updated for saving to PDF

https://www.nasa.gov/press-release/nasa-ingenuity-mars-helicopter-prepares-for-first-flight

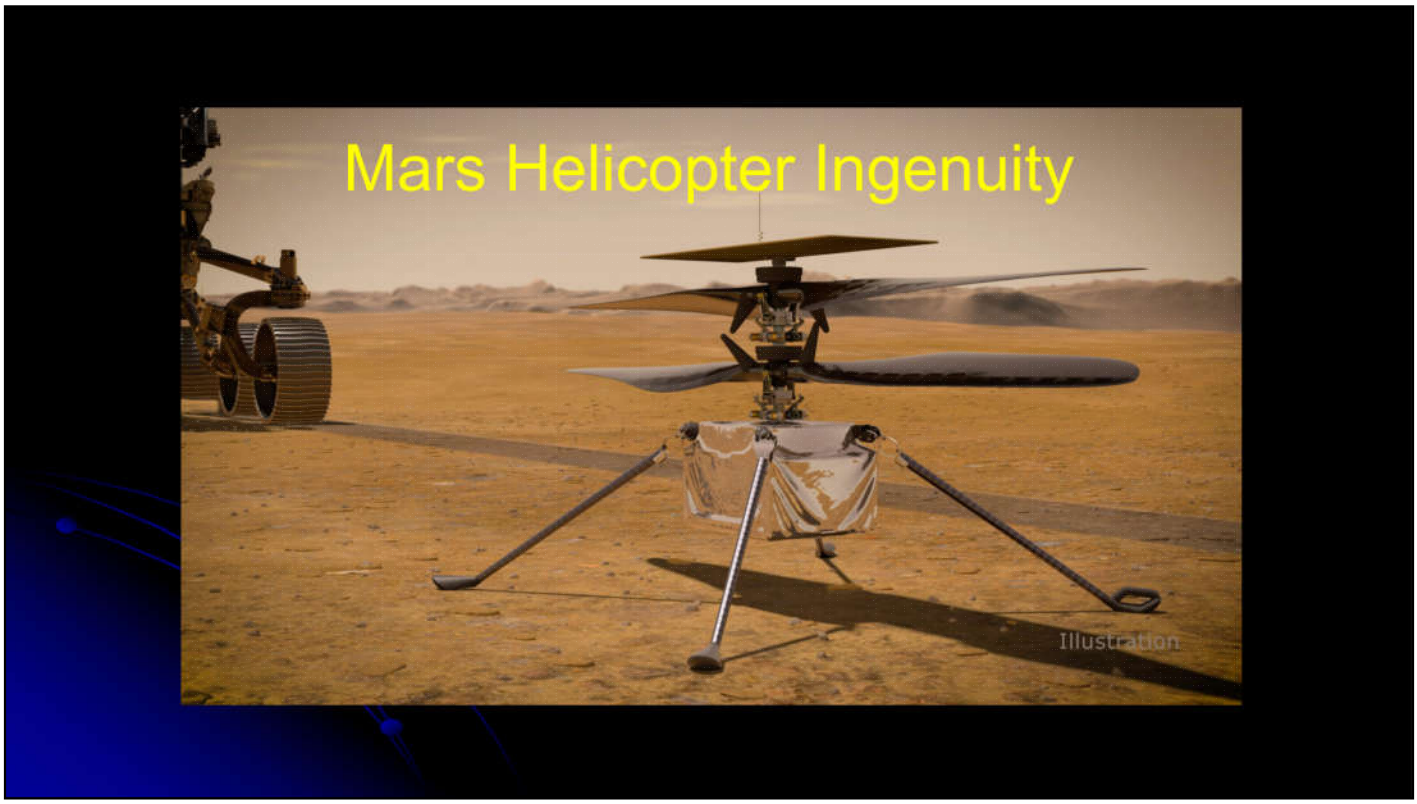


Image from https://mars.nasa.gov/news/8867/nasas-mars-helicopter-reports-in/

Ingenuity Technology Demo

- First aircraft to attempt flight on another planet
  - Dropped from belly of rover
  - Solar panels & ant. above blades
  - 4lbs on Earth, 1.5lbs Mars
  - 4' carbon fiber blades
  - Downward-looking Camera
  - Self-guided 90 second, 300m distance, 5m high, flights
- Atmosphere 1% of Earth
- First flight test spring 2021

Image: https://mars.nasa.gov/resources/24933/nasas-ingenuity-mars-helicopter/

https://mars.nasa.gov/technology/helicopter/#Five-Things

The flight model of NASA's Ingenuity Mars Helicopter.

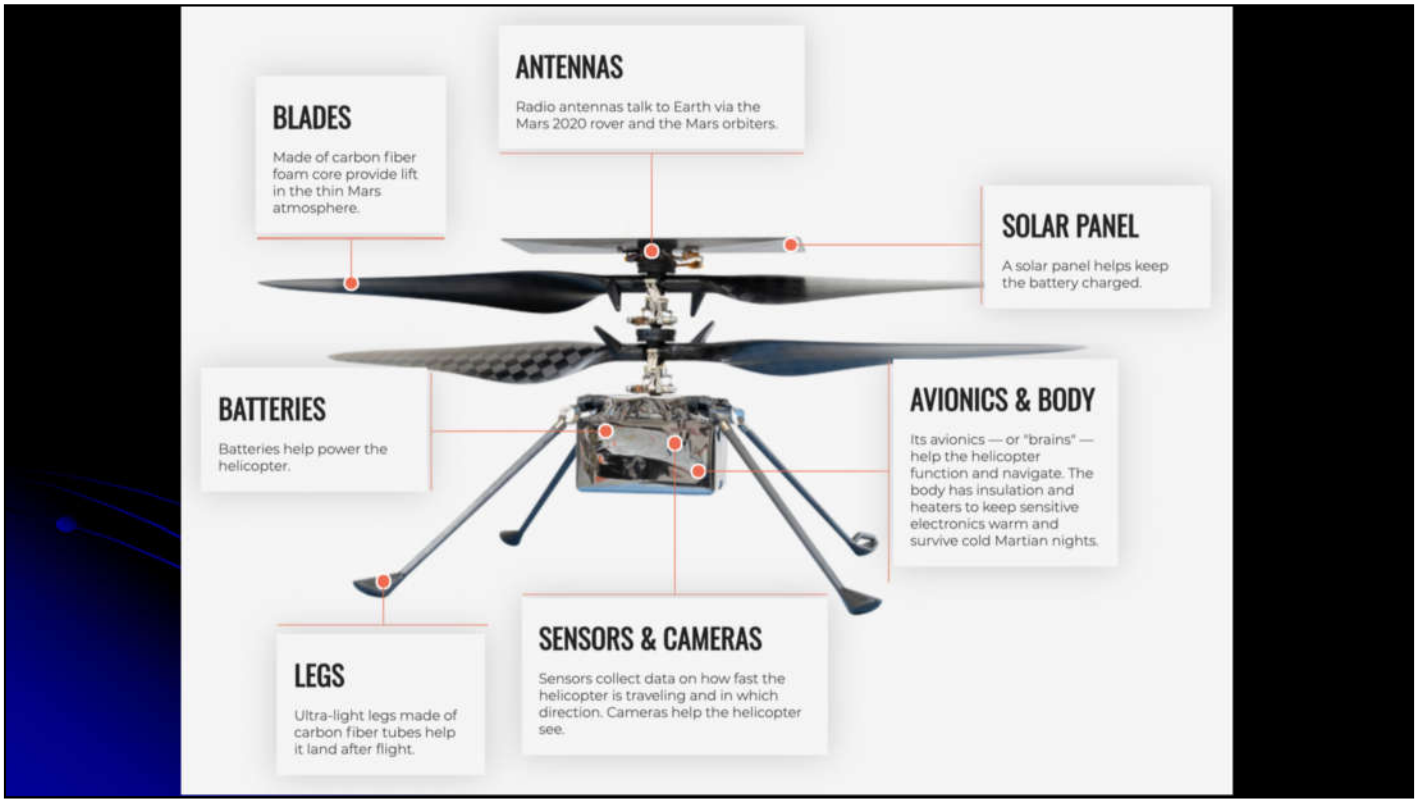
5 Things to Know

- First test of powered flight on another planet.
- Built to be light and strong enough to stow away under the rover while on the way to Mars, and survive the harsh Martian environment after arriving on the surface. The helicopter weighs less than 4 pounds (1.8 kilograms).
- Powerful enough to lift off in the thin Mars atmosphere. The atmosphere of Mars is very thin: less than 1% the density of Earth's.
- The helicopter may fly for up to 90 seconds, to distances of almost 980 feet (300 meters) at a time and about 10 to 15 feet from the ground. That's no small feat compared to the first 12-second flight of the Wright Brothers' airplane.
- The helicopter flies on its own, without human control. It must take off, fly, and land, with minimal commands from Earth sent in advance.

Basic Specifications

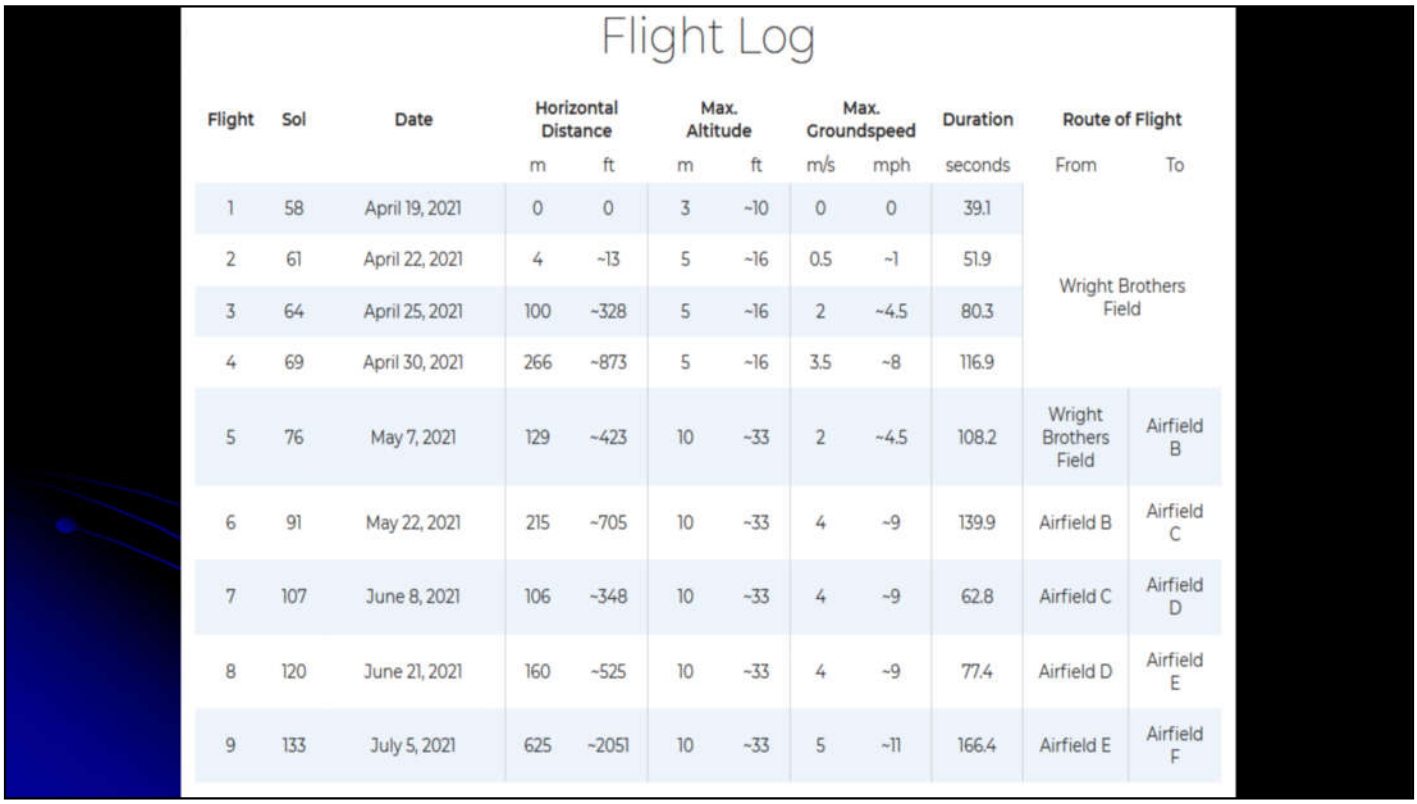
- Body: 5.4” x 7.7” x 6.4”
- Rotor Diamater: 4’
- Full Height: 1’ 7”
- Mass: 4.0 lb
  - Batteries 9.6 oz
- Power: 350 watts

https://mars.nasa.gov/technology/helicopter/#Tech-Specs



https://mars.nasa.gov/technology/helicopter/#Anatomy

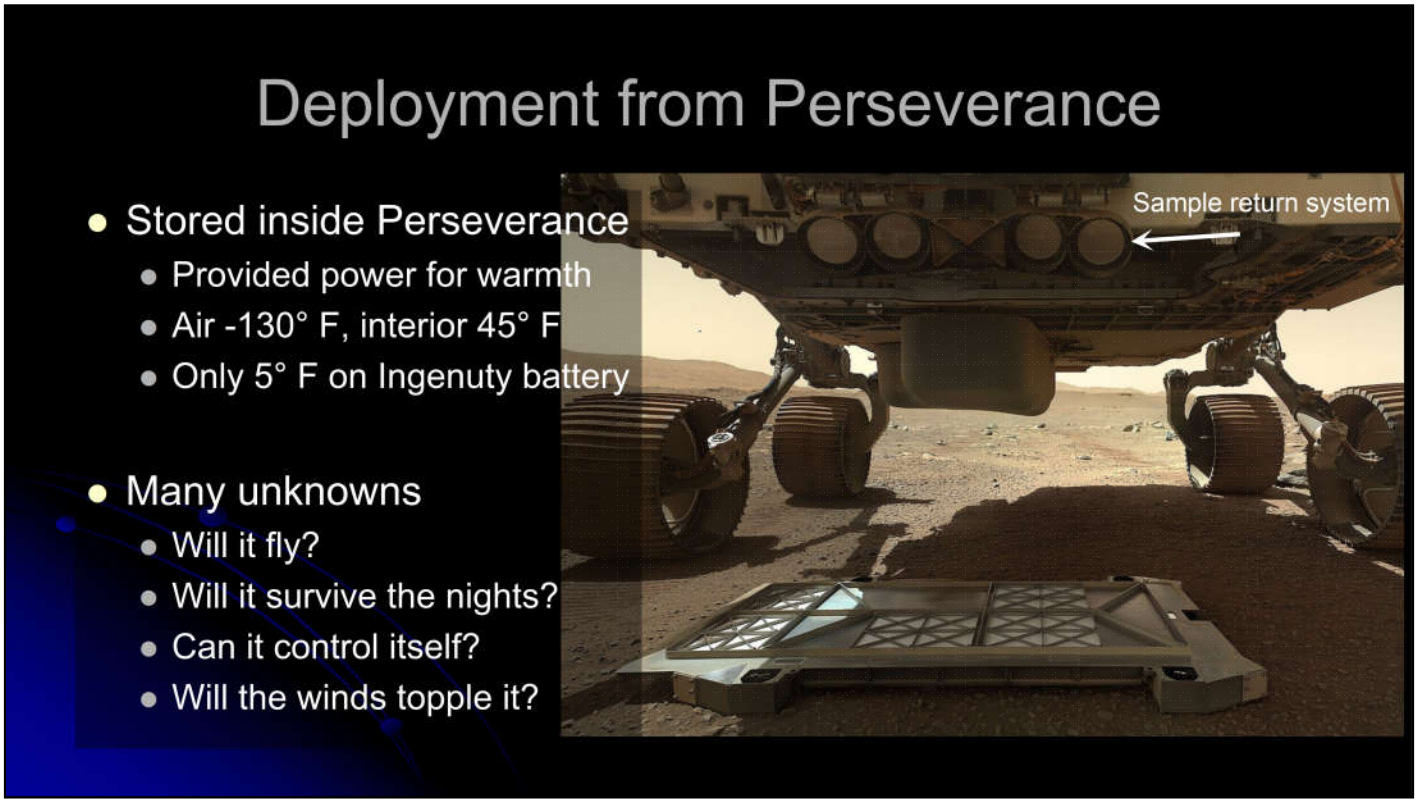
See the movie at https://mars.nasa.gov/resources/24931/mars-helicopter-arriving-at-the-red-planet-february-2021/



Flight Log

Flight	Sol	Date	Horizontal Distance		Max. Altitude		Max. Groundspeed		Duration	Route of Flight	
			m	ft	m	ft	m/s	mph	seconds	From	To
1	58	April 19, 2021	0	0	3	~10	0	0	39.1		
2	61	April 22, 2021	4	~13	5	~16	0.5	~1	51.9		
3	64	April 25, 2021	100	~328	5	~16	2	~4.5	80.3	Wright Brothers Field	
4	69	April 30, 2021	266	~873	5	~16	3.5	~8	116.9		
5	76	May 7, 2021	129	~423	10	~33	2	~4.5	108.2	Wright Brothers Field	Airfield B
6	91	May 22, 2021	215	~705	10	~33	4	~9	139.9	Airfield B	Airfield C
7	107	June 8, 2021	106	~348	10	~33	4	~9	62.8	Airfield C	Airfield D
8	120	June 21, 2021	160	~525	10	~33	4	~9	77.4	Airfield D	Airfield E
9	133	July 5, 2021	625	~2051	10	~33	5	~11	166.4	Airfield E	Airfield F

https://mars.nasa.gov/technology/helicopter/#Flight-Log



https://mars.nasa.gov/technology/helicopter/status/288/its-cold-on-mars/

Until now it has been connected to the Perseverance rover, which allowed Ingenuity to charge its battery as well as use a thermostat-controlled heater powered by the rover. This heater keeps the interior at about 45 degrees F through the bitter cold of the Martian night, where temperatures can drop to as low as -130F. That comfortably protects key components such as the battery and some of the sensitive electronics from harm at very cold temperatures.

The Sun's energy is weaker at Mars-a little over half of what we would find here on Earth on a bright, sunny day. But it's enough for Ingenuity's high-tech solar panel to charge the battery. Of course, this means that the rover will drive away from Ingenuity after the drop so that we uncover the solar panel. This will occur as soon as possible after the drop.

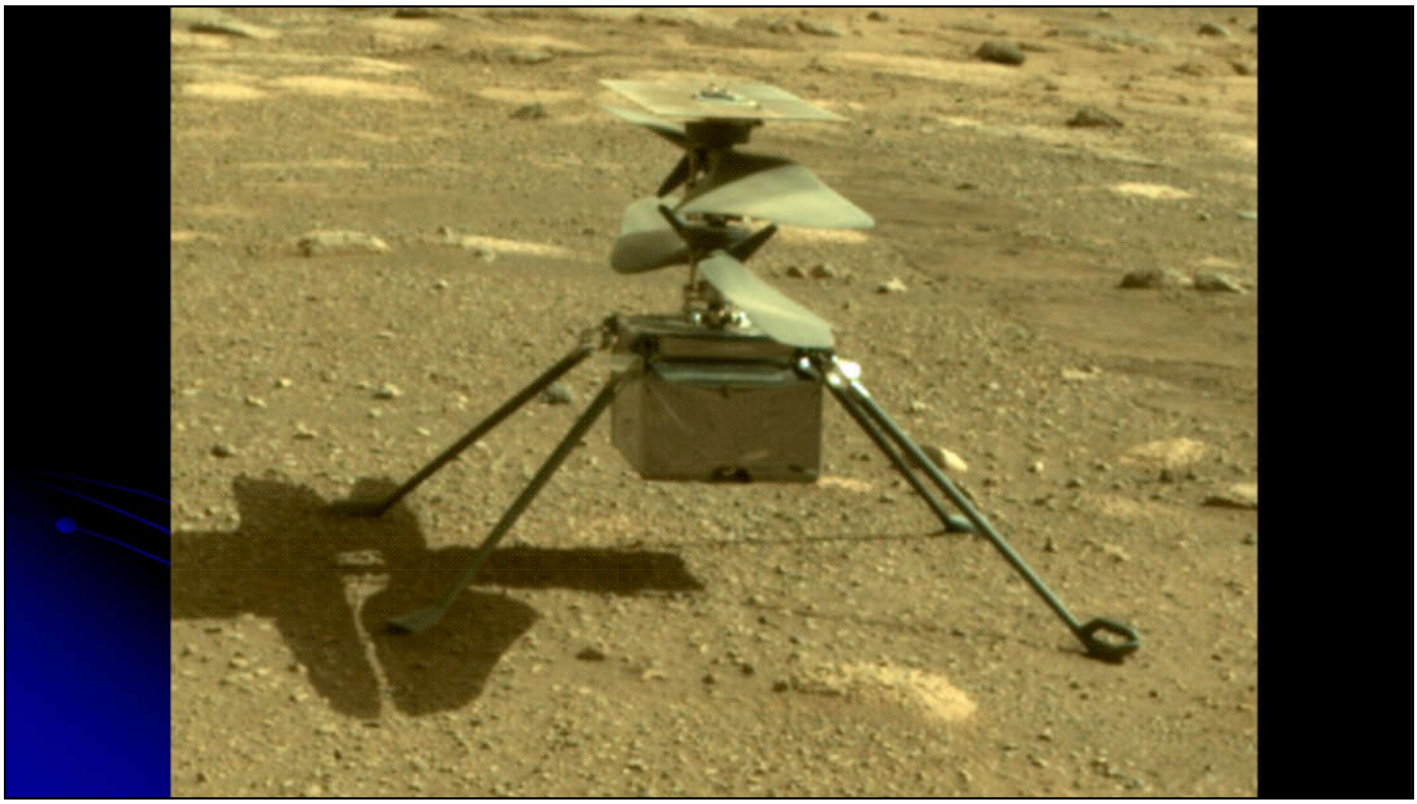
Debris shield removed after Rover repositioning

NASA/JPL-Caltech/MSSS - https://mars.nasa.gov/resources/25741/perseverance-rover-drops-its-debris-shield/

The debris shield, a protective covering on the bottom of NASA's Perseverance rover, was released on March 21, 2021, the 30th Martian day, or sol, of the mission. The debris shield protects the agency's Ingenuity helicopter during landing; releasing it allows the helicopter to rotate down out of the rover's belly.

https://mars.nasa.gov/resources/25778/ingenuity-helicopter-is-ready-to-drop/

While hanging from the bottom of the rover, it's attached to the rover's power to maintain the heat in the body of the helicopter. NASA scientists also did function checks and examined the the helicopter with the rover's cameras to ensure everything was ready for the next move.

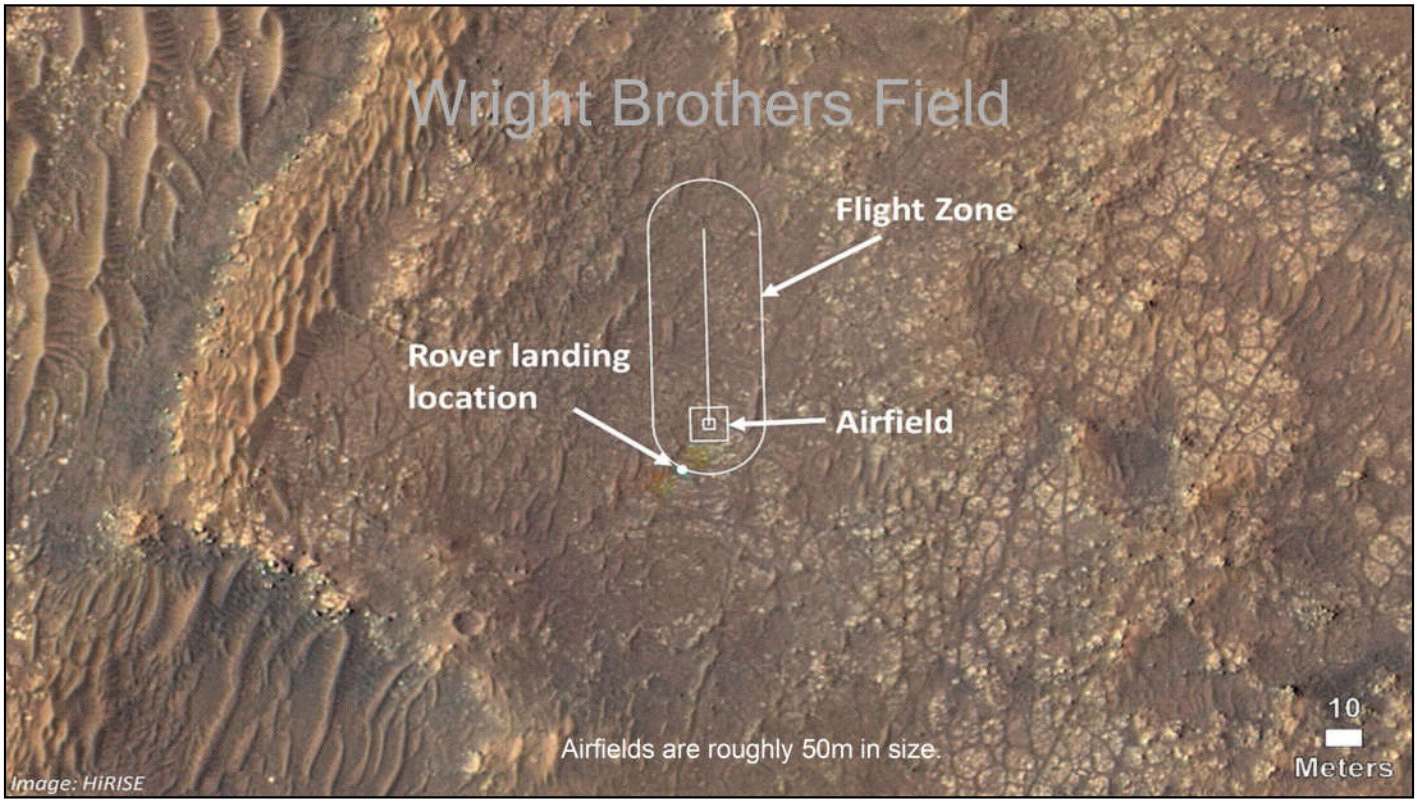


Successful deployment on Mars

NASA JPL - https://mars.nasa.gov/mars2020/multimedia/raw-images/RLF_0043_0670767844_862EBY_N0031398RHAZ02006_00_0LLJ

The Ingenuity helicopter after deployment on the Martian surface by the Mars 2020 Perseverance rover

https://mars.nasa.gov/resources/25782/ingenuitys-first-color-snap/



Airfields are roughly 50m in size, selected for a wide, flat space that allows for a flat landing and a spot for the rover to observe the flight.

https://mars.nasa.gov/resources/25744/map-of-ingenuity-helicopter-flight-zone/

Flight Factors

- Must have good light (camera navigation)
- Coordinate w/Perseverance
  - Monitor w/cameras
  - Not while P is busy
- Battery (hundreds of watts)
  - Must get full charge after noon
  - Must recharge for heater
- Winds must be low & calm

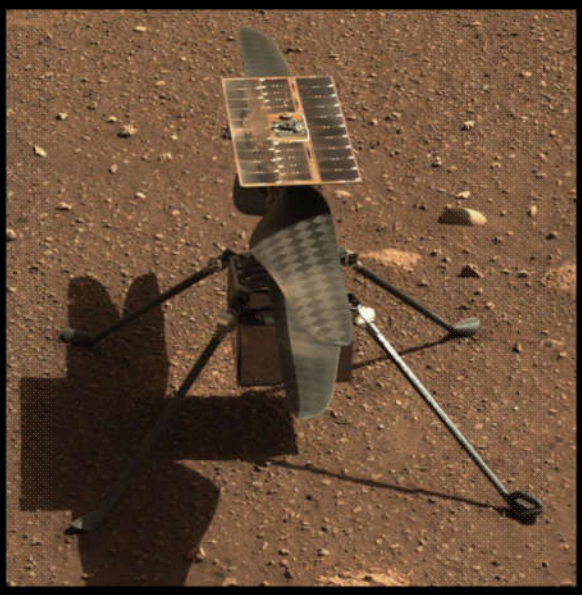
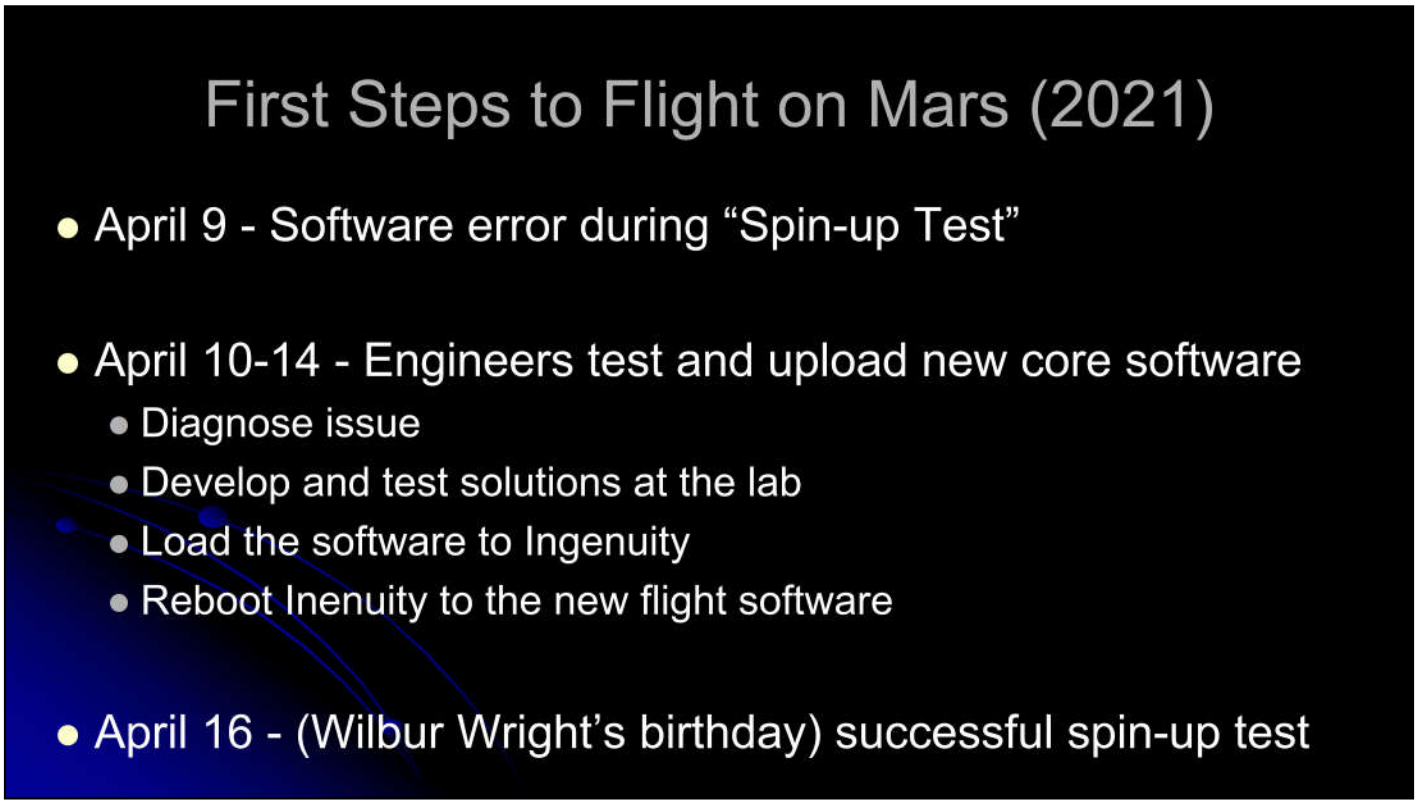


Image: https://mars.nasa.gov/resources/25784/mastcam-z-gives-ingenuity-a-close-up/

https://mars.nasa.gov/technology/helicopter/status/289/when-should-ingenuity-fly/

For example, Perseverance is keeping a watchful eye on Ingenuity with the rover's cameras, and needs to know when we are planning to do certain activities. There are also times when Perseverance is busy with transmitting on the radio to relay satellites overhead, or managing the many science instruments on the rover, or performing other spacecraft operations.



https://mars.nasa.gov/technology/helicopter/status/292/working-the-challenge-two-paths-to-first-flight-on-mars/

https://mars.nasa.gov/technology/helicopter/status/291/mars-helicopter-flight-delayed-to-no-earlier-than-april-14/

The process of updating Ingenuity’s flight control software will follow established processes for validation with careful and deliberate steps to move the new software through the rover to the base station and then to the helicopter. Intermediate milestones include:

Diagnose the issue and develop potential solutions

Develop/validate and upload software

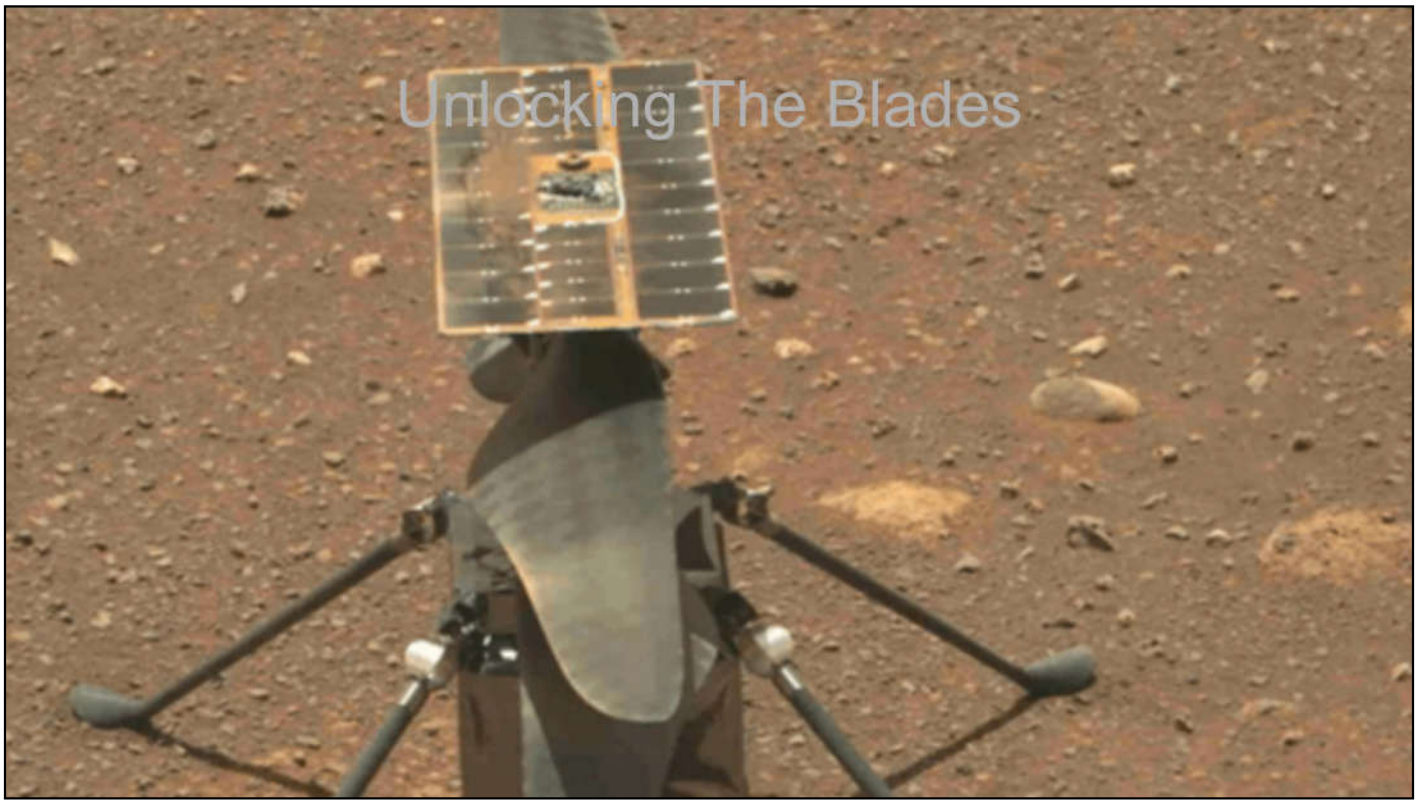
Load flight software onto flight controllers

Boot Ingenuity on new flight software

Once we have passed these milestones, we will prepare Ingenuity for its first flight, which will take several sols, or Mars days.

https://mars.nasa.gov/technology/helicopter/status/293/why-we-choose-to-try-our-first-helicopter-flight-on-monday/

Over the last week, we’ve been testing the two solutions to address the “watchdog” timer issue that prevented the helicopter from transitioning to “flight mode” and performing a high-speed spin test of the rotors on April 9. These



https://mars.nasa.gov/resources/25796/ingenuity-begins-to-spin-its-blades/

https://mars.nasa.gov/resources/25810/mastcam-z-captures-ingenuitys-blades-spinning/

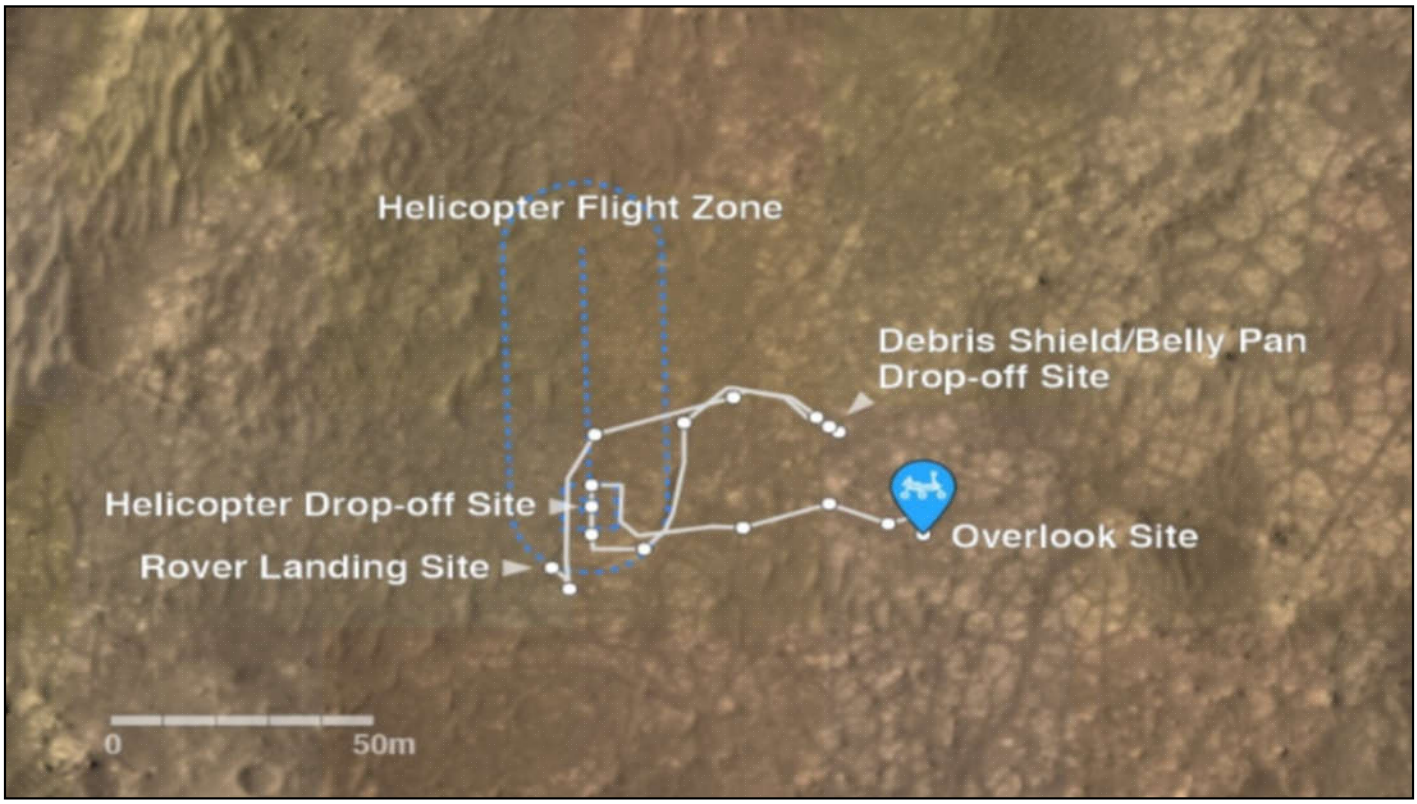
NASA/JPL-Caltech - This image or video was catalogued by Jet Propulsion Laboratory of the United States National Aeronautics and Space Administration (NASA) under Photo ID: PIA24549.

Ingenuity Helicopter Rotor Blades Unlocked for Flying

Ingenuity gives its blades a slow-speed spin up test or 50 rpm test spin on sol 48

Nasa - https://mars.nasa.gov/resources/25796/ingenuity-begins-to-spin-its-blades/

Ingenuity gives it's blades a slow speed or 50 rpm test spin

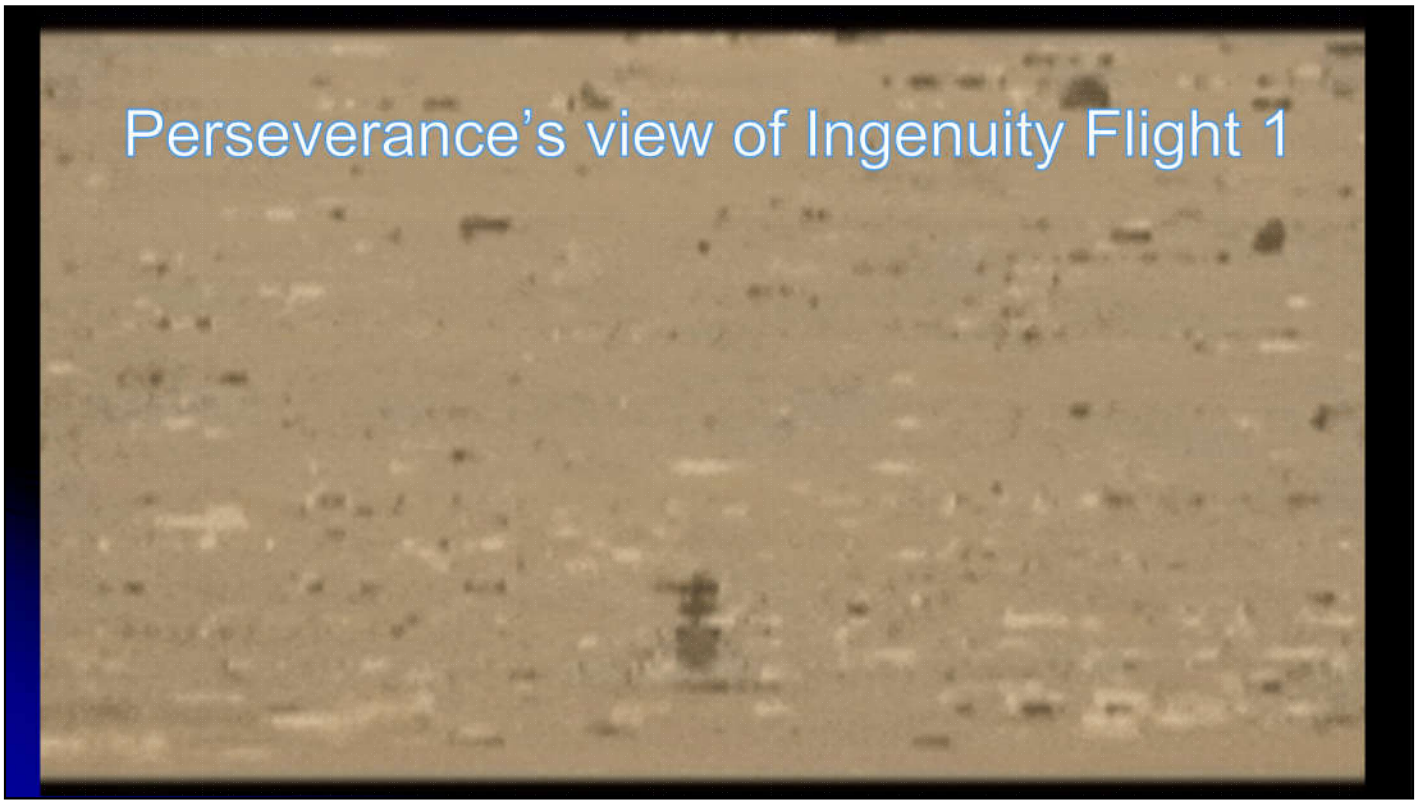


https://en.wikipedia.org/wiki/Ingenuity_(helicopter)#/media/File:Perseverance_rover_track_and_Ingenuity_Helicopter_Flight_Zone.jpg
Perseverance rover track and Ingenuity Helicopter Flight Zone seen after rover had reached Van Zyl Overlook

First Flights on Mars (2021)

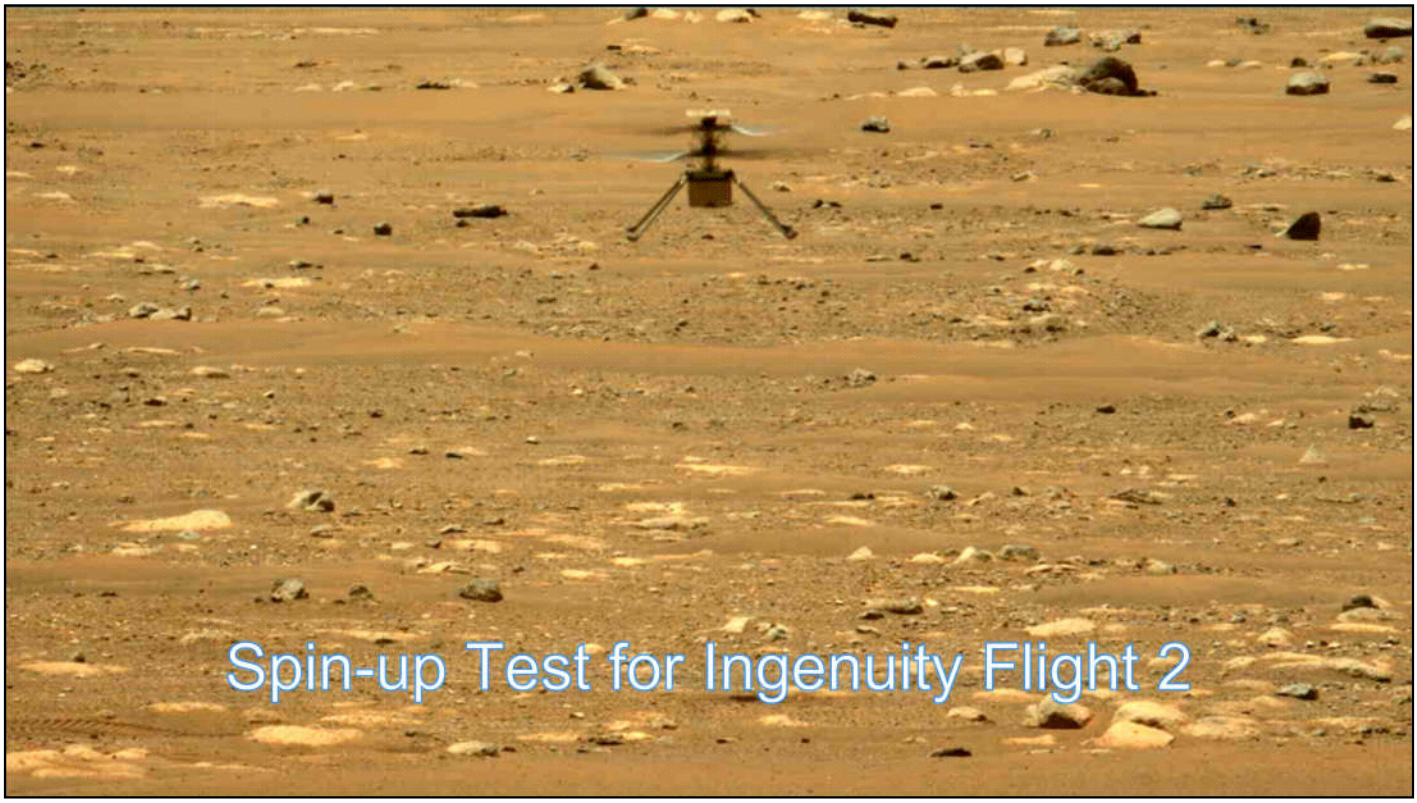
- Flight 1 - 4/19 - 40 sec. hover at 3m height,
  - rotation and camera control tests
- Flight 2 - 4/22 - 52 sec. 2m out and back at 5m height
  - Tilt, longer spin, and color camera tests
- Flight 3 - 4/25 - 80 sec. 100m out and back at 5m height
  - Distance and camera distance navigation tests

https://en.wikipedia.org/wiki/Ingenuity_(helicopter)

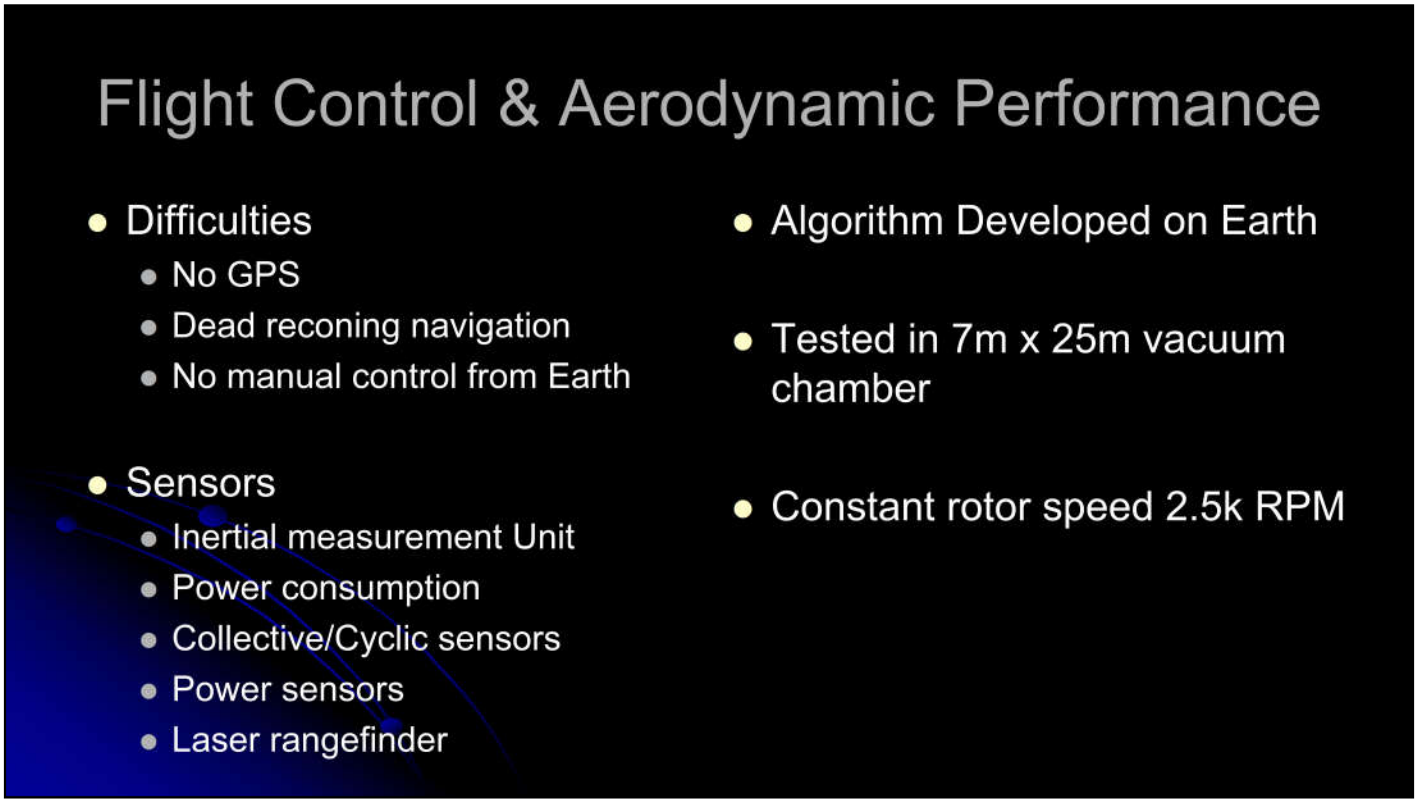


https://mars.nasa.gov/resources/25838/mastcam-z-video-of-ingenuity-taking-off-and-landing/

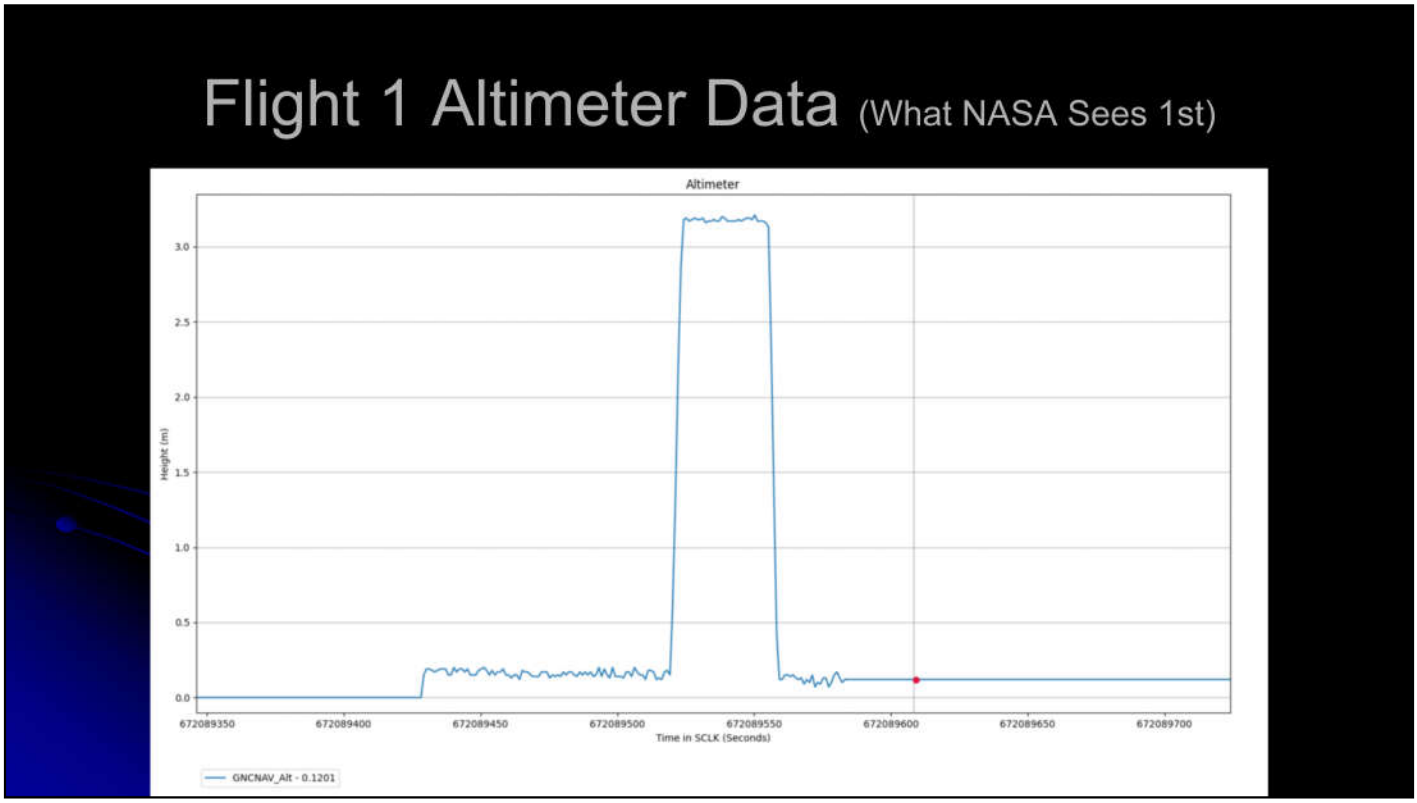
Sorry, I couldn't find the link for this image. I think it was in a NASA news release or blog.



https://mars.nasa.gov/resources/25840/ingenuitys-second-flight-as-seen-by-perseverance/

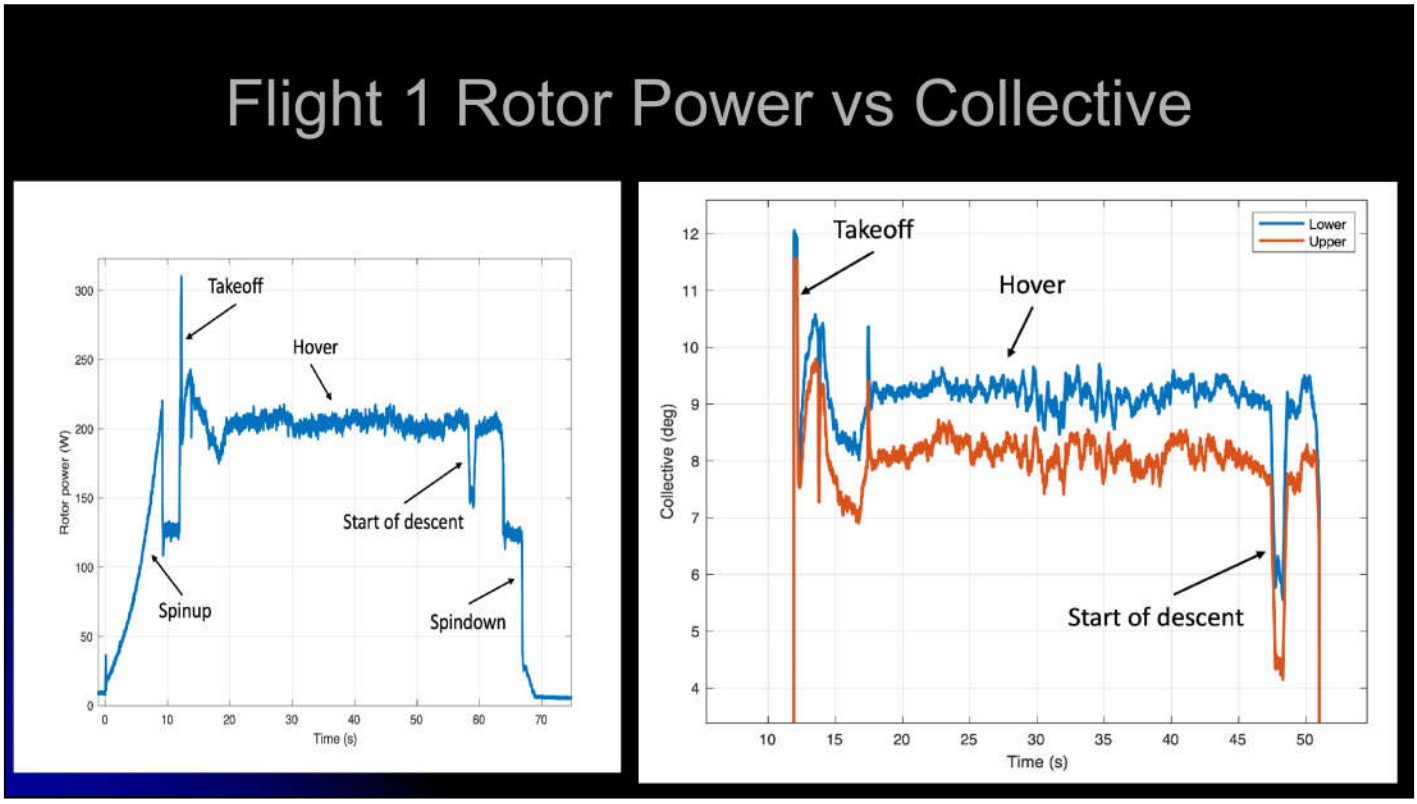


https://mars.nasa.gov/technology/helicopter/status/298/what-were-learning-about-ingenuitys-flight-control-and-aerodynamic-performance/



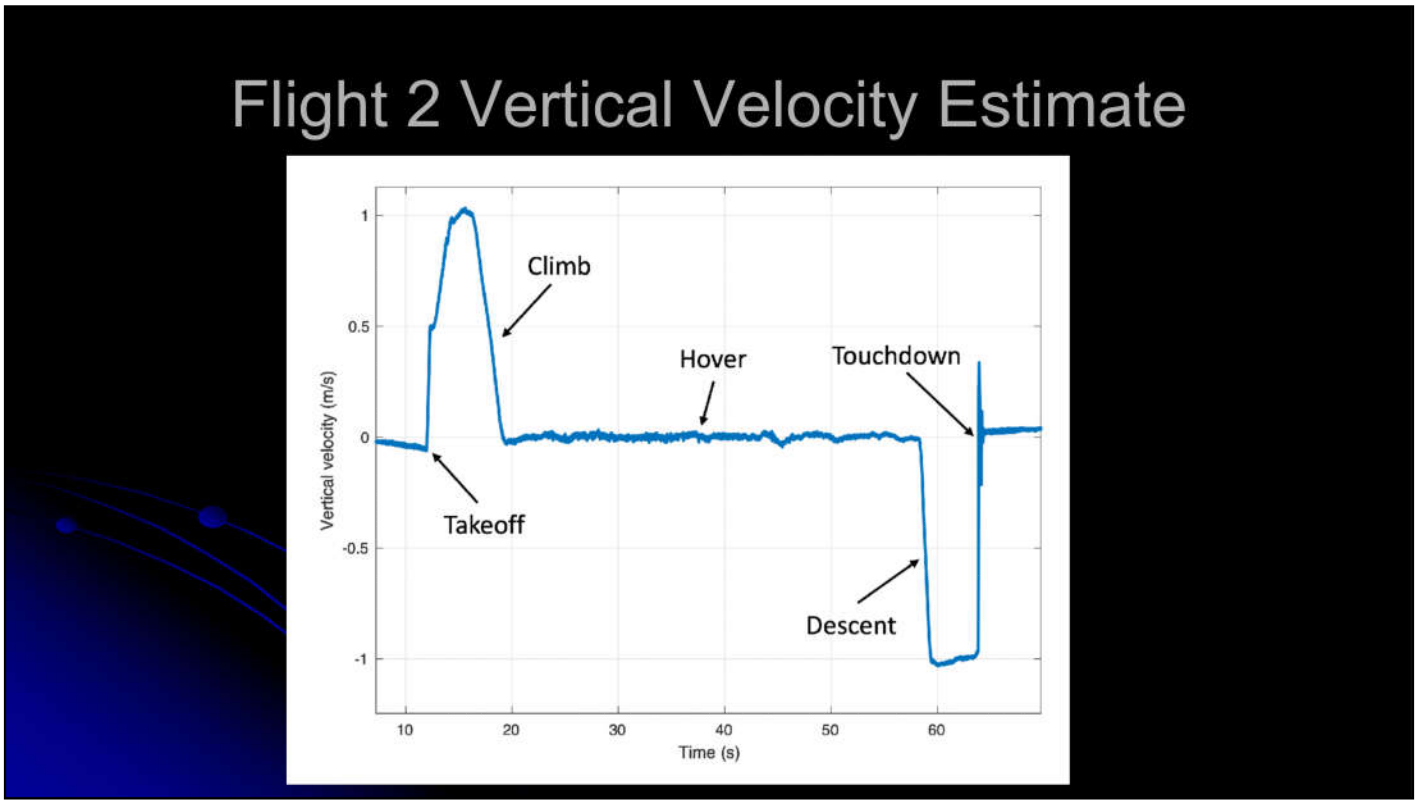
NASA/JPL-Caltech - https://mars.nasa.gov/resources/25820/altimeter-chart-for-ingenuitys-first-flight/ This plot was created with Matplotlib.

This altimeter chart shows data from the first flight of NASA's Ingenuity Mars Helicopter, which occurred on April 19, 2021. The Ingenuity Mars Helicopter was built by JPL, which also manages this technology demonstration project for NASA Headquarters. It is supported by NASA's Science Mission Directorate, Aeronautics Research Mission Directorate, and Space Technology Mission Directorate. NASA's Ames Research Center and Langley Research Center provided significant flight performance analysis and technical assistance during Ingenuity's development. A key objective for Perseverance's mission on Mars is astrobiology, including the search for signs of ancient microbial life. The rover will characterize the planet's geology and past climate, pave the way for human exploration of the Red Planet, and be the first mission to collect and cache Martian rock and regolith (broken rock and dust). Subsequent NASA missions, in cooperation with ESA (European Space Agency), would send spacecraft to Mars to collect these sealed samples from the surface and return them to Earth for in-depth analysis. The Mars 2020 Perseverance mission is part of NASA's Moon to Mars exploration approach, which includes Artemis missions to the Moon that will help prepare for human exploration of the Red Planet. JPL, which is managed for NASA by Caltech in Pasadena, California, built and manages operations of the Perseverance rover.



For the collective control (remember, that is the one that changes rotor blade pitch angle uniformly to affect helicopter's thrust), we would like to see hover values roughly consistent with prior expectations. During Flight One, we hovered with around 9.2 degrees collective on the lower rotor and 8.2-degree collective on the upper (that's the angle of the blade's "chord line" – an imaginary line drawn from the leading edge to the trailing edge of the rotor blade – at ¾ of the rotor radius). Those values are 0.7-0.8 degrees lower than the trim values we anticipated (9.0 degree on the upper rotor and 9.9 degree on the lower rotor).

https://mars.nasa.gov/technology/helicopter/status/298/what-were-learning-about-ingenuitys-flight-control-and-aerodynamic-performance/

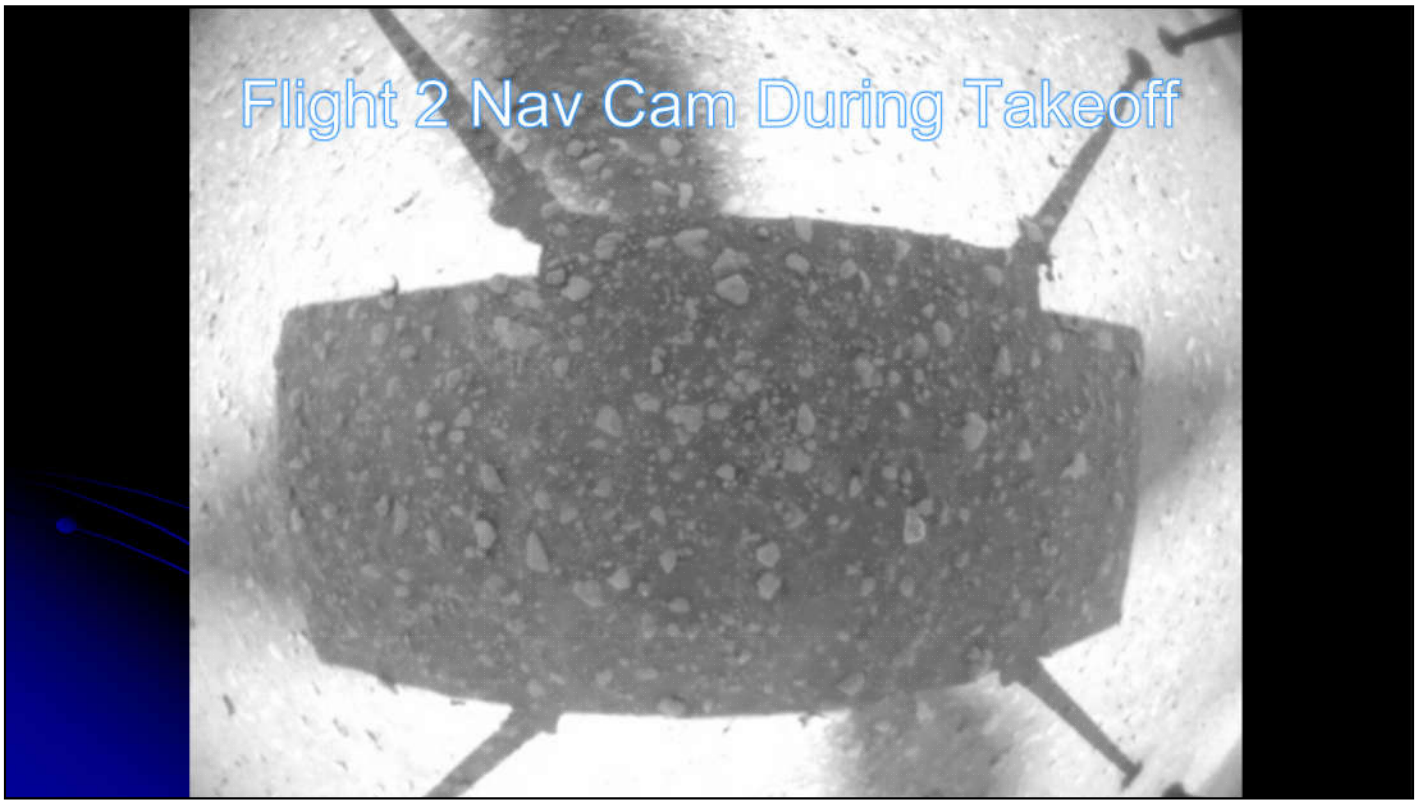


https://mars.nasa.gov/resources/25875/ingenuitys-estimate-of-vertical-velocity-during-flight-two/

Remember that horizontal trace means hover or on the ground. Vertical traces show the velocity (not distance) of movement.

Trace going up means the helicopter is rising. Trace down is the helicopter sinking.

That means the first hump shows a speedy takeoff followed by a period of slowing to the hover phase. That's reversed in the descent and the trace at touchdown shows it bounced a bit.



April 30, 2021

A picture from the navigation camera aboard Ingenuity captured the helicopter on takeoff during Flight Two, **showing little sign of dust.**

https://mars.nasa.gov/resources/25872/ingenuity-flight-two/

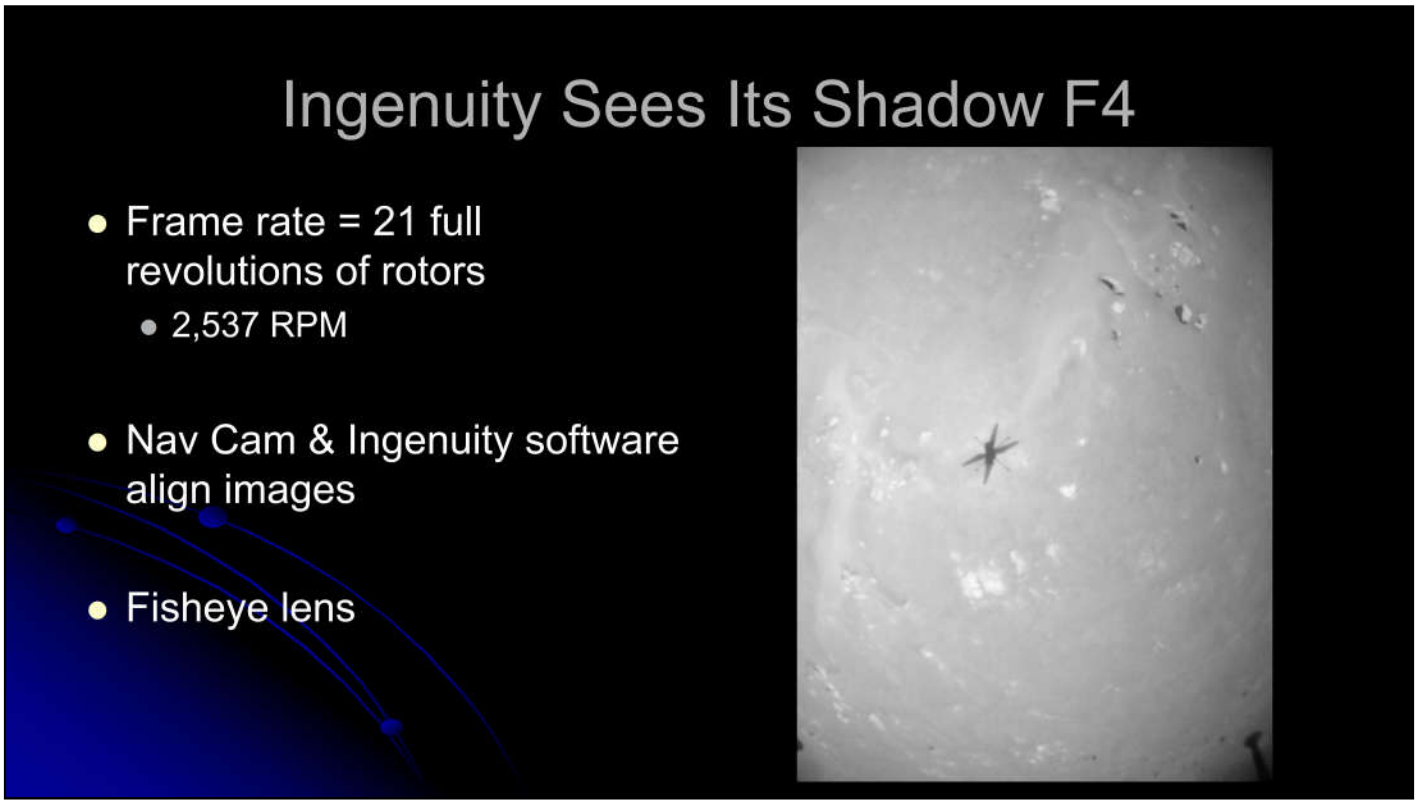
https://mars.nasa.gov/resources/25846/first-aerial-color-image-of-mars/

Mars Ingenuity Helicopter Views Perseverance Rover From Air - April 25, 2021
PIA24625: Ingenuity Spots Perseverance From the Air
https://photojournal.jpl.nasa.gov/catalog/PIA24625 NASA's Perseverance Mars rover is visible in the upper left corner of this image the agency's Ingenuity Mars Helicopter took during its third flight, on April 25, 2021. The helicopter was flying at an altitude of 16 feet (5 meters) and roughly 279 feet (85 meters) from the rover at the time.

The Ingenuity helicopter views the Perseverance rover (left) about 85 m (279 ft) away from 5.0 m (16.4 ft) in the air (25 April 2021)

NASA/JPL-Caltech - https://photojournal.jpl.nasa.gov/catalog/PIA24625; https://photojournal.jpl.nasa.gov/jpeg/PIA24625.jpg

Mars Ingenuity Helicopter Views Perseverance Rover From Air - Annotated Crop - April 25, 2021 PIA24625: Ingenuity Spots Perseverance From the Air - Annotated Crop NASA's Perseverance Mars rover is visible in the upper left corner of this image the agency's Ingenuity Mars Helicopter took during its third flight, on April 25, 2021. The helicopter was flying at an altitude of 16 feet (5 meters) and roughly 279 feet (85 meters) from the rover at the time.



NASA / JPL - Caltech - https://mars.nasa.gov/resources/25890/black-and-white-view-of-ingenuitys-fourth-flight/

NASA’s Ingenuity Mars Helicopter took these images on its fourth flight, on April 30, 2021, using its navigation camera. The camera, which tracks surface features below the helicopter, takes images at a rate at which the helicopter’s blades appear frozen in place, despite making 21 full rotations in-between each image. In flight, the blades spin at 2,537 rpm. The images are aligned entirely using Ingenuity's on-board position tracking system highlighting the stability and accuracy of the navigation algorithm.

Flight 4 - Ambitious Tests

- Attempt 1 - Failed to transition to flight mode
- Flight 4 - 4/29 - 117 sec, 133m out and back at 5m height
  - Scouting for a new landing spot

- Numerous Firsts:
  - Record number of images by an aircraft on Mars
  - Created 1st 3D map by an aricraft on Mars
  - 1st interplanetary vehicle to record audio of another
  - Ingenuity traveled farther than Perseverance had

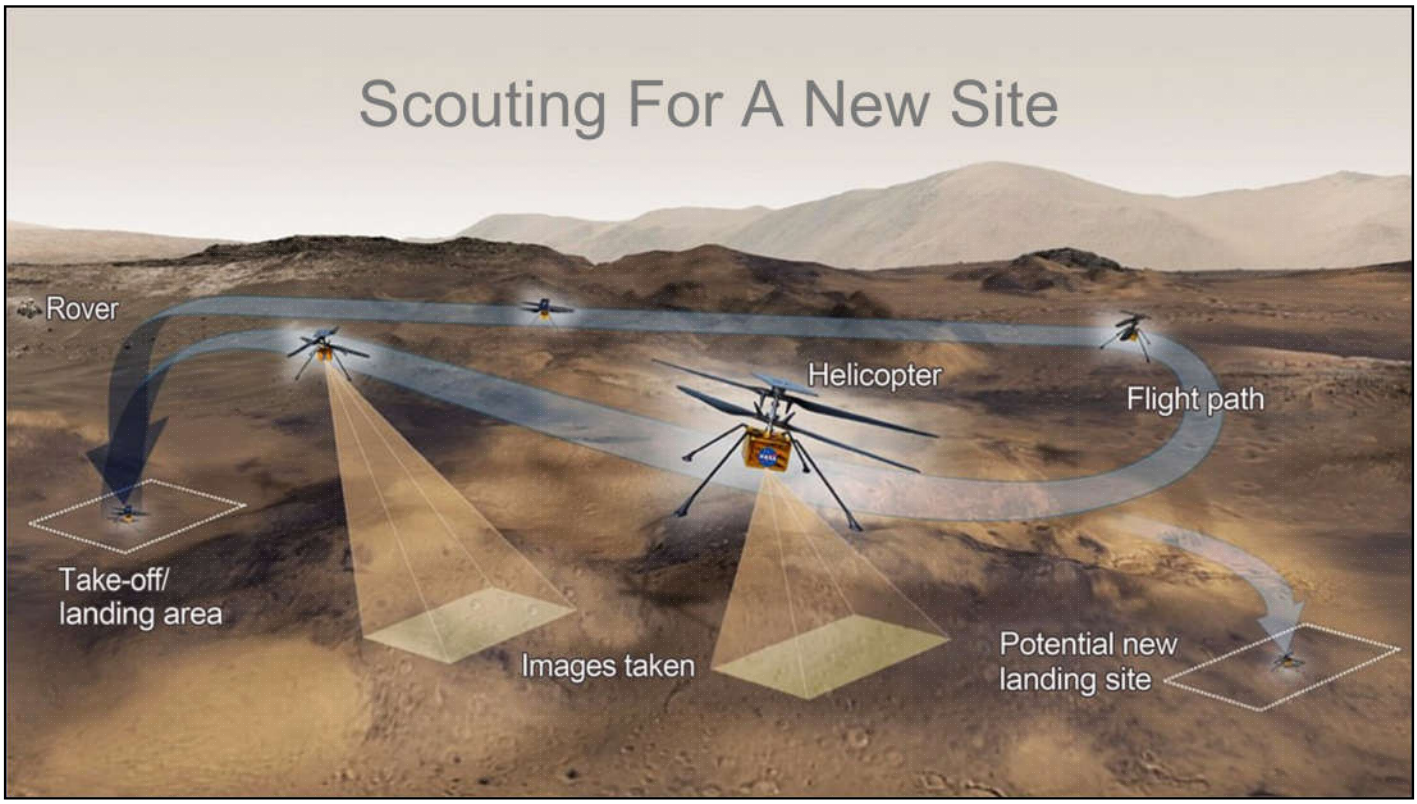
https://en.wikipedia.org/wiki/Ingenuity_(helicopter)

https://mars.nasa.gov/resources/25893/listen-to-nasas-ingenuity-mars-helicopter-in-flight/

For the first time, a spacecraft on another planet has recorded the sounds of a separate spacecraft. NASA's Perseverance Mars rover used its SuperCam microphone to listen to the Ingenuity helicopter on April 30, 2021 as it flew on Mars for the fourth time.

With Perseverance parked 262 feet (80 meters) from the helicopter's takeoff and landing spot, the mission wasn't sure if the microphone would pick up any sound of the flight. Even during flight when the helicopter's blades are spinning at 2,537 rpm, the sound is greatly muffled by the thin Martian atmosphere. It is further obscured by Martian wind gusts during the initial moments of the flight. Listen closely, though, and the helicopter's hum can be heard faintly above the sound of those winds.

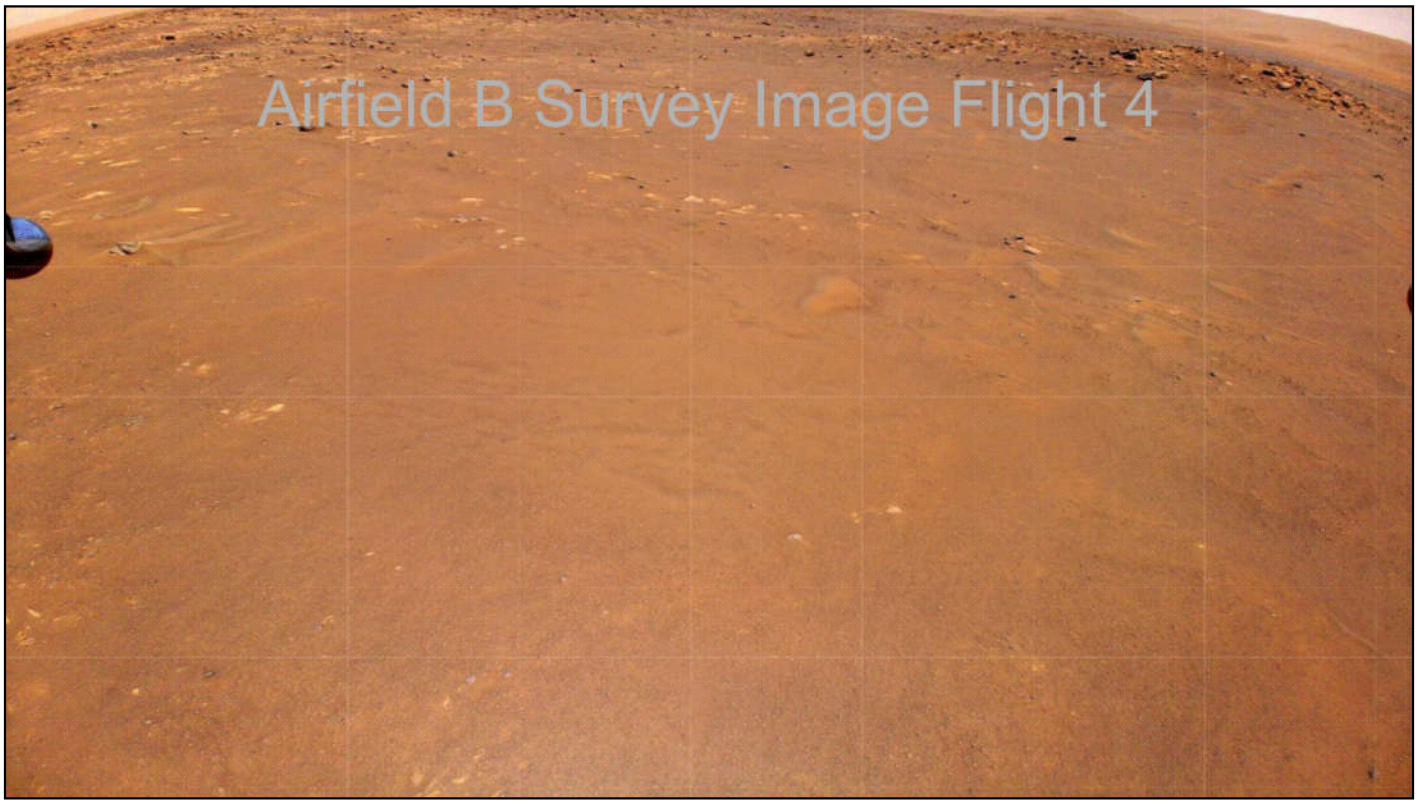
Scientists made the audio, which is recorded in mono, easier to hear by isolating the 84 hertz helicopter blade sound, reducing the frequencies below 80 hertz and above 90 hertz, and increasing the volume of the remaining signal. Some frequencies were clipped to bring out the helicopter's hum.



https://mars.nasa.gov/resources/25889/ingenuitys-color-camera-spies-helicopters-new-airfield/

https://en.wikipedia.org/wiki/Ingenuity_(helicopter)#/media/File:HiRISE's_View_of_Ingenuity's_Fourth_Flight_Path_Paving_the_Way_for_it_to_move_to_second_Airfeild.jpg

NASA’s Ingenuity Mars Helicopter’s fourth flight path is superimposed here atop terrain imaged by the HiRISE camera aboard the agency’s Mars Reconnaissance Orbiter. The University of Arizona, in Tucson, operates HiRISE, which was built by Ball Aerospace & Technologies Corp., in Boulder, Colorado. NASA's Jet Propulsion Laboratory, a division of Caltech in Pasadena, California, manages the Mars Reconnaissance Orbiter Project for NASA's Science Mission Directorate in Washington. The Ingenuity Mars Helicopter was built by JPL, which also manages the technology demonstration project for NASA Headquarters. It is supported by NASA’s Science, Aeronautics Research, and Space Technology mission directorates. NASA’s Ames Research Center in California’s Silicon Valley, and NASA’s Langley Research Center in Hampton, Virginia, provided significant flight performance analysis and technical assistance during Ingenuity’s development. AeroVironment Inc., Qualcomm, and SolAero also provided design assistance and major vehicle components. Lockheed Martin Space designed and manufactured the Mars Helicopter Delivery System.

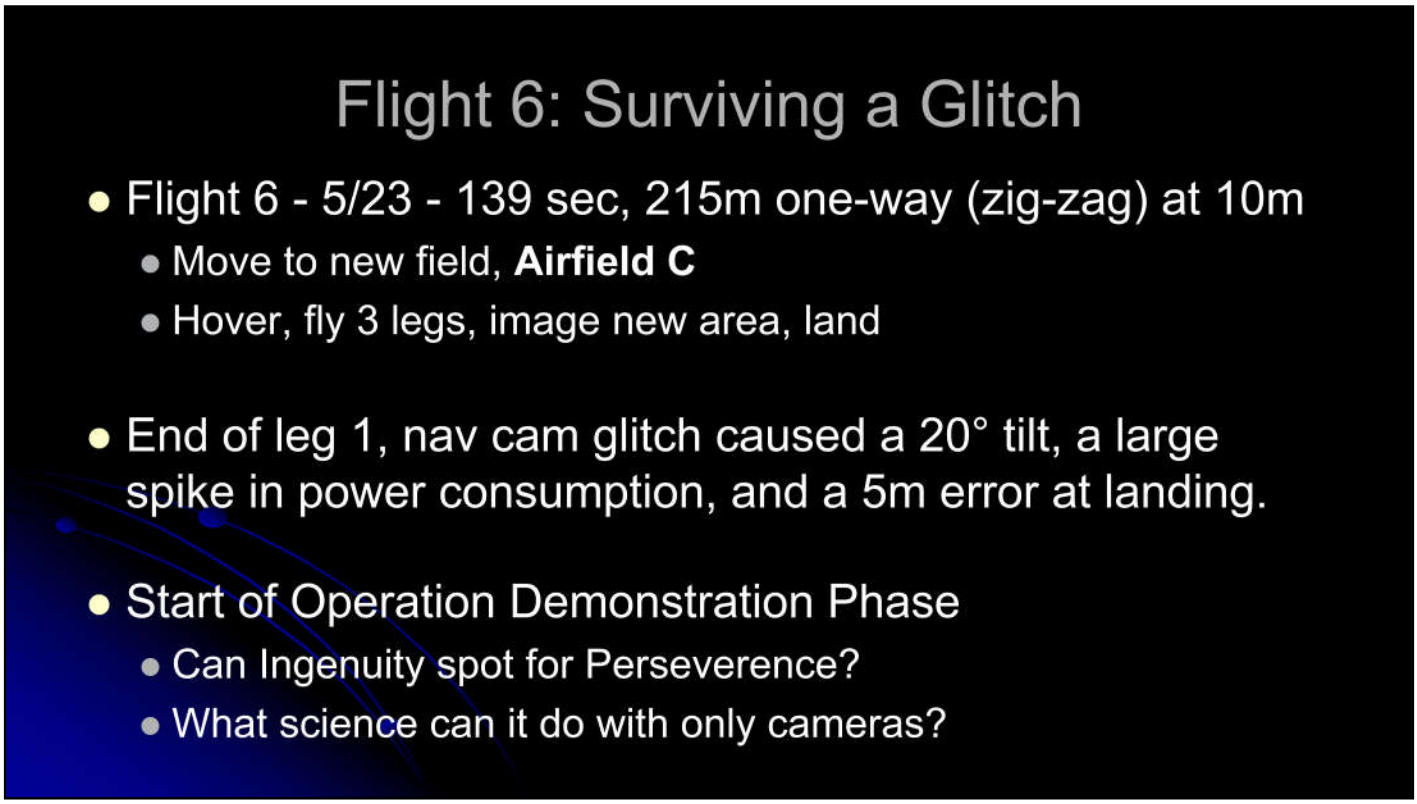


https://mars.nasa.gov/resources/25889/ingenuitys-color-camera-spies-helicopters-new-airfield/

Flight 5: A New Home

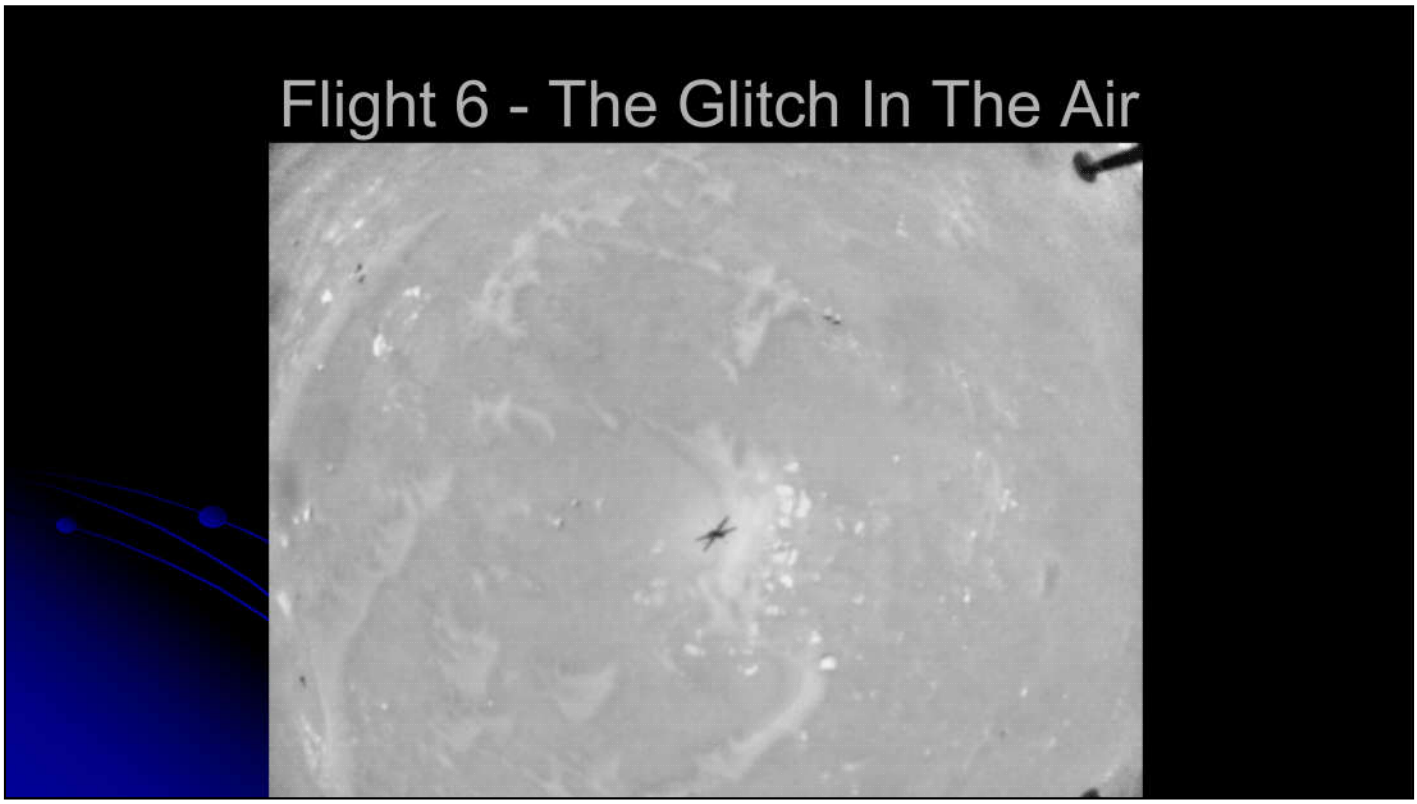
- Flight 5 - 5/7 - 108 sec, 129m one-way at 10m height
  - Move to new field, **Airfield B**
  - Hover, fly, image new area, land
- End of Technology Demonstration Phase
  - Aircraft flight proven in Mars' light gravity and thin air!
- Now to find new uses for the helicopter!

https://en.wikipedia.org/wiki/Ingenuity_(helicopter)



https://en.wikipedia.org/wiki/Ingenuity_(helicopter)

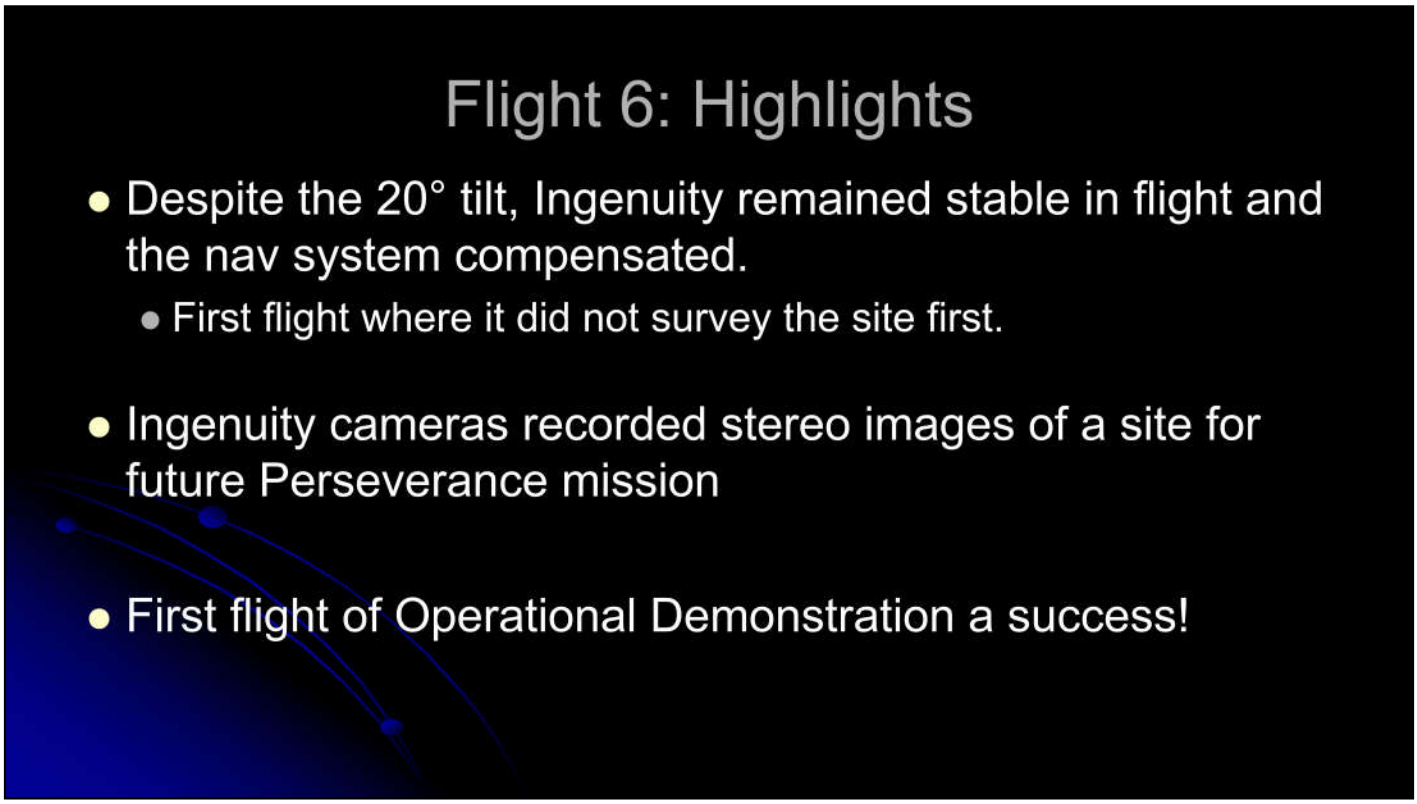
The flight had a problem towards the end of the first leg, when a glitch in the navigation camera system caused all following images to be marked with incorrect timestamps. This resulted in the craft tilting forward and backward up to 20 degrees, with large spikes in power consumption. Ingenuity continued flying the next two legs in that mode and landed about 5 m (16 ft) away from the planned site, assumed as its Airfield C. This was the first time it experienced an anomaly.[101][102] The flight also was the first in the operation demonstration phase following the technology demonstration.



Flight #6. Last 29 seconds of flight registered by navigation camera

NASA - https://mars.nasa.gov/resources/25941/ingenuity-flight-six-navcam-image/ https://mars.nasa.gov/mars2020/multimedia/raw-images/?af=HELI_NAV,HELI_RTE#raw-images

Ingenuity flight six navcam imagery showing last 29 seconds in flight along with navigation anomaly



https://en.wikipedia.org/wiki/Ingenuity_(helicopter)

The flight had a problem towards the end of the first leg, when a glitch in the navigation camera system caused all following images to be marked with incorrect timestamps. This resulted in the craft tilting forward and backward up to 20 degrees, with large spikes in power consumption. Ingenuity continued flying the next two legs in that mode and landed about 5 m (16 ft) away from the planned site, assumed as its Airfield C. This was the first time it experienced an anomaly.[101][102] The flight also was the first in the operation demonstration phase following the technology demonstration.

Ingenuity one day after its sixth flight (Sol 92)

NASA - https://mars.nasa.gov/resources/25942/ingenuity-at-third-airfield/

Ingenuity after its sixth flight on May 23, 2021, 1 day after the flight.

NASA/JPL-Caltech - https://photojournal.jpl.nasa.gov/catalog/PIA24600

This image looking west toward the Séítah geologic unit on Mars was taken from the height of 33 feet (10 meters) by NASA's Ingenuity Mars helicopter during its sixth flight, on May 22, 2021

https://en.wikipedia.org/wiki/Ingenuity_(helicopter)

Flight 7 summary:

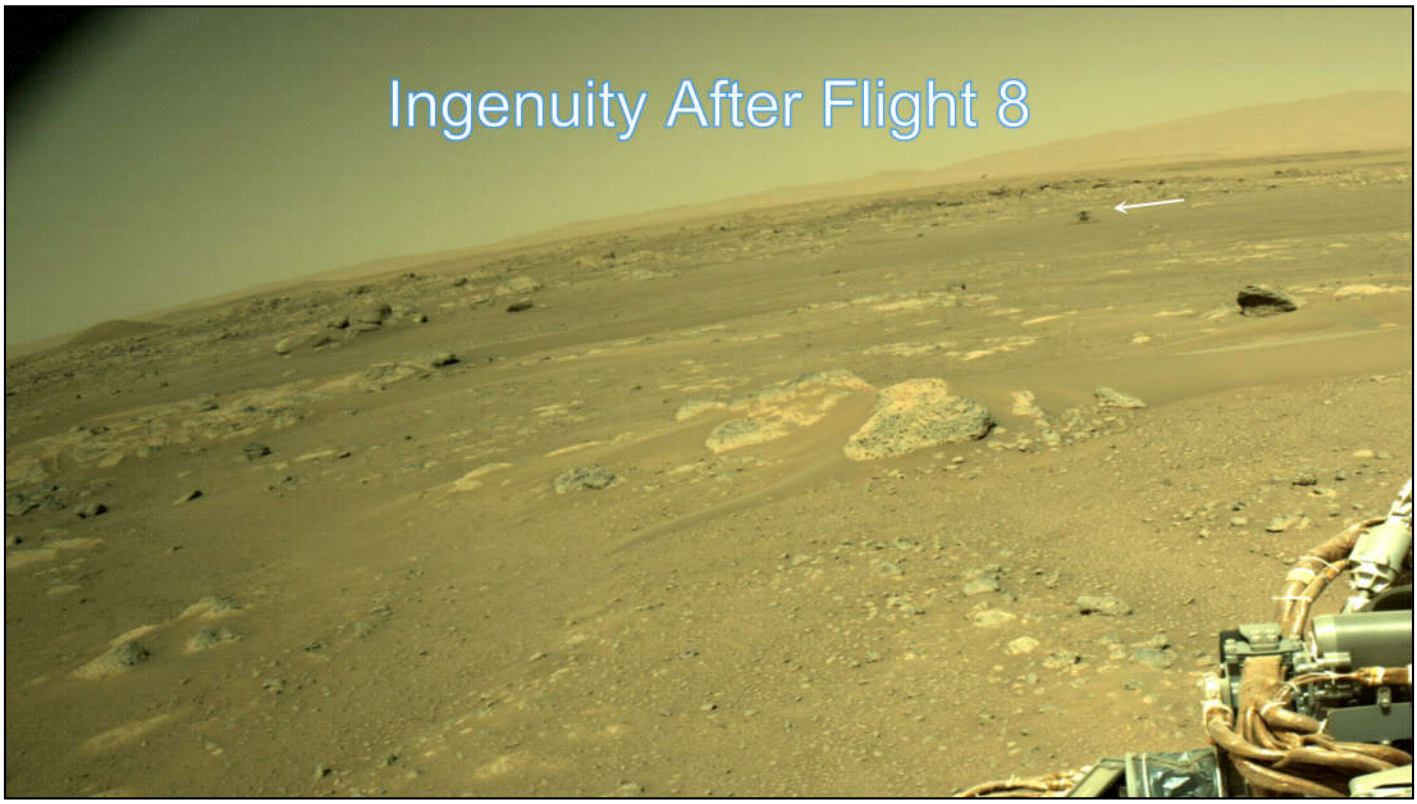
Ingenuity flew 106 m (348 ft) south to a new landing spot and landed at Airfield D. The color camera was not used to prevent glitch of flight 6 happening again.

Flight 8 summary:

Ingenuity flew about 160 m (520 ft) south to land at Airfield E, about 133.5 m (438 ft) away from Perseverance. Just like the last flight, the color camera was not used to prevent the glitch of flight 6 happening again. The bug was fixed before flight 9.

https://mars.nasa.gov/mars2020/multimedia/raw-images/NLF_0111_0676792771_816EBY_N0040922NCAM03111_03_0LLJ#.YMWXQR6v23E.mailto

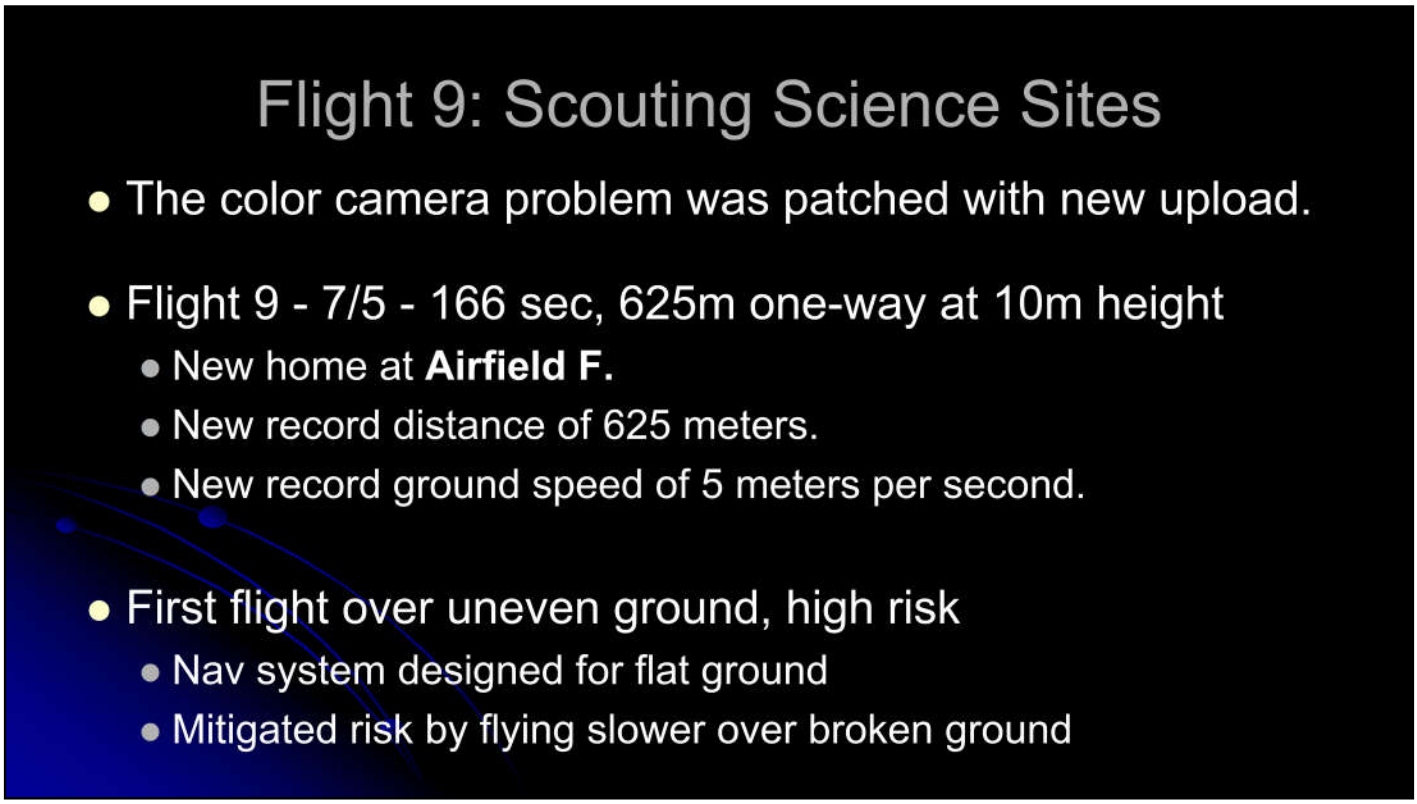
NASA's Mars Perseverance rover acquired this image using its onboard Left Navigation Camera (Navcam). The camera is located high on the rover's mast and aids in driving.



Ingenuity seven days after its eighth flight (Sol 127)

NASA/JPL-Caltech - https://mars.nasa.gov/mars2020/multimedia/raw-images/NLF_0127_0678218487_243ECM_N0041860NCAM03127_01_195J#.YNywTGvvCAI.mailto

Ingenuity at Sol 127, June 29, 2021

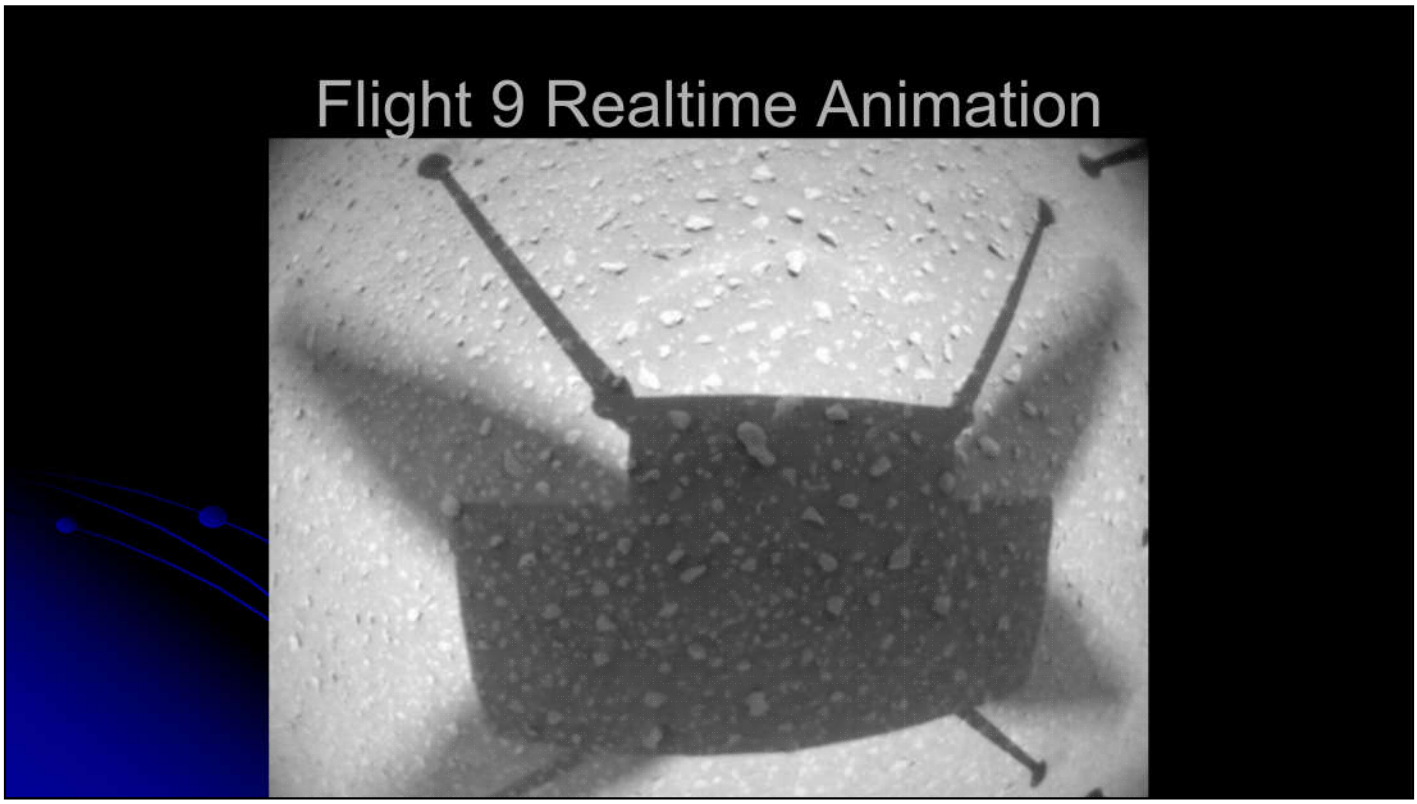


https://en.wikipedia.org/wiki/Ingenuity_(helicopter)

Flight 9 summary:

Ingenuity flew a record length of 625 m (2,050 ft) southwest, over Séítah, a prospective research location in Jezero crater, at a record speed of 5 meters per second.

This was a very risky flight, straining the navigation system, which assumed flat ground while Séítah had uneven sand dunes. This was partly mitigated with the helicopter flying slower over the more challenging regions of the flight. Due to these errors, Ingenuity landed 47 m (154 ft) from the center of the 50 m (160 ft) radius airfield. This flight made Ingenuity's travel distance exceed Perseverance again, and offered chances to study places rovers would never be able to visit



Flight #9. (July 5, 2021; full real-time animation

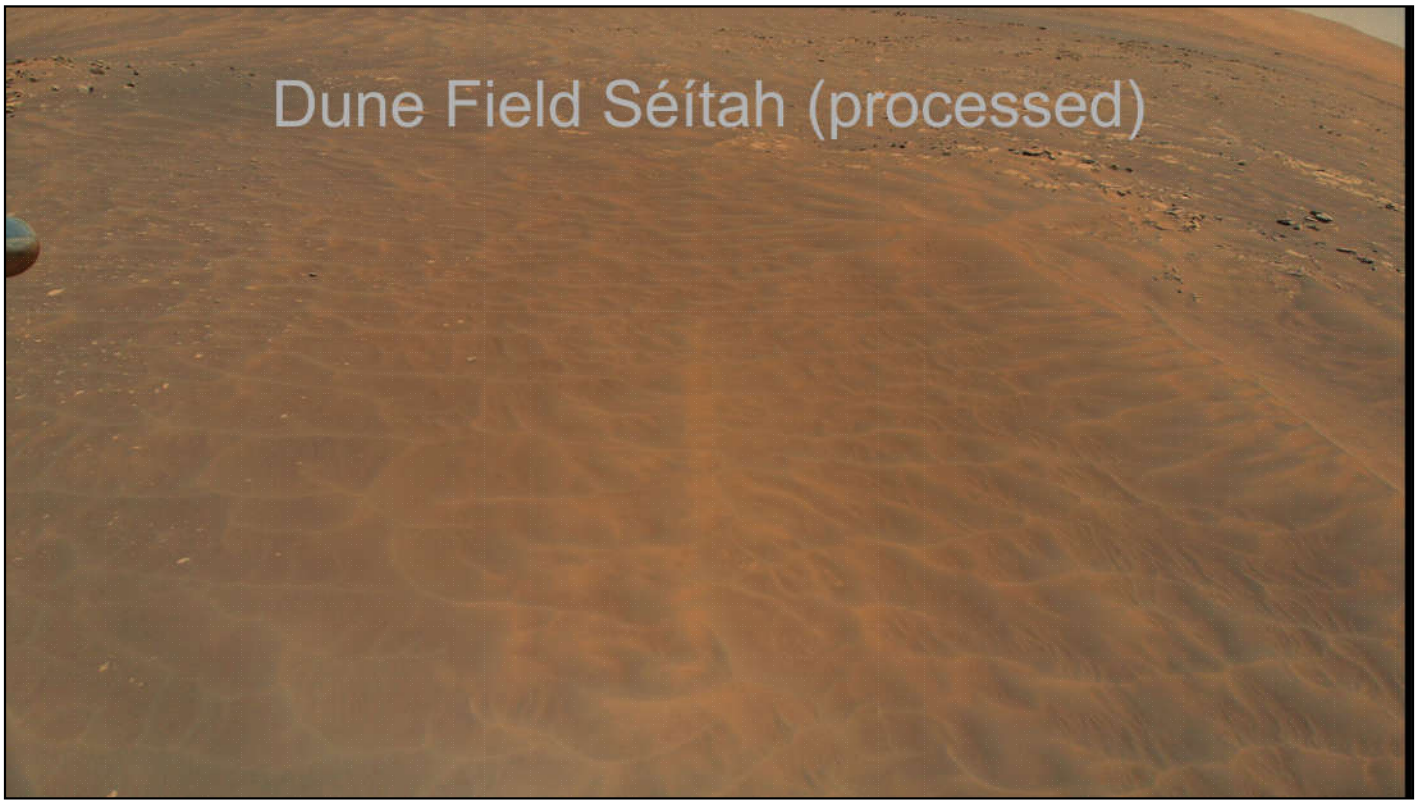
NASA - https://mars.nasa.gov/mars2020/multimedia/raw-images/?begin_sol=134&end_sol=134#raw-images

This animation of the flight 9 of Ingenuity is compiled from 193 frames shot by the navigation camera (NAV) of the helicopter, approximately 1 frame per second, from 12:33:06 through 12:35:48 local mean solar time on July 5, 2021 (sol 133 of the Perseverance rover mission). The NAV camera is mounted in the helicopter’s fuselage and points directly downward to track the ground during flight.

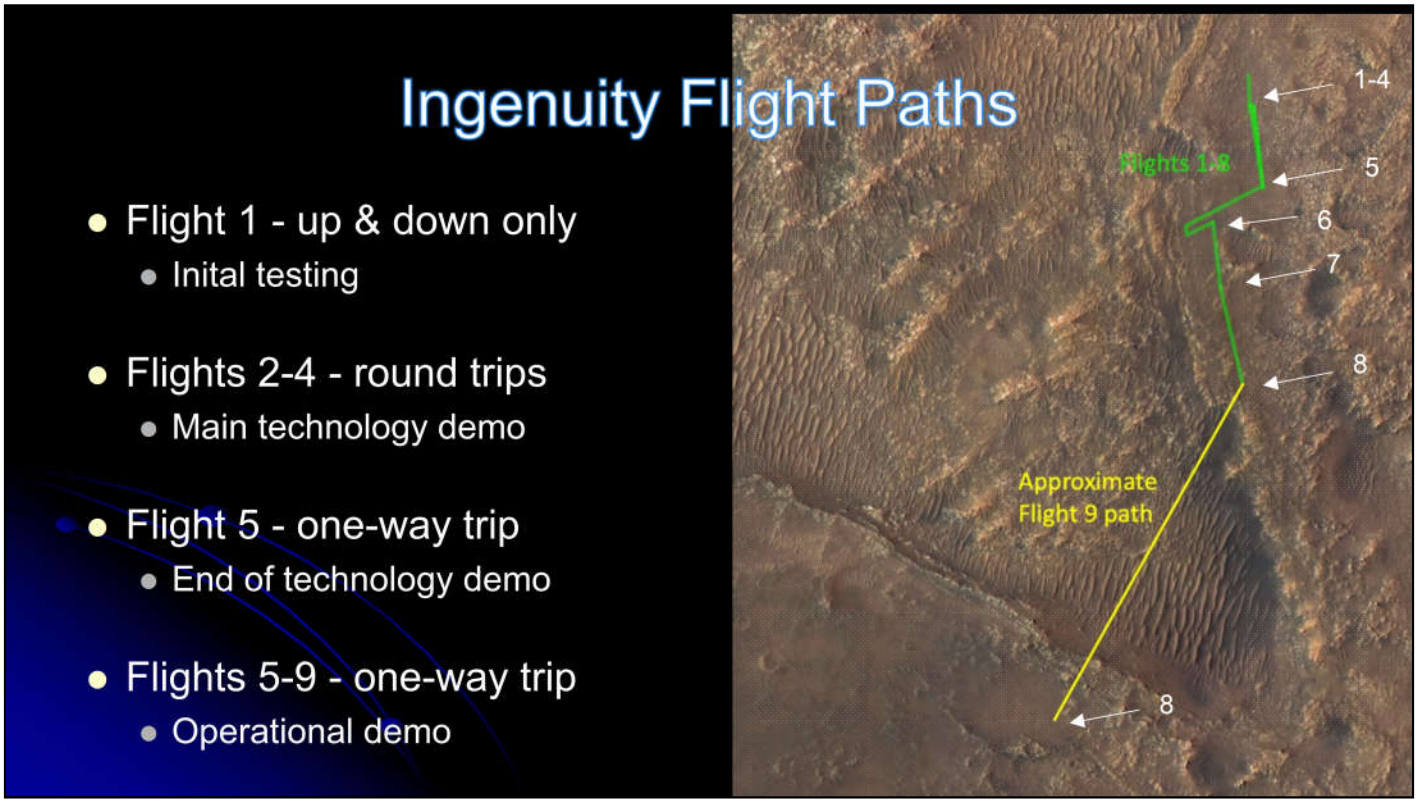
Flight #9. Flying over the Séítah (5 July 2021)

NASA - https://mars.nasa.gov/mars2020/multimedia/raw-images/HSF_0133_0678747636_233ECM_N0090001HELI00001_000085J

Ingenuity Mars Helicopter on her way across Seitah. NASA’s Ingenuity Mars Helicopter acquired this image using its high-resolution color camera. This camera is mounted in the helicopter's fuselage and pointed approximately 22 degree below the horizon. This image was acquired on Jul. 5, 2021 (Sol 133 of the Perseverance rover mission) at the local mean solar time of 12:33:33.



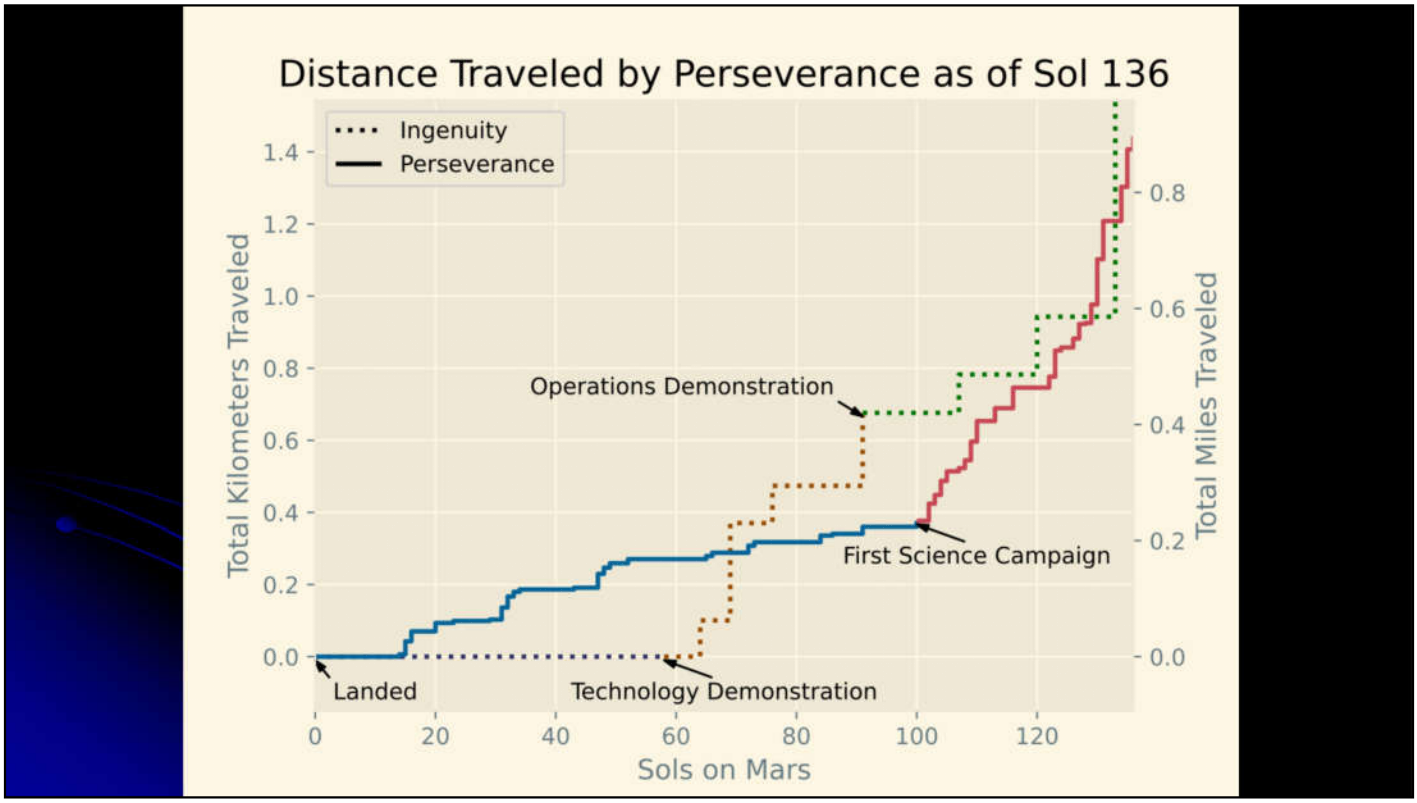
https://mars.nasa.gov/resources/26044/ingenuity-spots-dune-fields-during-ninth-flight/



Map of Ingenuity's 1-8 flights vs Ninth Flight

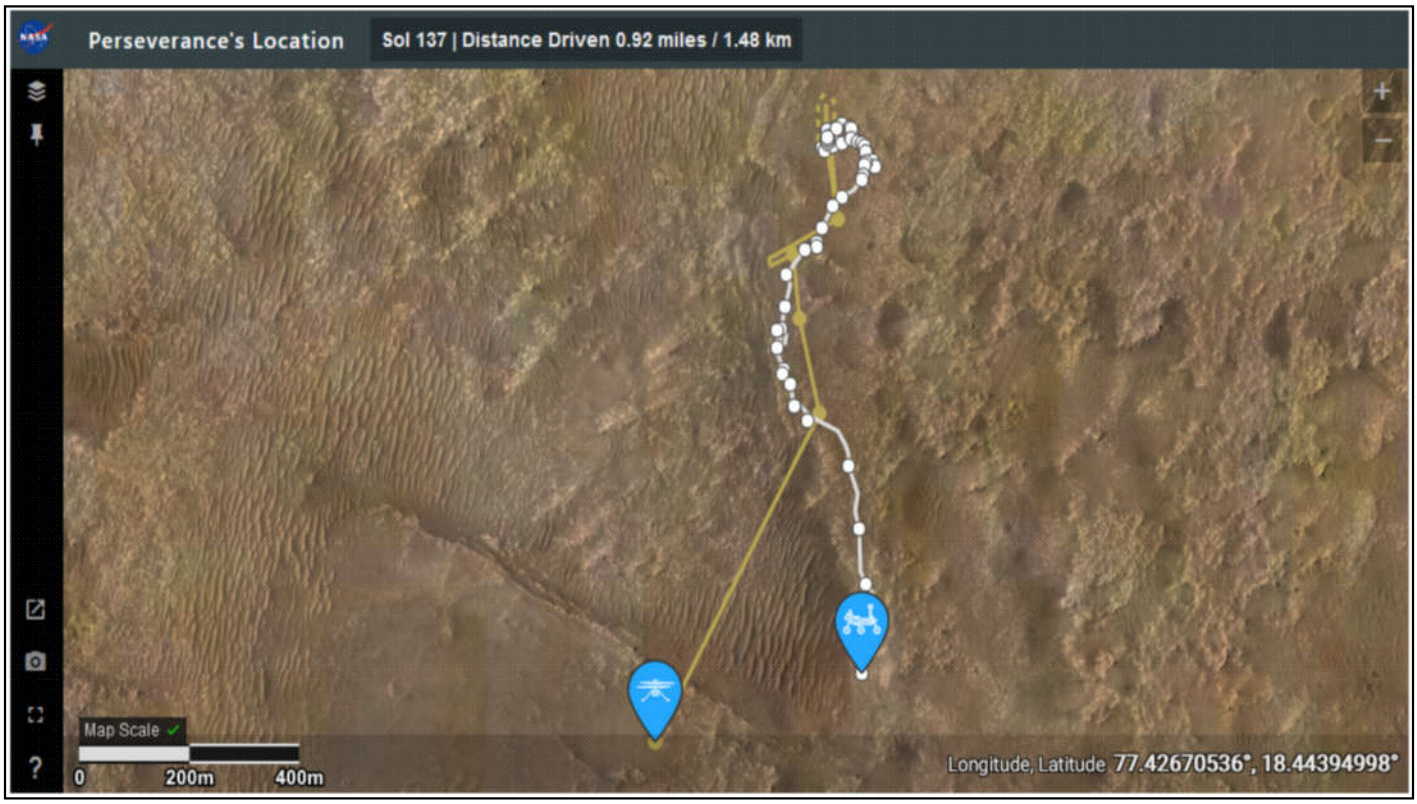
NASA/JPL - https://mars.nasa.gov/resources/26035/map-of-ingenuitys-ninth-flight/

This map shows the approximate flight path of NASA's Ingenuity Mars Helicopter during its ninth flight vs 1-8 Flights, on July 5.



https://en.wikipedia.org/wiki/Ingenuity_(helicopter)#/media/File:Perseverance_Distance_Graph.svg

Distance is vertical. Each time Ingenuity crosses Perseverance going upwards, Ingenuity has traveled farther at that point than Perseverance.



https://mars.nasa.gov/mars2020/mission/where-is-the-rover/

Perseverance Rover Location: This interactive map shows the landing site for NASA's Perseverance rover within Jezero Crater. Perseverance landed on Feb. 18, 2021. The map also shows the location of the Mars Helicopter.

NASA/JPL-Caltech - https://photojournal.jpl.nasa.gov/jpeg/PIA24440.jpg

Signing the book: https://mars.nasa.gov/resources/25844/pilot-logs-first-flight-on-another-world/

PIA24440: Ingenuity Mars Helicopter Pilot's Logbook https://photojournal.jpl.nasa.gov/catalog/PIA24440 This image of the official pilot's logbook for the Ingenuity Mars Helicopter flights — the "Nominal Pilot's Logbook for Planets and Moons" — was taken at NASA's Jet Propulsion Laboratory in Southern California on April 19, 2021, the day of Ingenuity's first historic flight. Pilot logbooks are used by aviators to provide a record of their flights, including current and accumulated flight time, number and locations of takeoffs and landings, as well as unique operating conditions and certifications.

Ingenuity Links

- https://mars.nasa.gov
- https://mars.nasa.gov/mars2020/ Perseverance
- https://mars.nasa.gov/technology/helicopter/ Ingenuity
- https://en.wikipedia.org/wiki/Ingenuity_(helicopter)