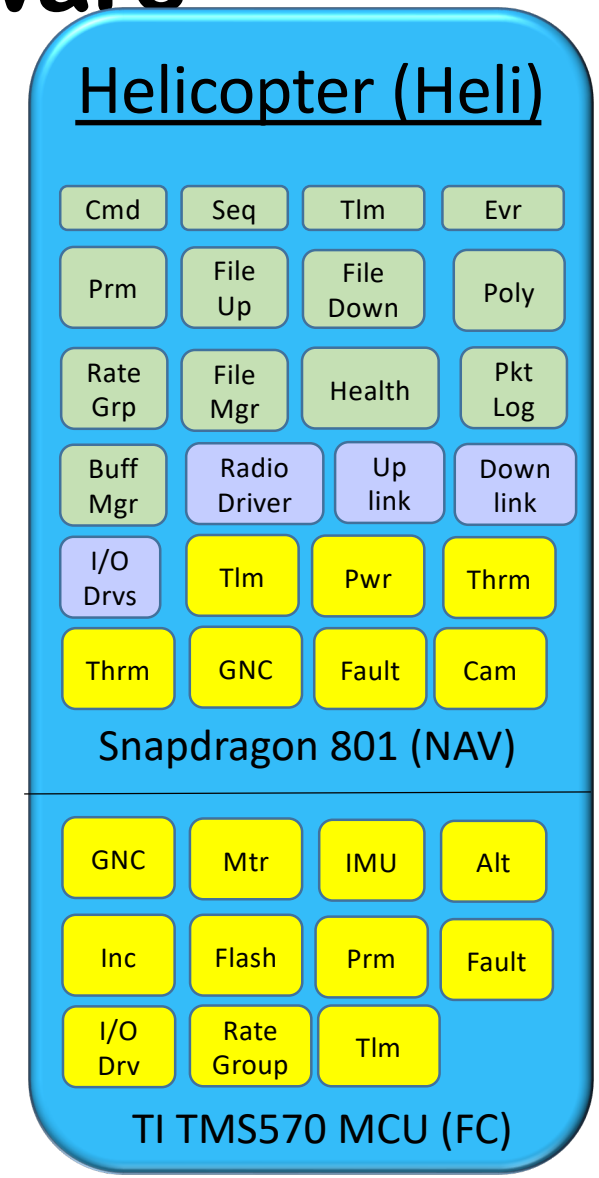


Helicopter Flight Software

- Two processors and major functions
  - NAV processor does command, telemetry, and radio functions, power/thermal management, feature tracking and “outer” guidance loop
    - 500Hz guidance
    - 30Hz tracking
    - Linux OS
  - FC processor does “inner” guidance loop, flight attitude control, motor control and high-rate telemetry
    - 500Hz guidance and control
    - “Bare Metal”
    - no OS



F Prime Inherited

Heli Shared

Heli Unique

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[Credit: NASA/JPL-Caltech]

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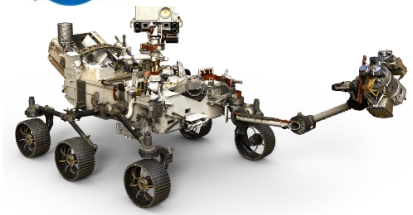
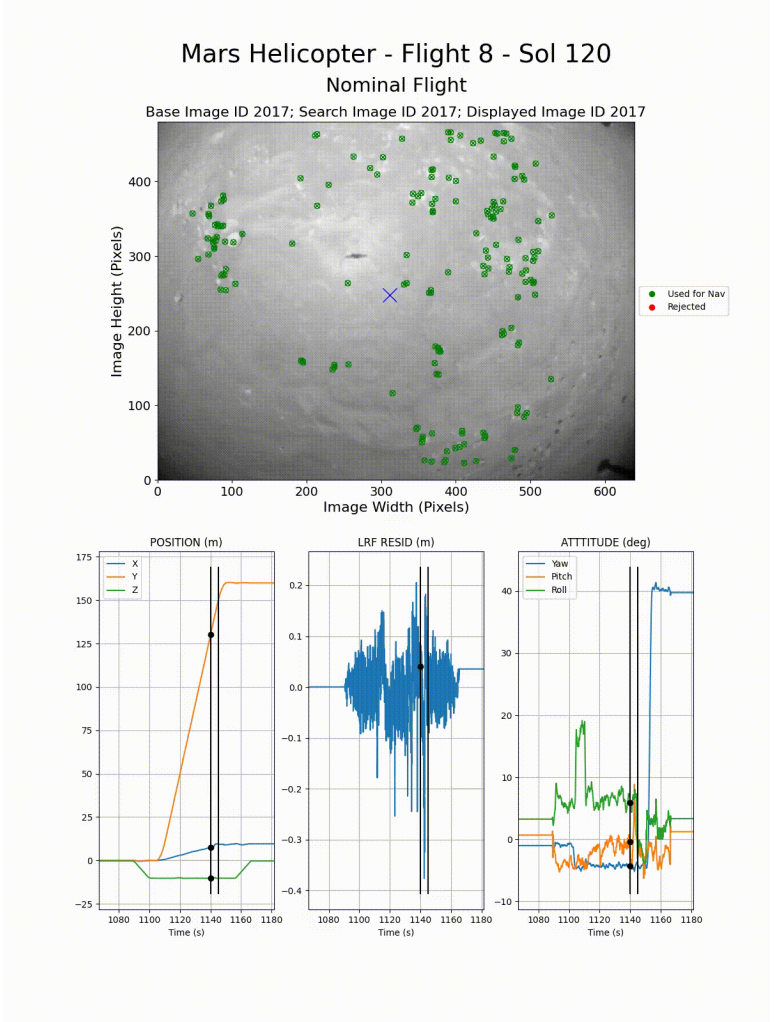


Software Performance

- GNC (Guidance Navigation Control) has high loop rates compared to the Rover during EDL
  - Rover: 64Hz
  - Helicopter:
    - 500Hz GNC loop
    - 30Hz feature tracking loop
- Testing was piecewise
  - Flights in chamber
    - No significant translation
  - Feature tracking on COTS quadcopter in arroyo near JPL
- System finally fully played together on Mars



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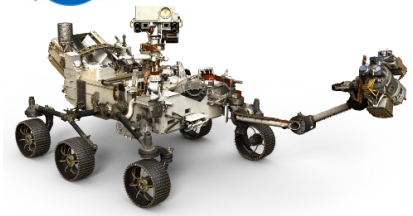
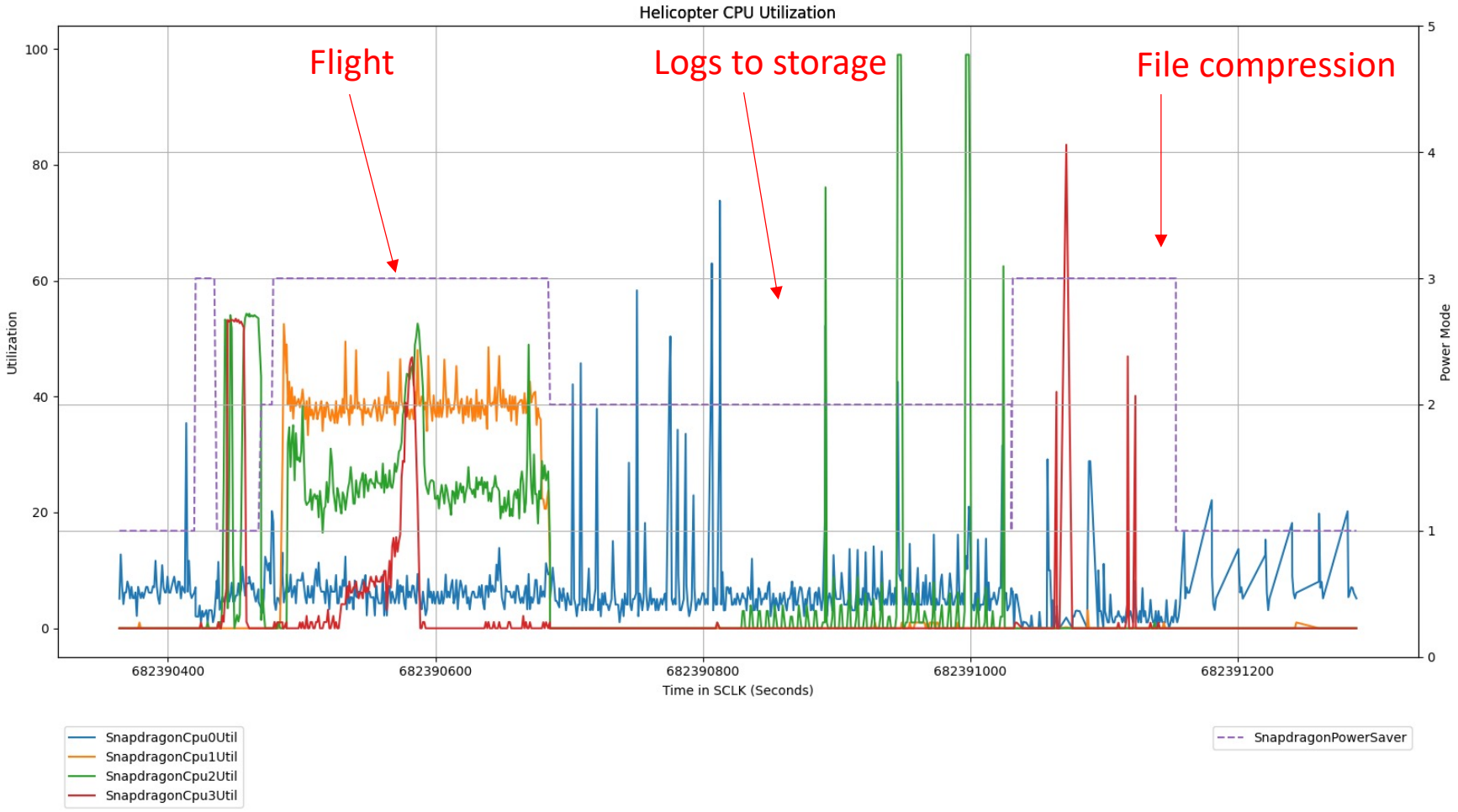


CPU Utilization During Flights



- **Core 0**
  - **Data handling and logging**
  - **Telecom**
  - **Device I/O**
- **Core 1**
  - **Cameras**
- **Core 2**
  - **Visual processing**
  - **Image logging**
  - **Data routing to MCU**
- **Core 3**
  - **Guidance/Navigation processing**

[Credit: Canham/CL#19-7128 /CL#22-0146]

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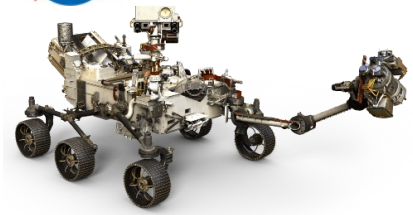
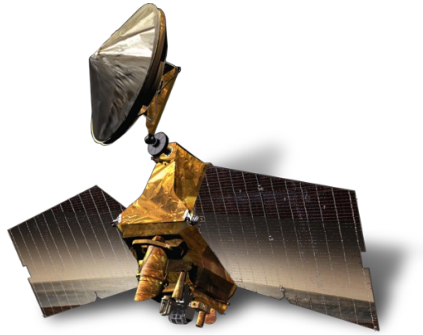
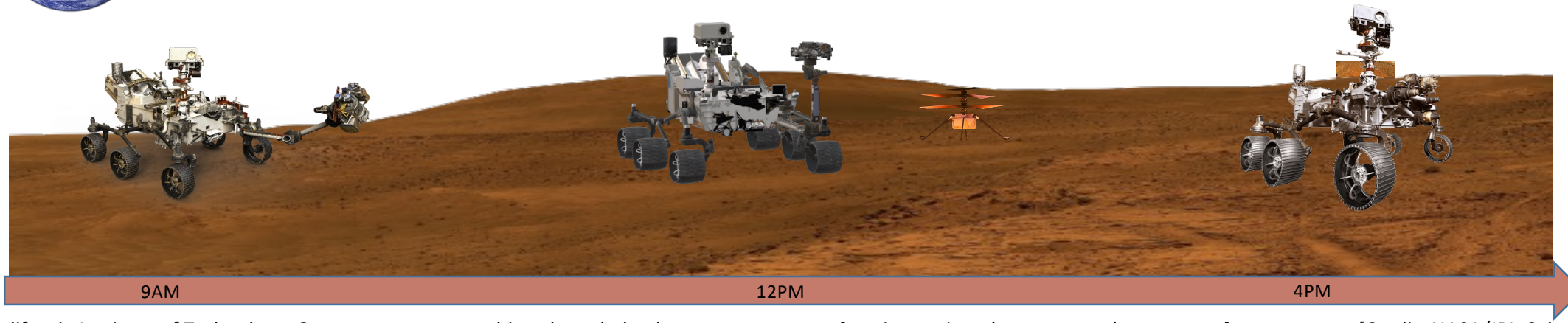


Concept of Operations

- Rover operations follow **Mars Sol**
- Uplink sequences direct from Earth in the morning
- Helicopter flights are typically around noon
- Downlink data in the afternoon/evening via relays
- No live coverage of flights





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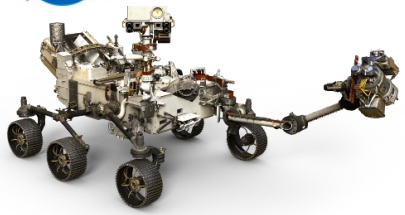

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- Growth of FSW Complexity & Size
- Mars2020 Rover Project
- Mars2020 FSW Architecture
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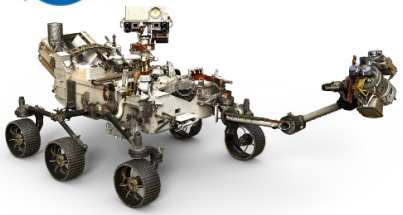
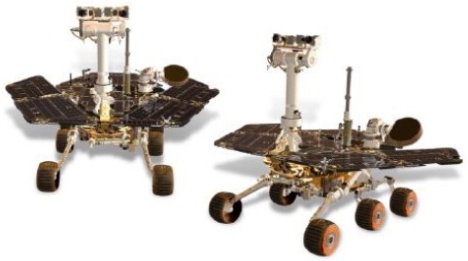
Mars Rover Family Portrait



Sojourner	Spirit and Opportunity	Curiosity	Perseverance
			
Mars Pathfinder (1996-1997)	**Mars Exploration Rover (2003-2018)**	**Mars Science Laboratory (2011-Present)**	**Mars2020 (2020-Present)**

MPF Project

- Lander and 10kg micro-rover
- Airbag landing
- Single string
- RAD6K + VxWorks
- 3 science instruments
- 7 Sol mission (rover)
- 30 Sol mission (lander)

MER Project

- ✓ 2 185kg rovers
- ✓ Airbag landing
- ✓ Single string
- ✓ RAD6K + VxWorks
- ✓ 6 science instruments
- ✓ 90 Sol science mission

MSL Project

- ❖ 900kg mega-rover
- ❖ Staged powered descent
- ❖ Dual string
- ❖ RAD750 + VxWorks
- ❖ 10 science instruments
- ❖ 2 year mission

[CL#22-4140]
[Credit: NASA/JPL-Caltech]

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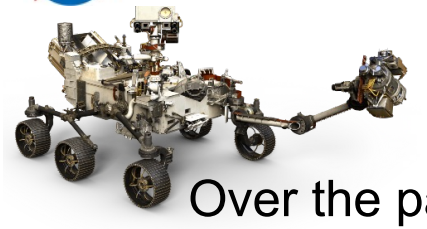
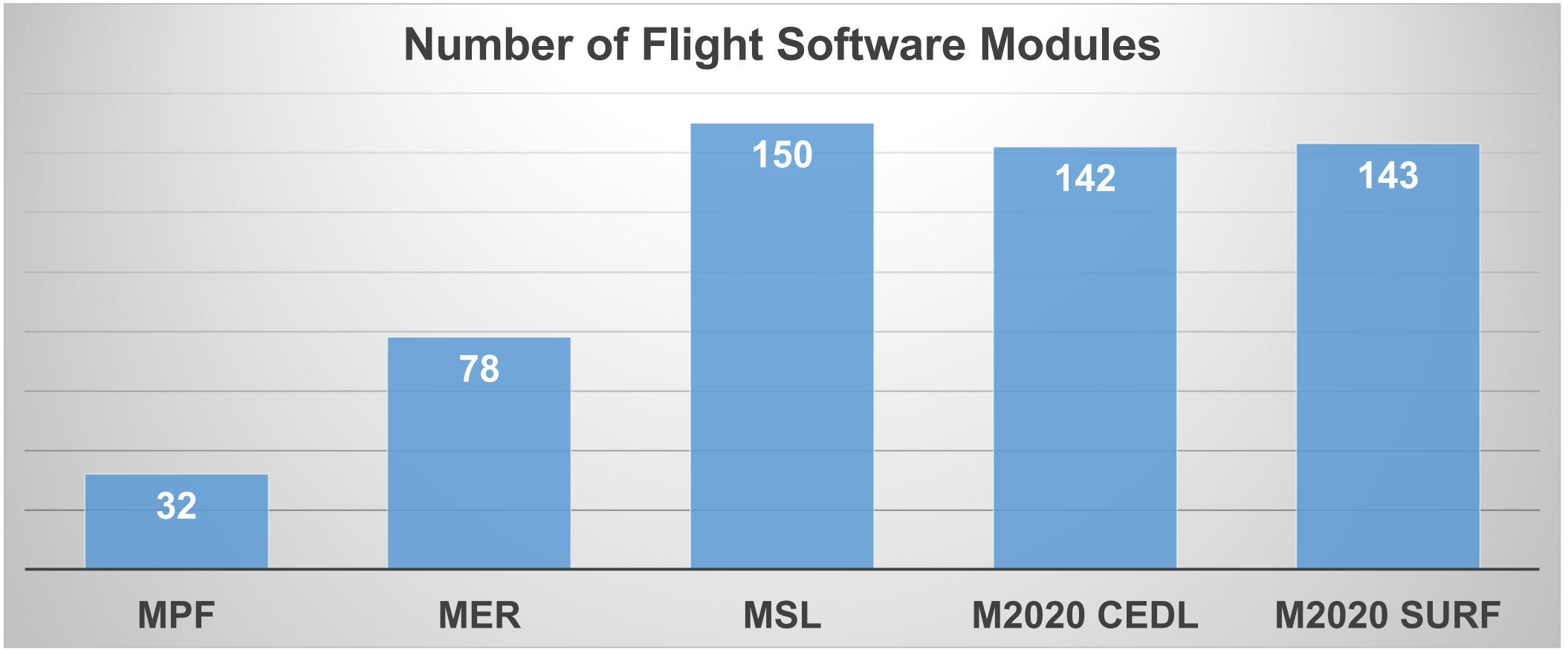


Growth of FSW Complexity

Over the past three decades, the rovers launched by JPL have grown larger, more autonomous, and more capable of performing challenging science on the surface of Mars.



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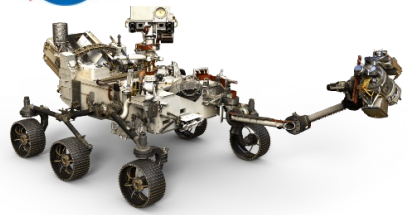
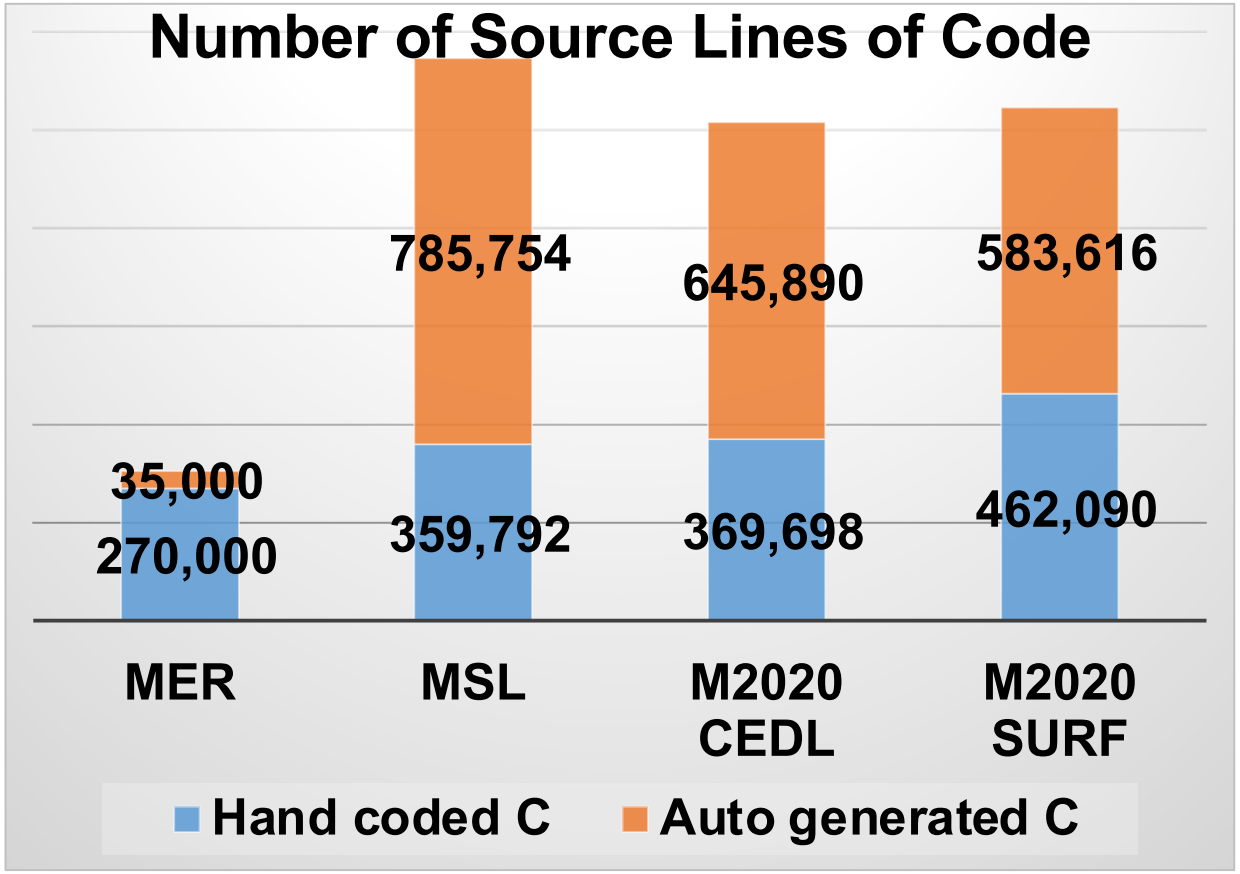


Growth of FSW Size

- **JPL Developed Autocoder** has become a proven tool for flight software implementation.
- The developer can focus on the unique software programming elements and leave repetitive elements to the Autocoder.
- In particular, the frequent change of flight commands, telemetry, data products, and parameters is amenable to this autocoding throughout the incremental lifecycle.



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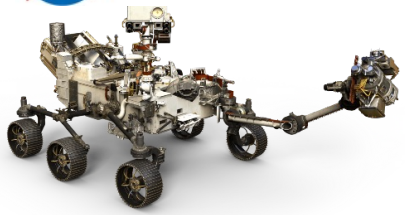

Mars2020 Rover Project

LAUNCH

- MSL Class / Capability LV
- Period: Jul/Aug 2020

CRUISE/APPROACH

- 7.5 month cruise
- Arrive Feb 2021

ENTRY, DESCENT & LANDING

- MSL EDL system: guided entry and powered descent/Sky Crane
- 16 x 14 km landing ellipse (range trigger baselined)
- Access to landing sites ±30° latitude, ≤ -0.5 km elevation
- ~950 kg rover

SURFACE MISSION

- Prime mission of one Mars year
- 20 km traverse distance capability
- Seeking signs of past life
- Returnable cache of samples
- Prepare for human exploration of Mars

http://mars.jpl.nasa.gov/mars2020/

[Credit: NASA/JPL-Caltech]

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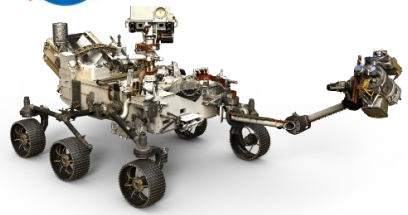
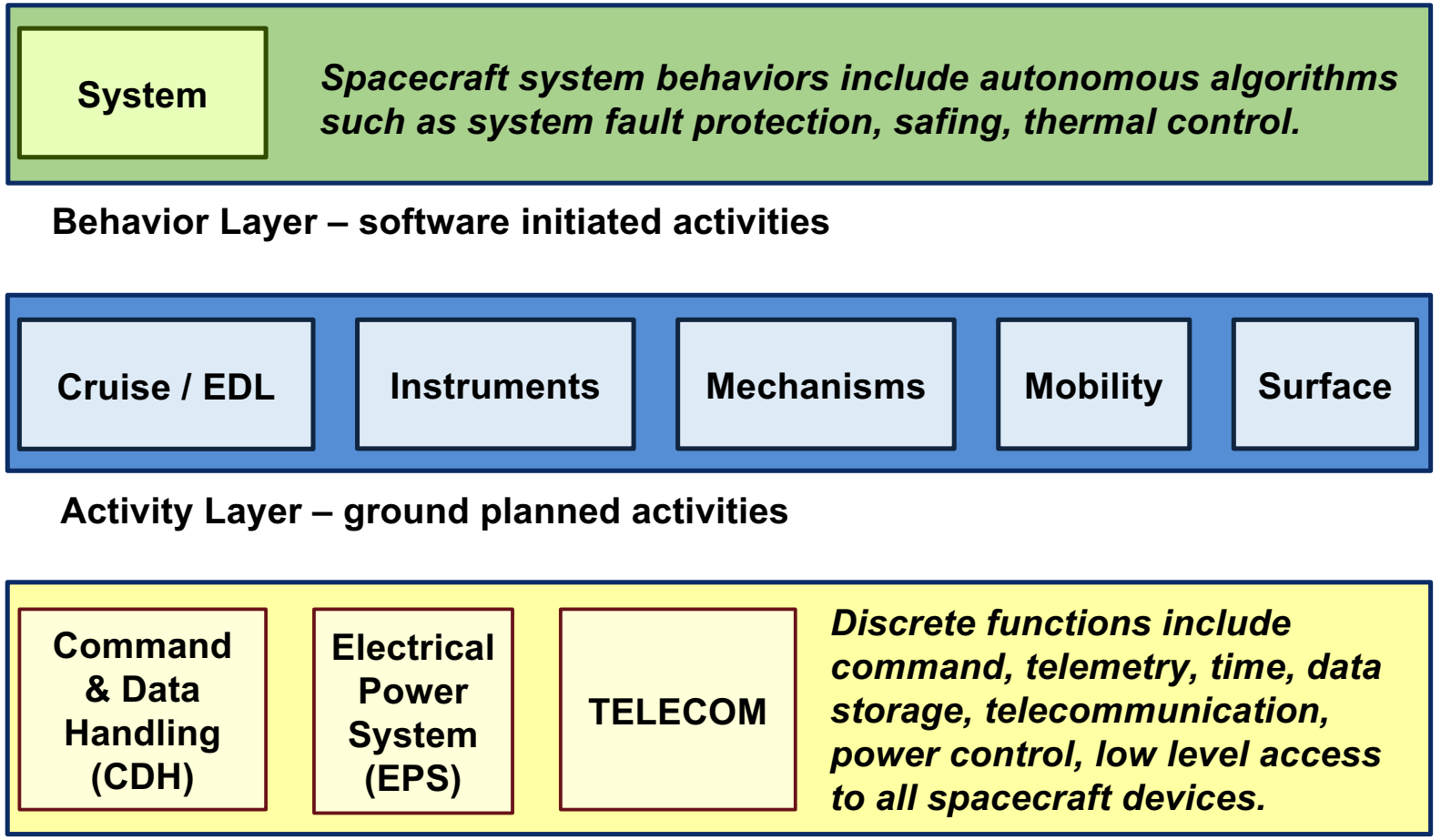


Mars2020 FSW Architecture

- Mars Rover FSW Components are organized into layers with functional components at the lowest layer, activity components at the middle layer, and behavior components at the top layer.



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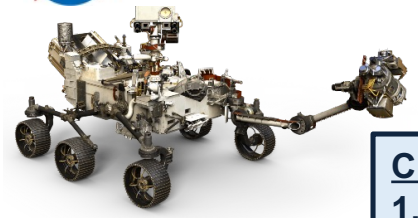
Mars2020 FSW Modules



System
1. cbm
2. csm
3. fsm
4. plan
5. planc
6. scfg
7. smm
8. thermal
9. timeline
10. fbm
11. fbmavs
12. fbmcomm
13. fbmpwr
14. fbmsafe

Cruise/EDL
1. acs
2. aman
3. dimu
4. dsa
5. edl
6. edlbg
7. edlcomm
8. edlgnc
9. gid
10. latchv
11. medli
12. ssa
13. sync
14. tds
15. thruster

Mobility
1. mom
2. nav
3. navlib
4. rcm
5. pnt
6. pntlib

Instruments
1. imf
2. mmm
3. ats
4. edlcam
5. mcamz
6. pixl
7. sherloc
8. srlc
9. scam
10. helo
11. meda
12. moxi
13. rimfax

Mechanisms
1. aca
2. arm
3. drill
4. drive
5. gdrt
6. hga
7. mca
8. mot
9. rsm

Surface
1. acm
2. arb
3. cmod
4. fm
5. ial
6. img
7. ivp
8. mat3
9. mathf
10. rimu
11. sapp
12. scsvis
13. sgnc
14. sid
15. spam
16. vgnc
17. vislib
18. vtt

CDH
1. adf
2. aut
3. bcdrv
4. bcmgr
5. btp
6. cmd
7. comp
8. cp
9. cpu
10. crcdrv
11. crcmgr
12. ddi
13. dmadrv
14. dms
15. dmsbg
16. dwn
17. dwndrv
18. eha
19. enet
20. evr
21. files
22. fvs
23. gbl
24. health
25. hsm
26. hst
27. iccitcdrv
28. idle
29. iml
30. ipc
31. lap
32. math
33. mcicdis
34. mcicdrv
35. mem
36. msiadis
37. msiadrv
38. mtifdis
39. mtifdrv
40. npm
41. nvds
42. nvfs
43. nvmcamdrv
44. nvmcammgr
45. nvmcfg
46. osal
47. pdp
48. pie
49. pty
50. ramfs
51. rtdrv
52. rtmgr
53. rts
54. sarb
55. seq
56. tim
57. uartdrv
58. uartio
59. upl
60. upldrv
61. vcemgr
62. vid

EPS
1. acmgr
2. adc
3. bcb
4. dim
5. mcmgr
6. pammgr
7. pwr
8. pyro
9. reumgr
10. rm
11. srm

TELECOM
1. mfsk
2. rfr
3. sdst
4. sspa
5. twta
6. uhft

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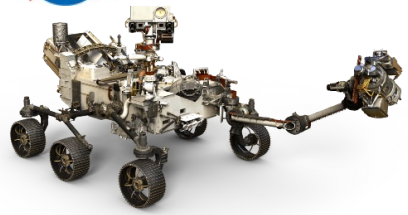
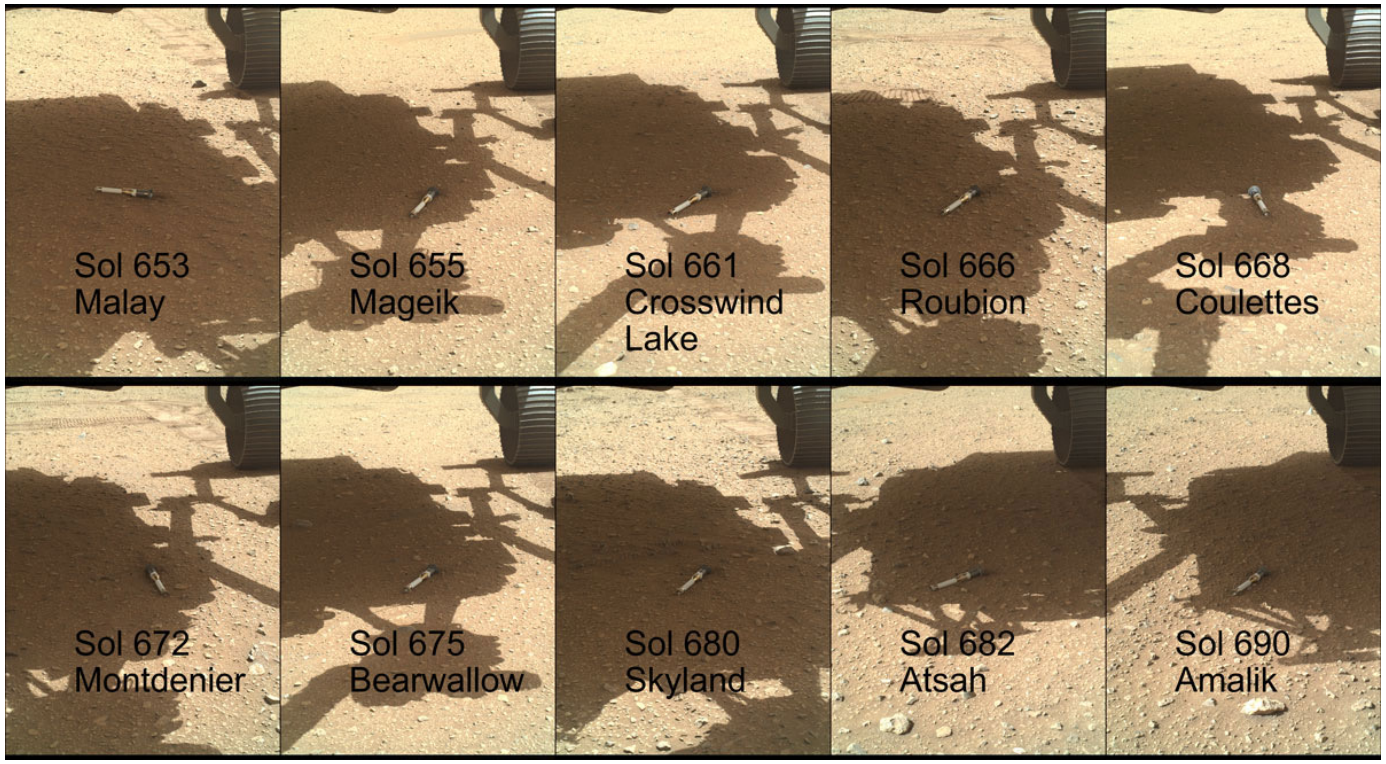


Mars2020 Surface Operations FSW

The Mars2020 Perseverance rover carries seven instruments, which interface with spacecraft FSW, to conduct its science and exploration including sample collections.

The Mars2020 Sampling and Caching Subsystem has deposited a total of 10 sample tubes on Mars surface at "Three Forks," a location within Jezero Crater.



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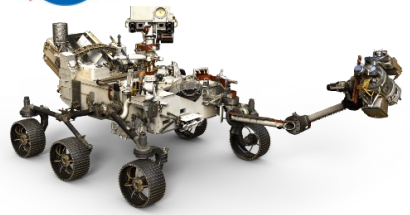

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- **Flight Project Funding Strategy**
- **NASA's Ten Centers**
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- **NASA JPL's 160 Flight Projects [1958-2027]**

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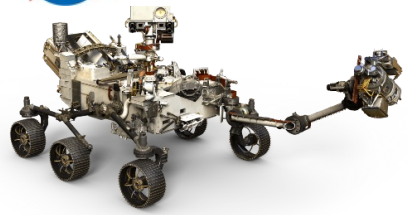
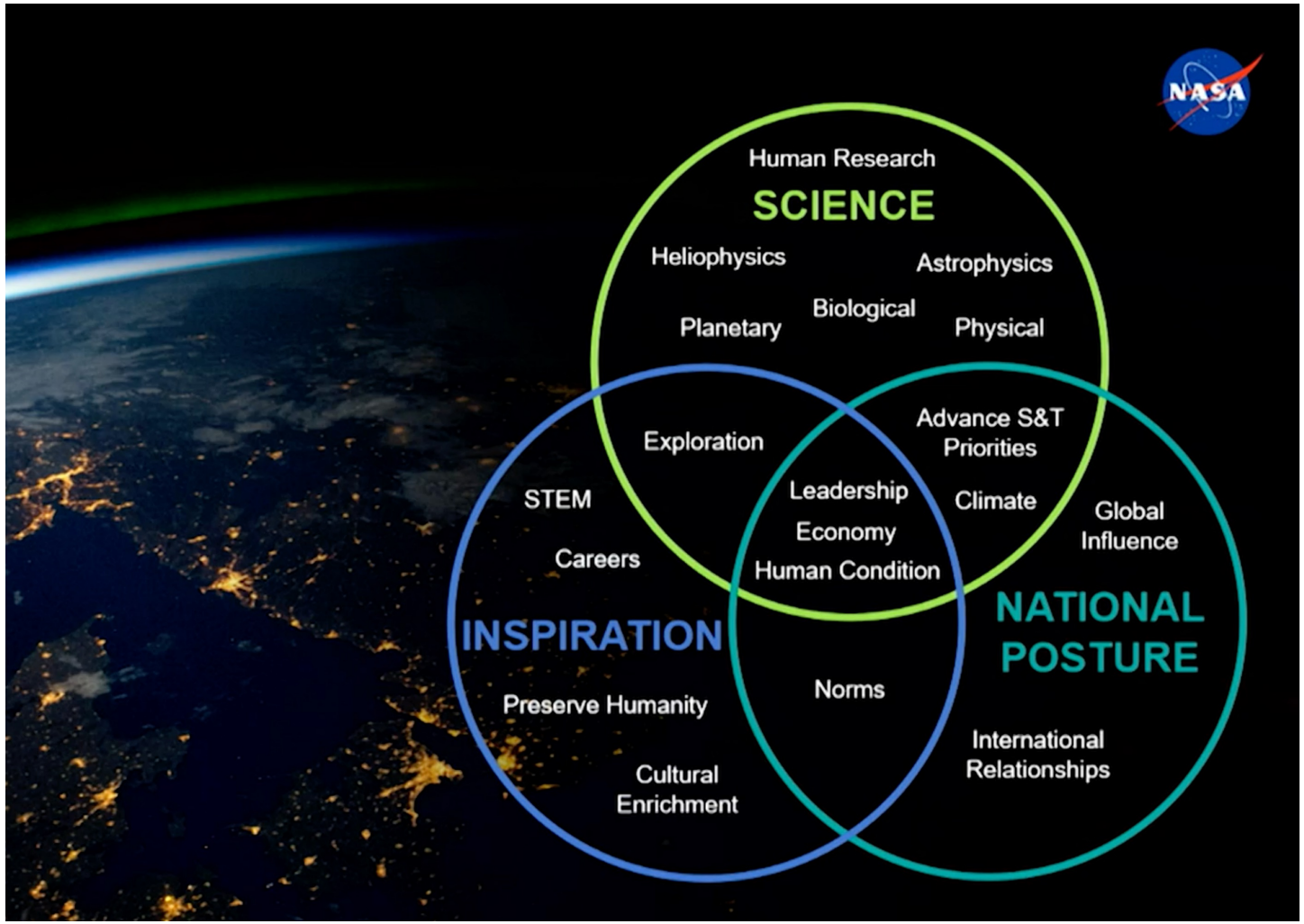


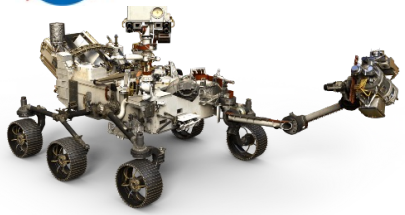
NASA's Three Balanced Pillars



[CL#23-6361]

[Credit: NASA/JPL-Caltech]

Jet Propulsion Laboratory
California Institute of Technology



Flight Project Funding Strategy

- Developing and testing one-off, novel spacecraft and systems (instruments, rovers, software) means thinking differently.
- NASA asks the National Academy to prioritize research areas and release decadal surveys once every 10 years. The decadal survey document provides a framework for all discussions on funding priorities in NASA, the White House, and Congress.
  - "Thriving on Our Changing Planet: A Decadal Strategy for Earth Observations from Space 2017-2026"
  - "Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032"
- NASA's flight projects are either assigned to a NASA Center or selected through a competitive process such as an Announcement of Opportunity.
  - Today, a large portion of NASA Center's flight projects come from competed missions, where the scientific merit of the proposed investigations must be demonstrated in written proposals submitted to NASA and are led by a Principal Investigator.

[CL#23-6361]
[Credit: NASA/JPL-Caltech]

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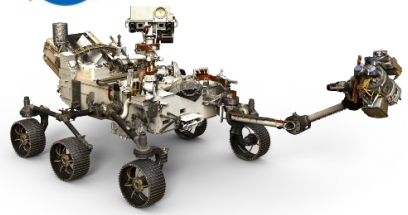
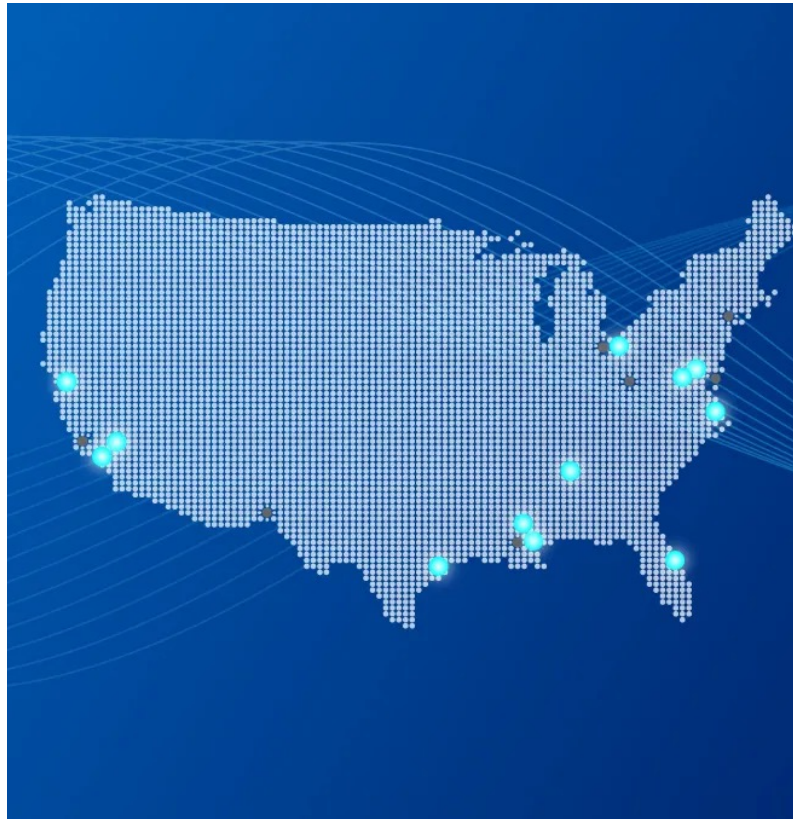


NASA's Ten Centers

NASA Headquarters [Founded: 1958, State: Washington D.C.]

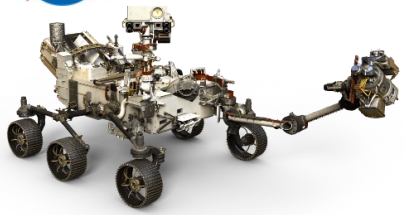
1) **Jet Propulsion Laboratory at California Institute of Technology (JPL-Caltech) [Founded: 1936, State: California]**
2) Ames Research Center [Founded: 1939, State: California]
3) Armstrong Flight Research Center [Founded: 1946, State: CA]
4) Glenn Research Center [Founded: 1941, State: Ohio]
5) Goddard Space Flight Center [Founded: 1959, State: Maryland]
6) Marshall Space Flight Center [Founded: 1960, State: Alabama]
7) Johnson Space Center [Founded: 1961, State: Texas]
8) Langley Research Center [Founded: 1917, State: Virginia]
9) Stennis Space Center [Founded: 1961, State: Mississippi]
10) Kennedy Space Center [Founded: 1962, State: Florida]



[CL#23-6361]
[Credit: NASA/JPL-Caltech]

Jet Propulsion Laboratory
California Institute of Technology

JPL Beginnings…



SEPTEMBER 23, 1891

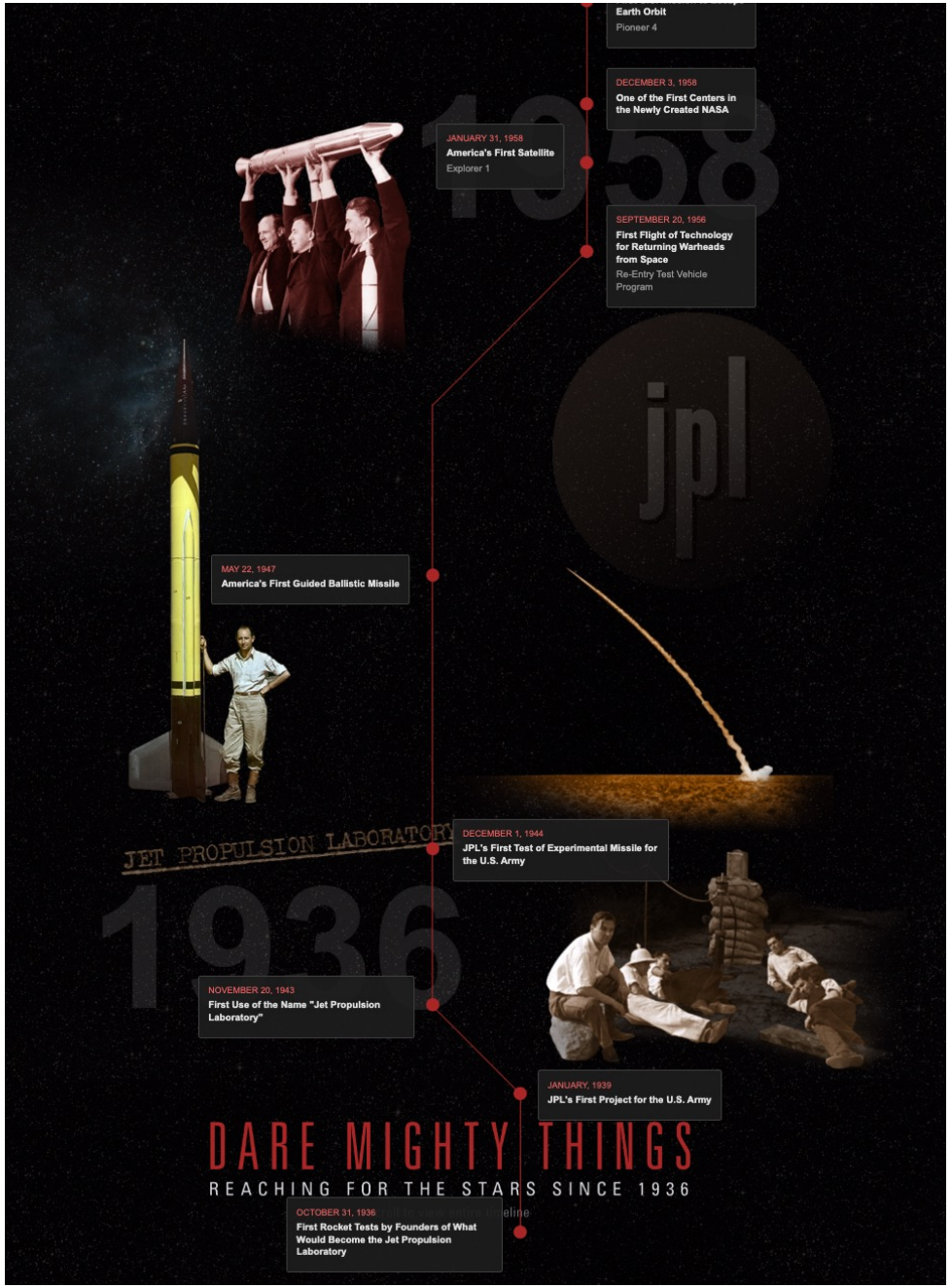
- The California Institute of Technology (Caltech) was founded as a private research university.
- To date, 46 Caltech alumni and faculty have **won a total of 47 Nobel Prizes**.

OCTOBER 31, 1936

- **First Rocket Tests** by founders of what would become the Jet Propulsion Laboratory (JPL).

1936

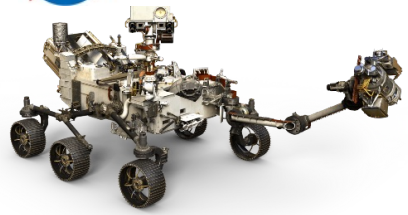
Present



[CL#23-6361]
[Credit: NASA/JPL-Caltech]

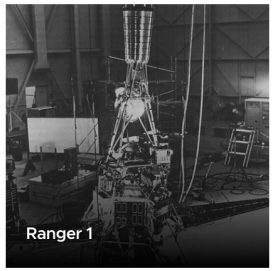
Jet Propulsion Laboratory
California Institute of Technology

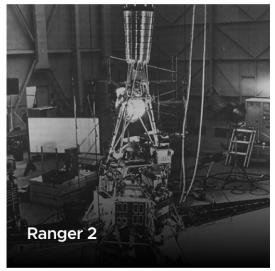
NASA JPL's Flight Projects [1958-1967]

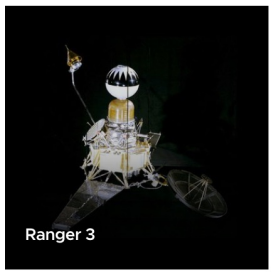


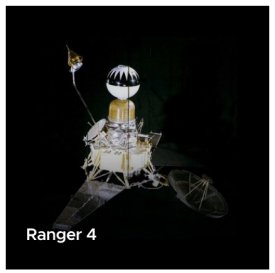
1) Explorer 1
2) Explorer 2
3) Explorer 3
4) Explorer 4
5) Explorer 5
6) Pioneer 3
7) Pioneer 4
8) Ranger 1
9) Ranger 2
10) Ranger 3
11) Ranger 4
12) Mariner 1
13) Mariner 2
14) Ranger 5
15) Ranger 6
16) Ranger 7
17) Mariner 3
18) Mariner 4
19) Ranger 8
20) Ranger 9
21) Surveyor 1
22) Surveyor 2
23) Surveyor 3
24) Mariner 5

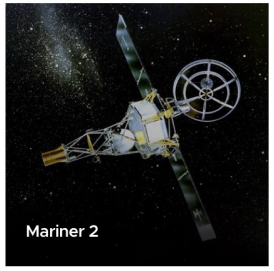
1958

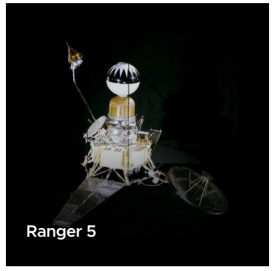


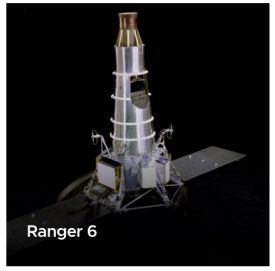


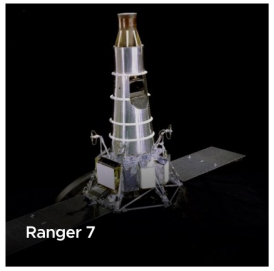


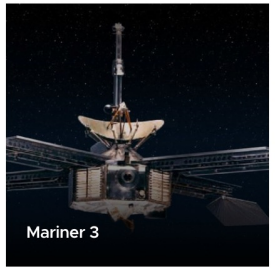


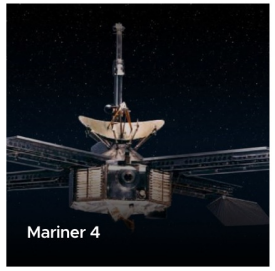


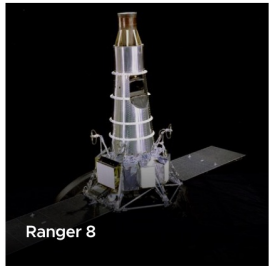


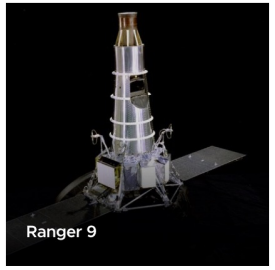


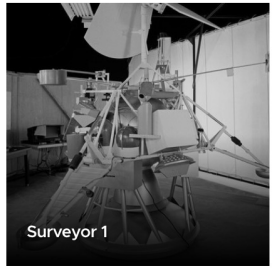


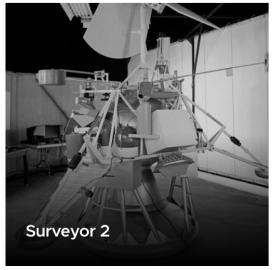












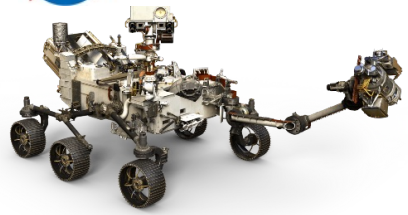
1967

[CL#23-6361]

[Credit: NASA/JPL-Caltech]

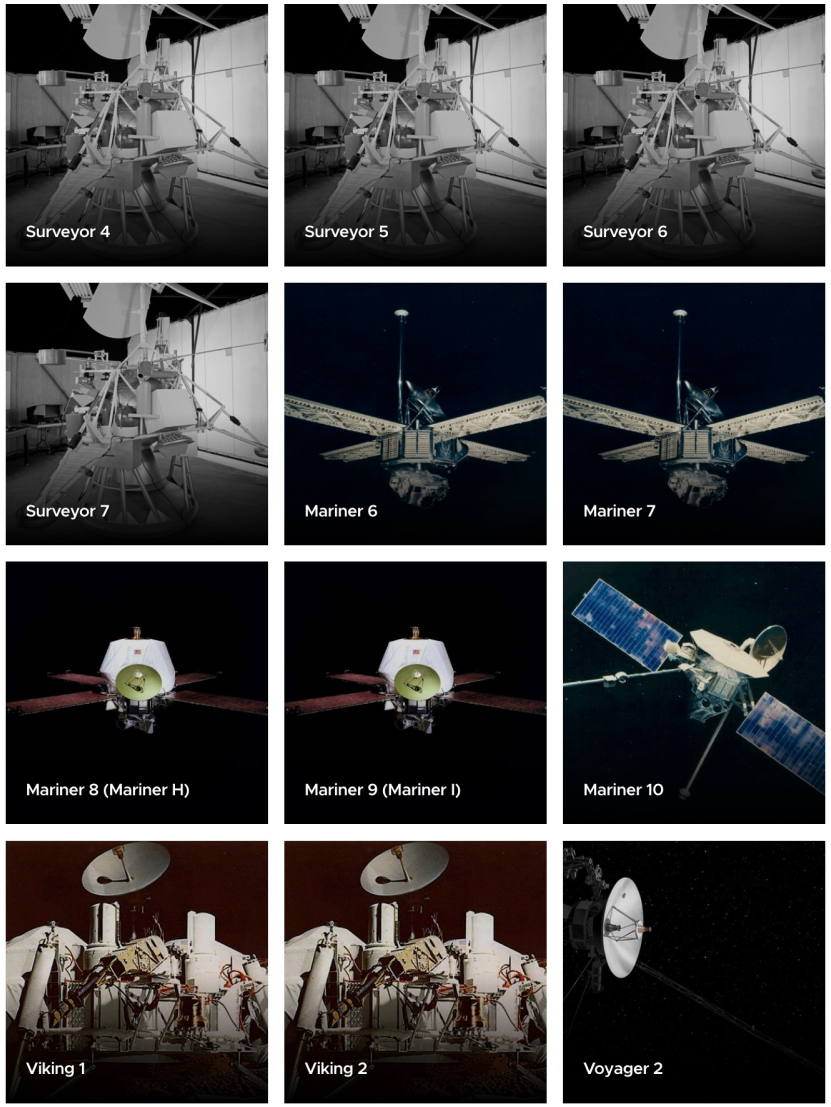
Jet Propulsion Laboratory
California Institute of Technology

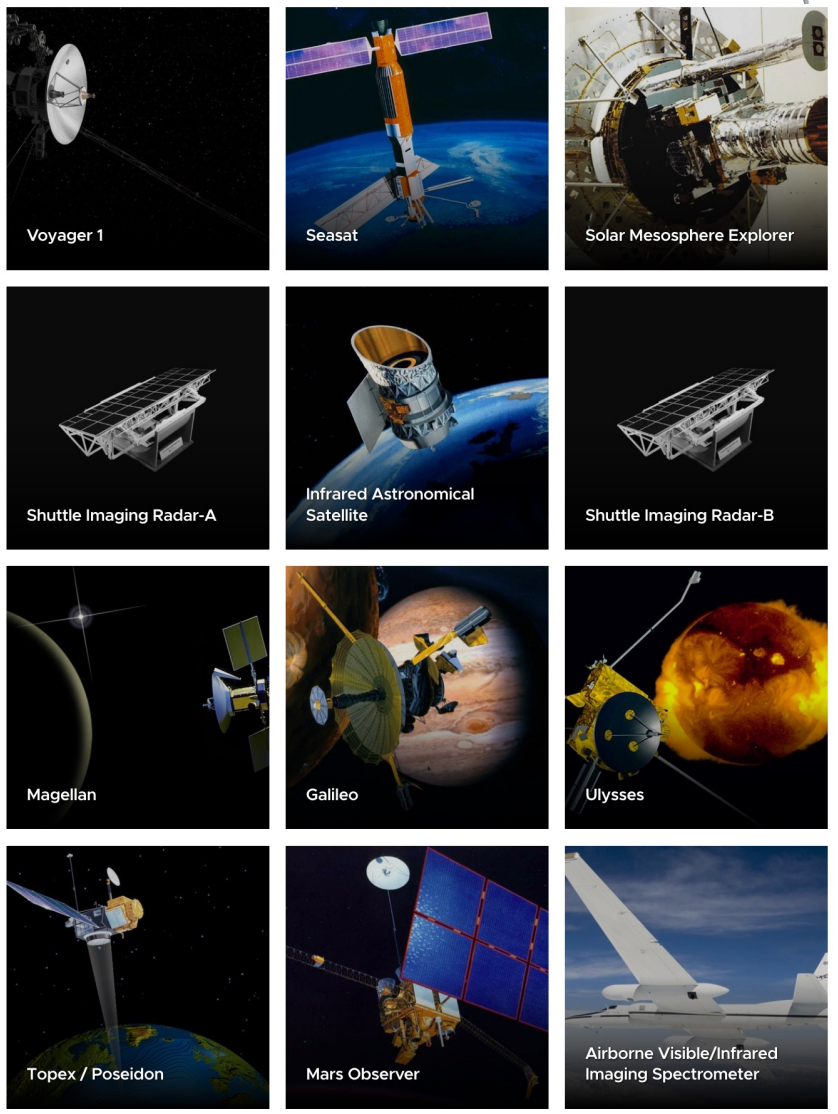
NASA JPL's Flight Projects [1967-1993]



25) Surveyor 4
26) Surveyor 5
27) Surveyor 6
28) Surveyor 7
29) Mariner 6
30) Mariner 7
31) Mariner 8 (Mariner H)
32) Mariner 9 (Mariner I)
33) Mariner 10
34) Viking 1
35) Viking 2
36) Voyager 2
37) Voyager 1
38) Seasat
39) Solar Mesosphere Explorer
40) Shuttle Imaging Radar-A
41) Infrared Astronomical Satellite
42) Shuttle Imaging Radar-B
43) Magellan
44) Galileo
45) Ulysses
46) Topex / Poseidon
47) Mars Observer
48) Airborne Visible/Infrared Imaging Spectrometer

1967





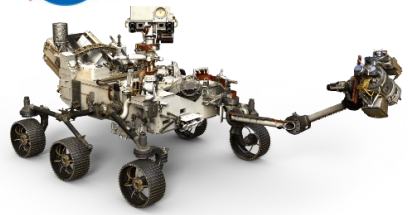
1993

[CL#23-6361]

[Credit: NASA/JPL-Caltech]

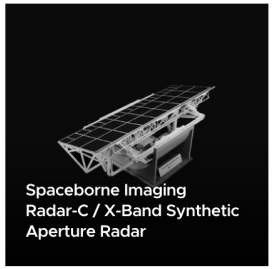
Jet Propulsion Laboratory
California Institute of Technology

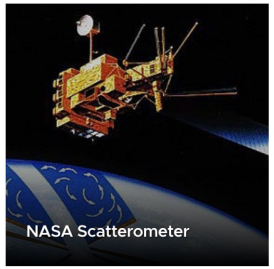
NASA JPL's Flight Projects [1993-2002]

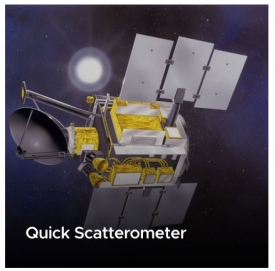


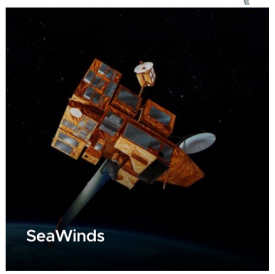
49) Wide Field and Planetary Camera 2
50) Spaceborne Imaging Radar-C / X-Band Synthetic Aperture Radar
51) NASA Scatterometer
52) Mars Global Surveyor
53) Mars Pathfinder / Sojourner Rover
54) Space Very Long Baseline Interferometry
55) Cassini-Huygens
56) Deep Space 1
57) Mars Climate Orbiter
58) Mars Polar Lander / Deep Space
59) Stardust
60) Stardust NExT
61) Wide-field Infrared Explorer
62) Quick Scatterometer
63) SeaWinds
64) ASTER
65) MISR
66) AcrimSat
67) Shuttle Radar Topography Mission
68) Keck Interferometer
69) Mars Odyssey
70) Genesis
71) Jason-1
72) GRACE

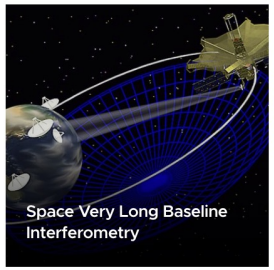
1993

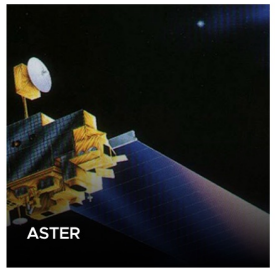


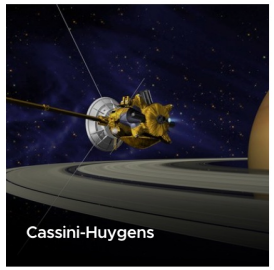


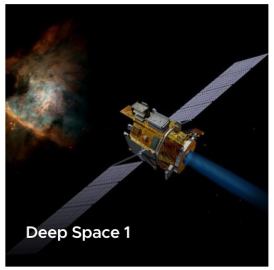


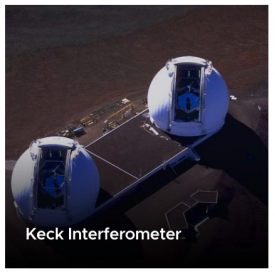


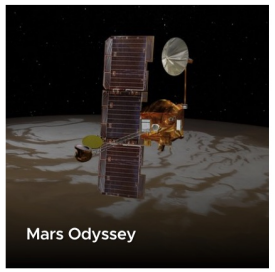


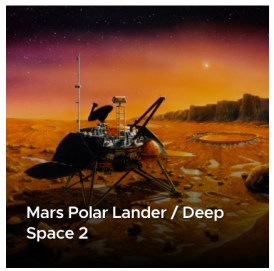












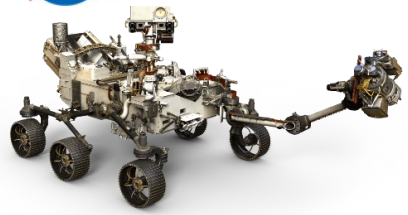
2002

[CL#23-6361]

[Credit: NASA/JPL-Caltech]

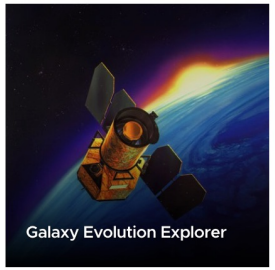
Jet Propulsion Laboratory
California Institute of Technology

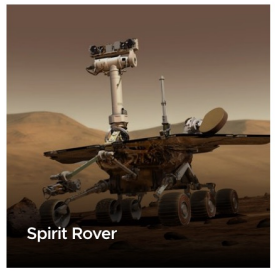
NASA JPL's Flight Projects [2002-2009]

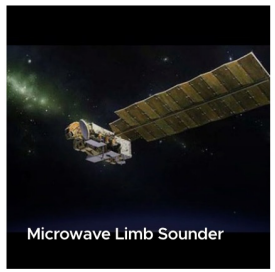


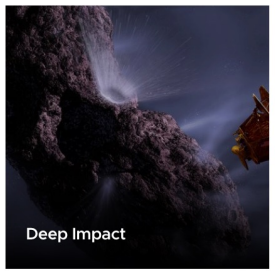
73) Atmospheric Infrared Sounder
74) Galaxy Evolution Explorer
75) Hayabusa
76) Spirit Rover
77) Opportunity Rover
78) Spitzer Space Telescope
79) Microwave Instrument for the Rosetta Orbiter
80) Autonomous Sciencecraft Experiment
81) Tropospheric Emission Spectrometer
82) Microwave Limb Sounder
83) Deep Impact
84) Deep Impact – EPOXI
85) Mars Reconnaissance Orbiter
86) CloudSat
87) Phoenix
88) Uninhabited Aerial Vehicle Synthetic Aperture Radar
89) Dawn
90) Jason-2
91) Moon Mineralogy Mapper
92) Orbiting Carbon Observatory
93) Kepler Exoplanet Mission
94) Herschel Space Observatory
95) Planck
96) Diviner Lunar Radiometer Experiment

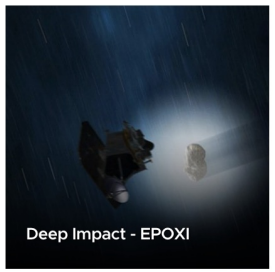
2002

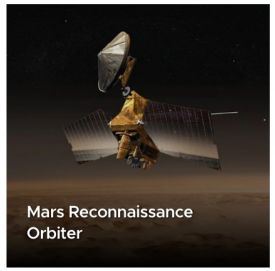


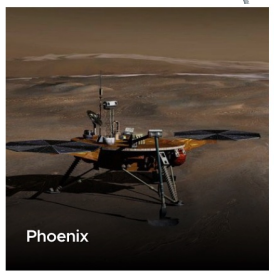


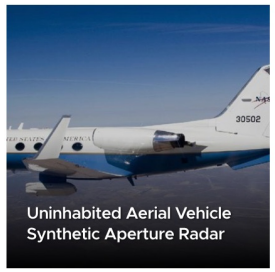


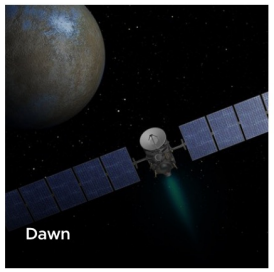


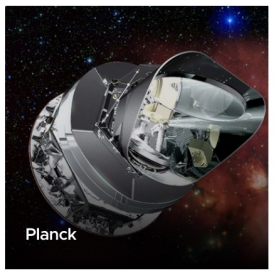












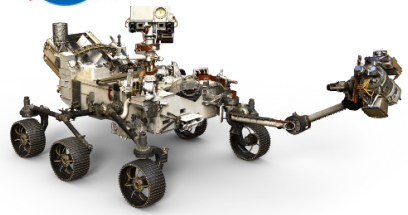
2009

[CL#23-6361]

[Credit: NASA/JPL-Caltech]

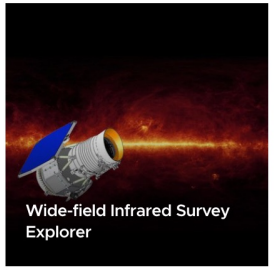
Jet Propulsion Laboratory
California Institute of Technology

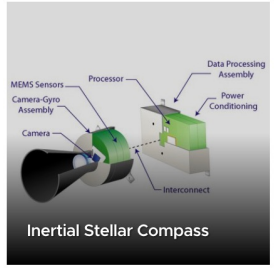
NASA JPL's Flight Projects [2009-2017]

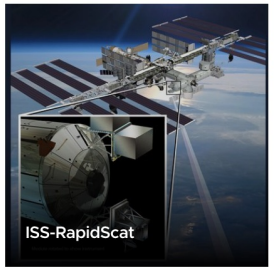


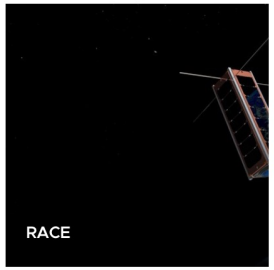
97) Wide-field Infrared Survey Explorer
98) NEOWISE
99) Large Binocular Telescope Interferometer
100) Aquarius
101) Juno
102) GRAIL
103) Curiosity Rover
104) NuSTAR
105) Airborne Snow Observatory
106) M-Cubed / COVE-2
107) OPALS
108) Orbiting Carbon Observatory 2
109) Inertial Stellar Compass
110) ISS-RapidScat
111) RACE
112) GRIFEX
113) SMAP
114) AVIRIS-NG
115) PRISIM
116) Disturbance Reduction System
117) IPEX
118) Jason-3
119) ASTERIA
120) ASTERIA – Extended Mission

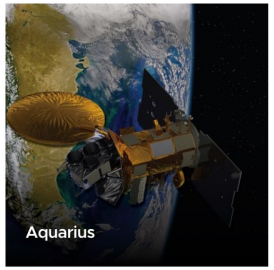
2009

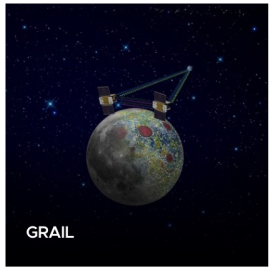


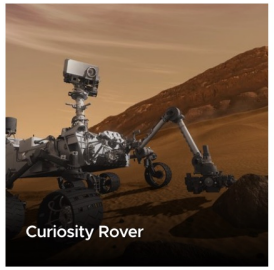


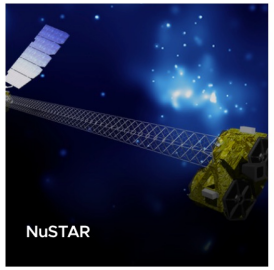


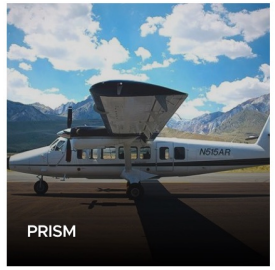


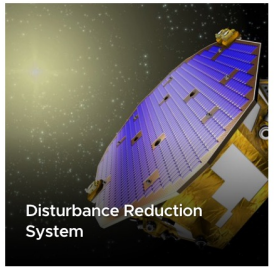


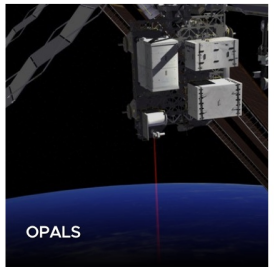


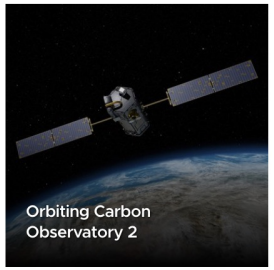












2017

[CL#23-6361]

[Credit: NASA/JPL-Caltech]

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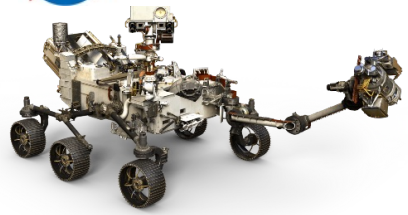
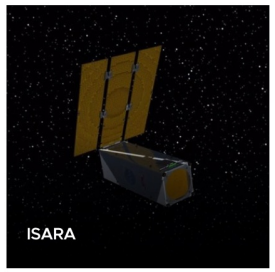
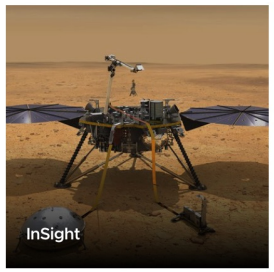
NASA JPL's Flight Projects [2017-2021]

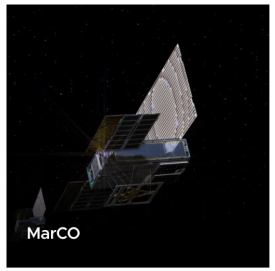


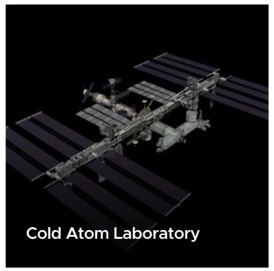
121) ISARA
122) FINESSE
123) InSight
124) MarCO
125) Cold Atom Laboratory
126) CubeRRT
127) TEMPEST-D
128) RainCube
129) GRACE-FO
130) ECOSTRESS
131) Asteroid Redirect Robotic Mission
132) INSPIRE
133) MAIA
134) Orbiting Carbon Observatory 3
135) Deep Space Atomic Clock
136) NISAR
137) Mars Sample Return
138) The Nancy Grace Roman Space Telescope
139) Europa Lander
140) Perseverance Rover
141) Ingenuity
142) SPHEREx
143) Sentinel-6 Michael Freilich Satellite
144) Deep Space Network

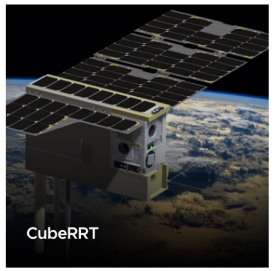
2017

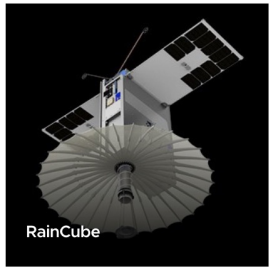


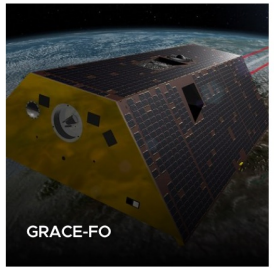


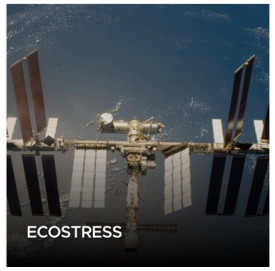


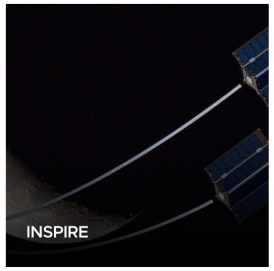


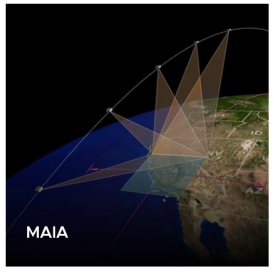


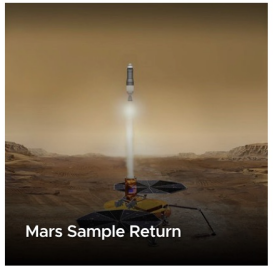


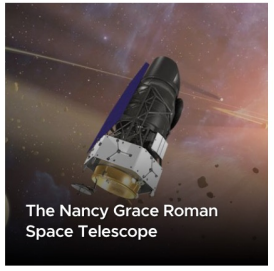


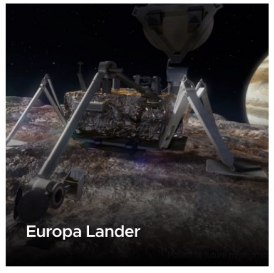


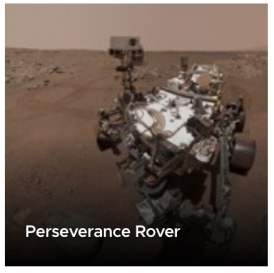


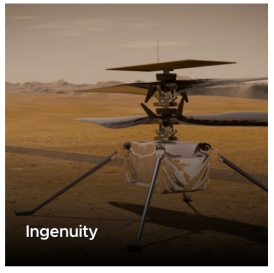


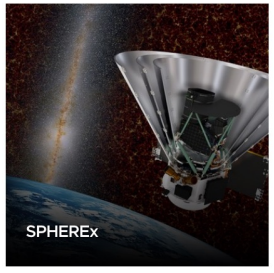


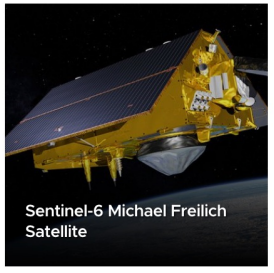


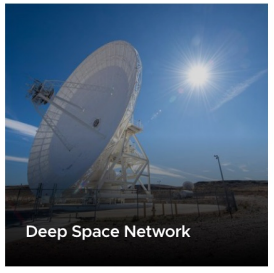












2021

[CL#23-6361]

[Credit: NASA/JPL-Caltech]

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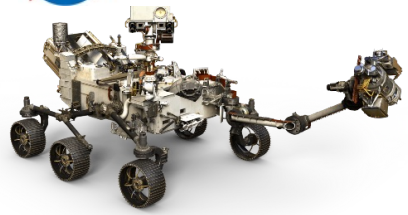
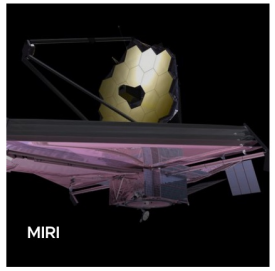
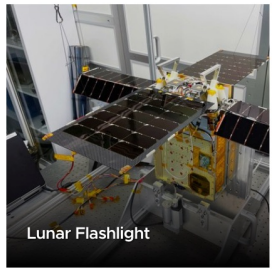
NASA JPL's Flight Projects [2021-2027]

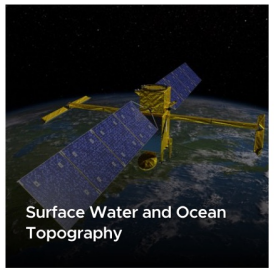


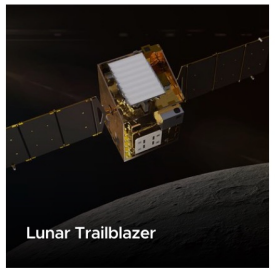
145) SunRISE
146) VERITAS
147) MIRI
148) EMIT
149) Near Earth Asteroid Scout
150) Lunar Flashlight
151) Surface Water and Ocean Topography
152) Lunar Trailblazer
153) Euclid
154) Deep Space Optical Communications (DSOC)
155) Psyche
156) CADRE
157) Europa Clipper
158) ASTHROS
159) The Farside Seismic Suite
160) Near-Earth Object Surveyor

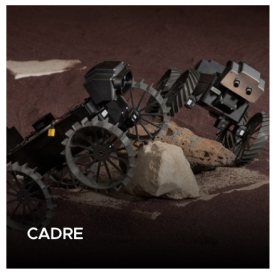
2021

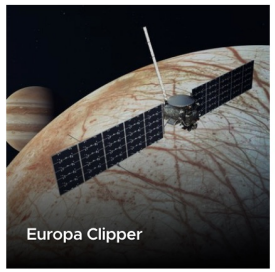


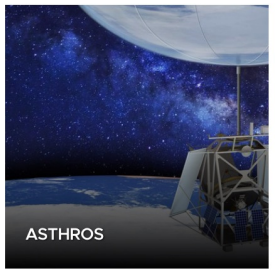


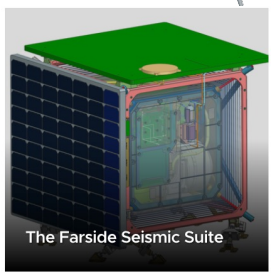


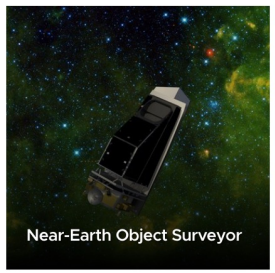












2027

A total of 160 JPL's Flight Project Status [1958-2027]:

- **Past (97)**
- **Current (43)**
- **Future (15)**
- **Proposed (5)**

A total of 160 JPL's Flight Project Science [1958-2027]:

- **Earth (56)**
- **Mars (24)**
- **Moon (23)**
- **Stars and Galaxies (16)**
- **Asteroids & Comets (12)**
- **Exoplanets (9)**
- **Venus (6)**
- **Jupiter (4)**
- **Europa (3)**
- **Interstellar Space (2)**
- **Solar System (2)**
- **Sun (2)**
- **Mercury (1)**
- **Saturn (1)**
- **Deep Space Network (1)**

[CL#23-6361]

[Credit: NASA/JPL-Caltech]

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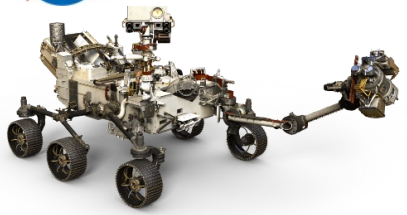

Thank You!

[Credit: NASA/JPL-Caltech]