

Future Flight on Mars: Ingenuity and the ROAMX Project

Ames Research Center Summer Speaker Series
10 August 2021

Haley Cummings
NASA Ames Rotorcraft Aeromechanics Branch (Code AV)



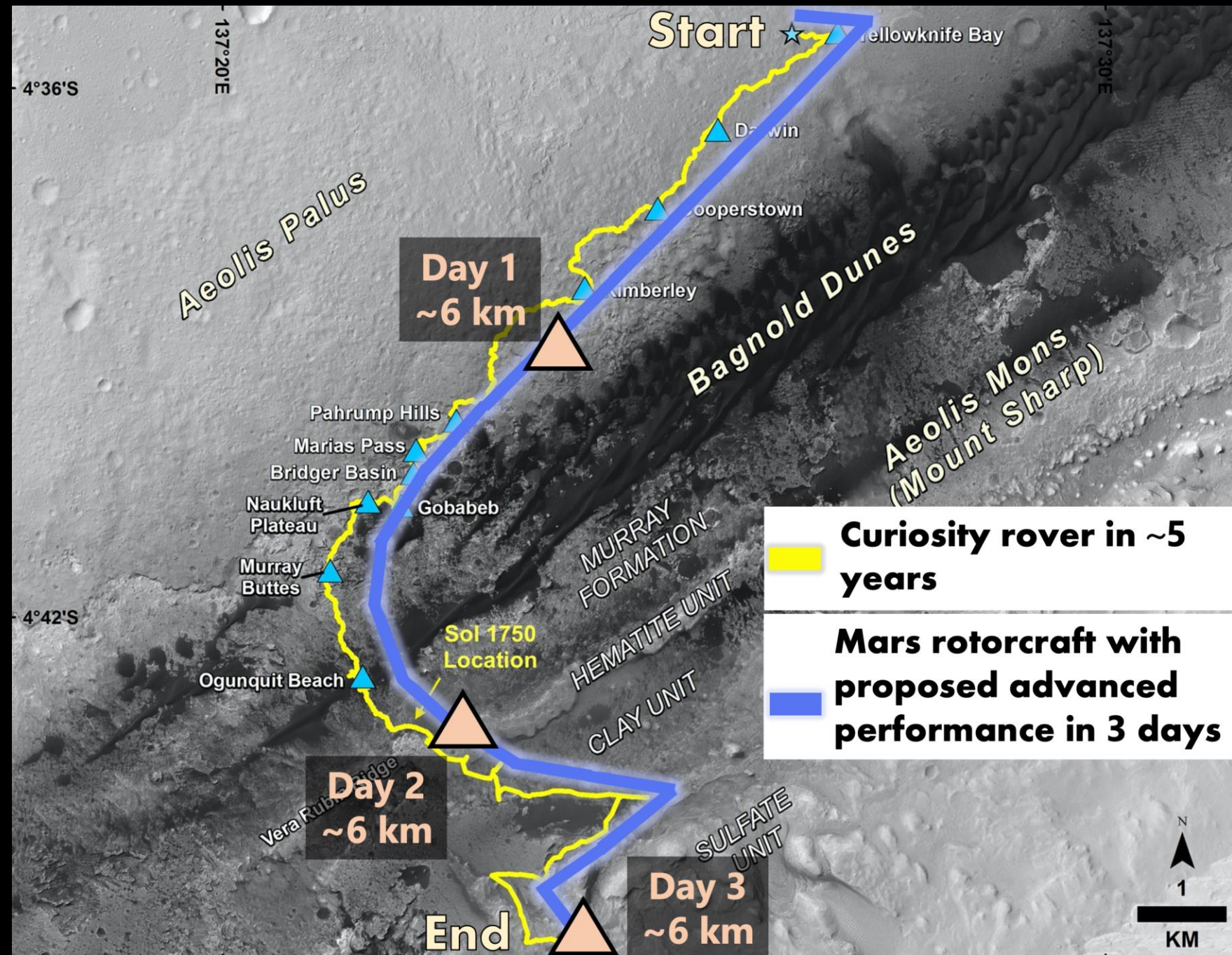
Outline

- Flying on Mars
- Ingenuity and Ames Contributions
- ROAMX
- Future Planetary Rotorcraft



WHY fly on Mars?

- Rovers are limited to relatively flat terrain
- Satellites have low resolution
- Rotorcraft can bridge the gap between the two





Why is it hard to fly on Mars?

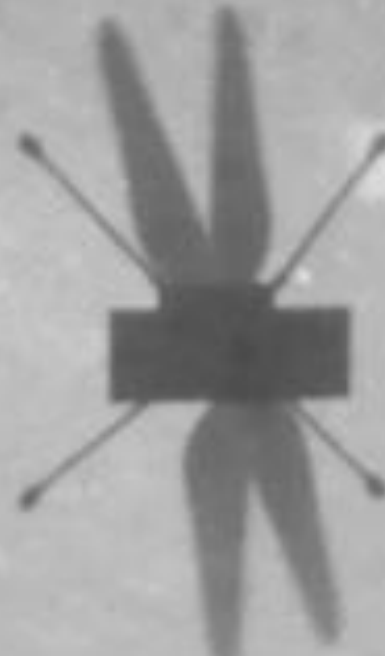
Challenges of Flying On Mars

Challenge
Autonomous Navigation
Flight Dynamics and Control
Weight Reduction
Aerodynamic Performance



Challenges of Flying On Mars

Parameter	Earth	Mars
Density (kg/m ³)	1.225	0.017
Temperature (C)	15	-50
Air composition	N ₂ -based	CO ₂ -based
Sound speed (m/s)	340.3	233.1

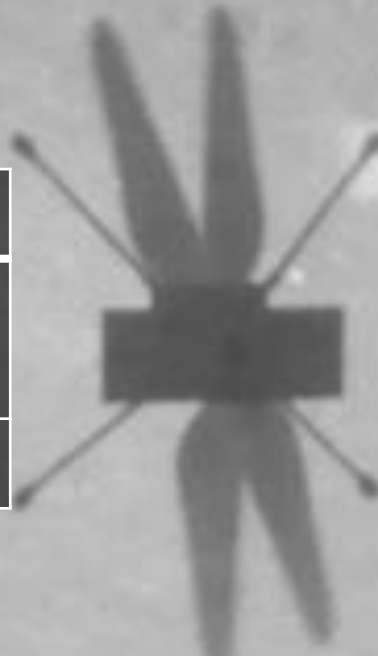


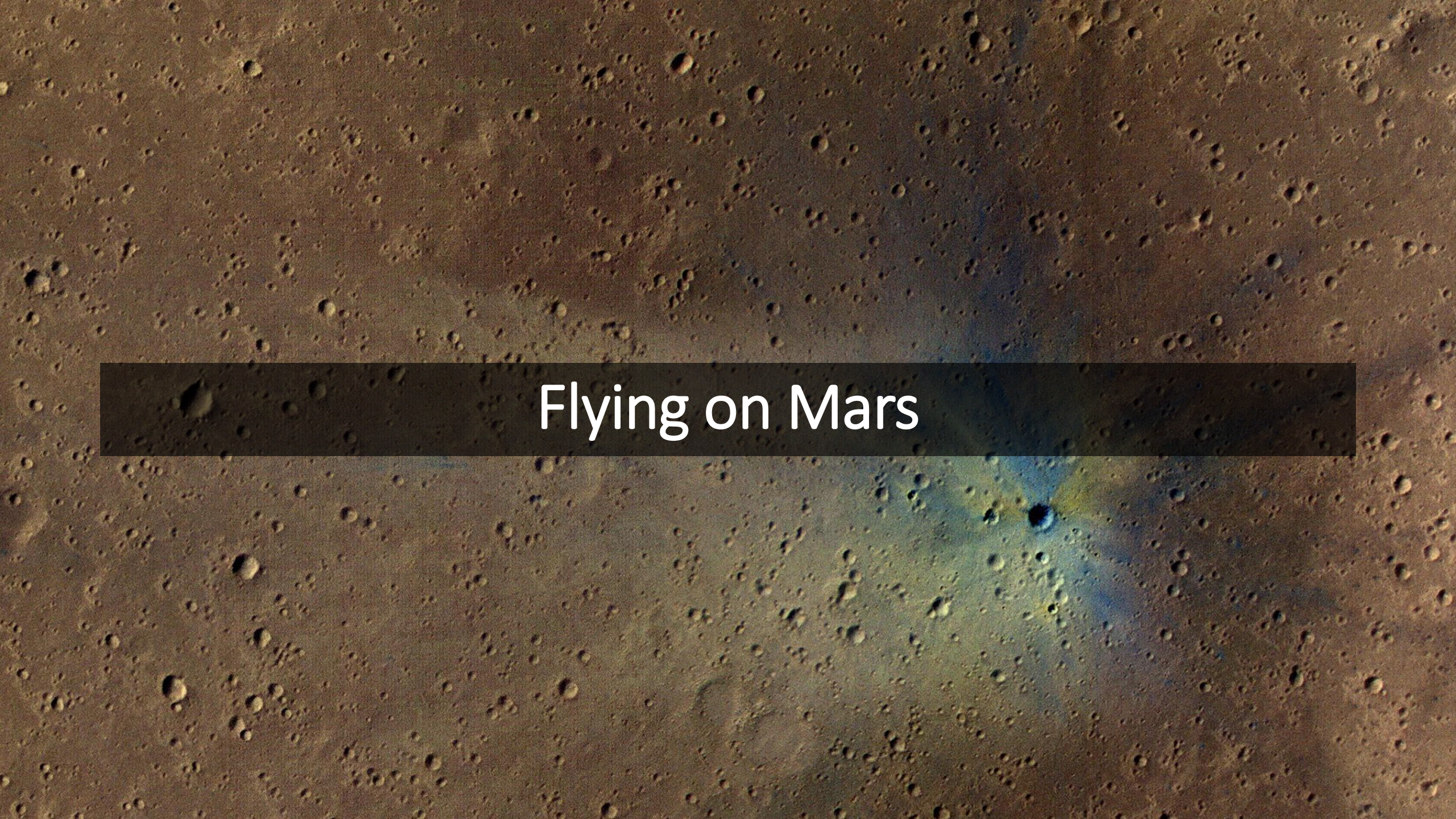
Challenges of Flying On Mars

Parameter	Earth	Mars
Density (kg/m ³)	1.225	0.017
Temperature (C)	15	-50
Air composition	N ₂ -based	CO ₂ -based
Sound speed (m/s)	340.3	233.1



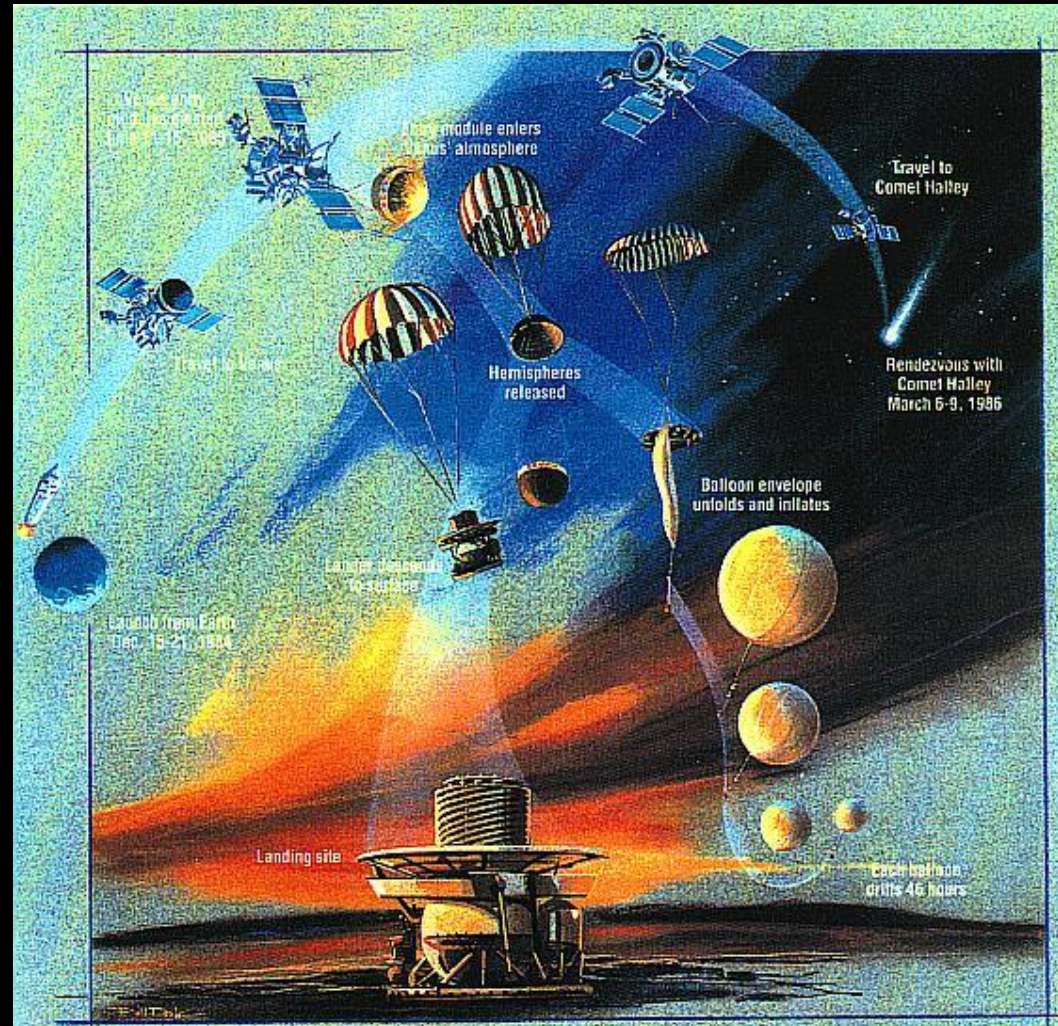
Parameter	Earth	Mars
Reynolds number (rotorcraft flight)	$\sim 10^6$	$\sim 10^4$
Tip Mach number	~ 0.6	0.7-0.95





Flying on Mars

The “First” Planetary Aerial Vehicles



Soviet Union's Vega I and II missions successfully flew two small pressurized balloons at an altitude of ~54 km in the atmosphere of Venus in 1985 Source:
<http://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1984-128F>

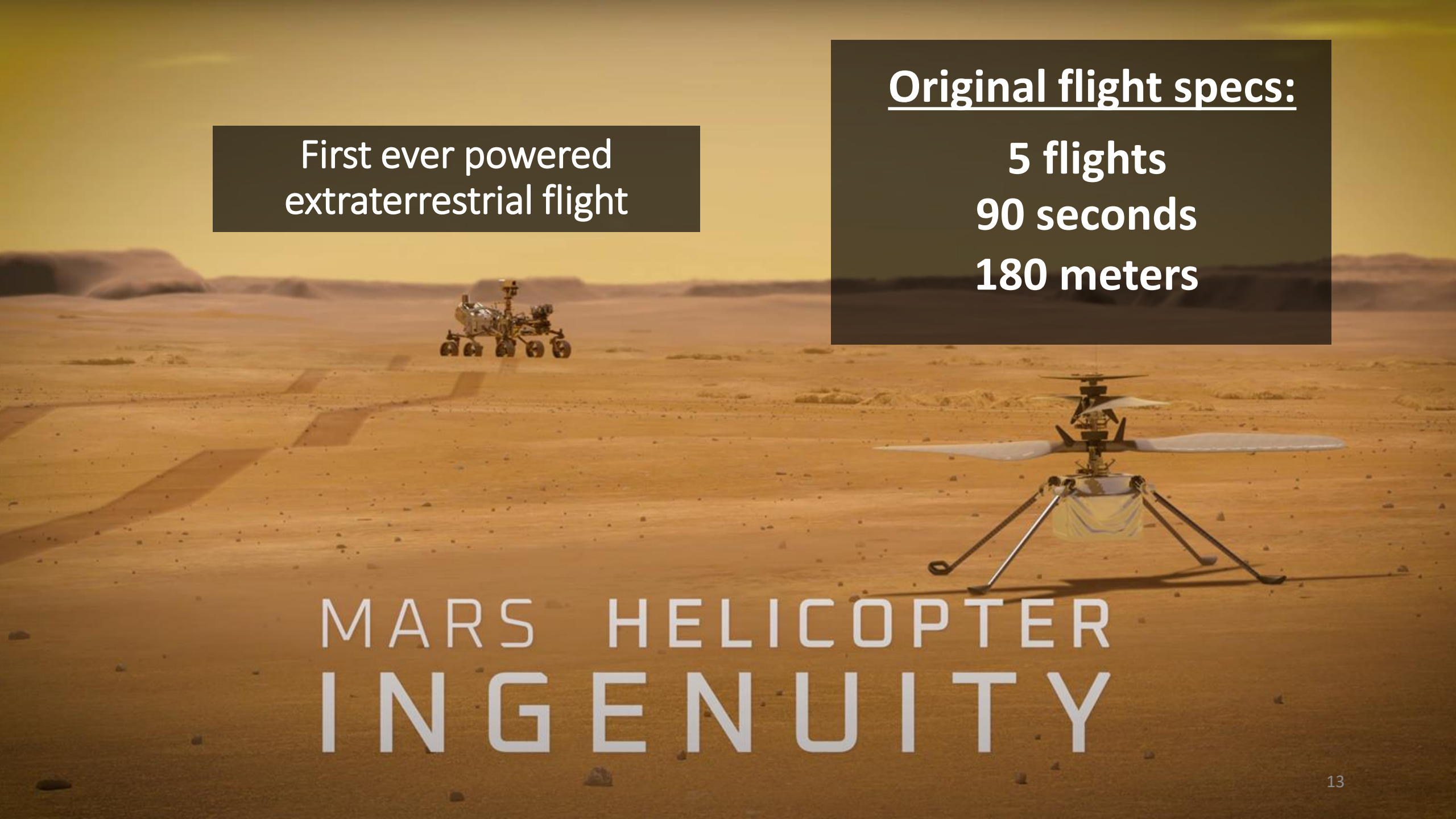
Mars Airplanes



Reed's (DFRC) "Mini-Sniffer" (hydrazine mono-propellant reciprocating engine)
Source: <http://www.dfrc.nasa.gov/gallery/photo/Mini-Sniffer/Large/index.html>

Mars Rotorcraft Research at Ames: 1997-Present



The background image shows the Martian surface with a reddish-orange hue. In the foreground, the Mars Helicopter Ingenuity is positioned on the right, showing its four rotors and landing legs. In the middle ground, the Mars Rover Curiosity is visible on the left, with its six wheels and various instruments. The horizon is marked by low, rolling hills under a hazy sky.

First ever powered
extraterrestrial flight

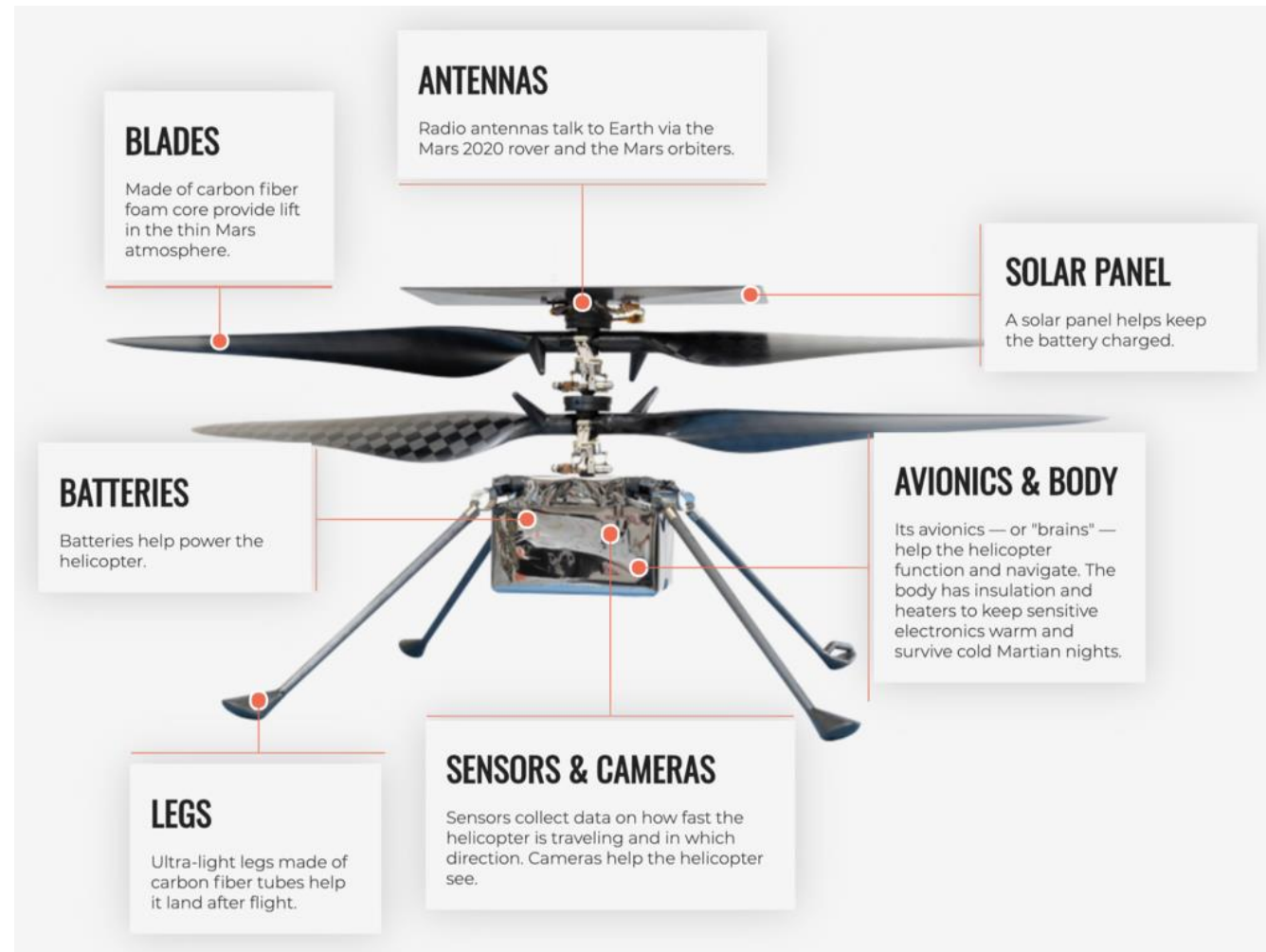
Original flight specs:

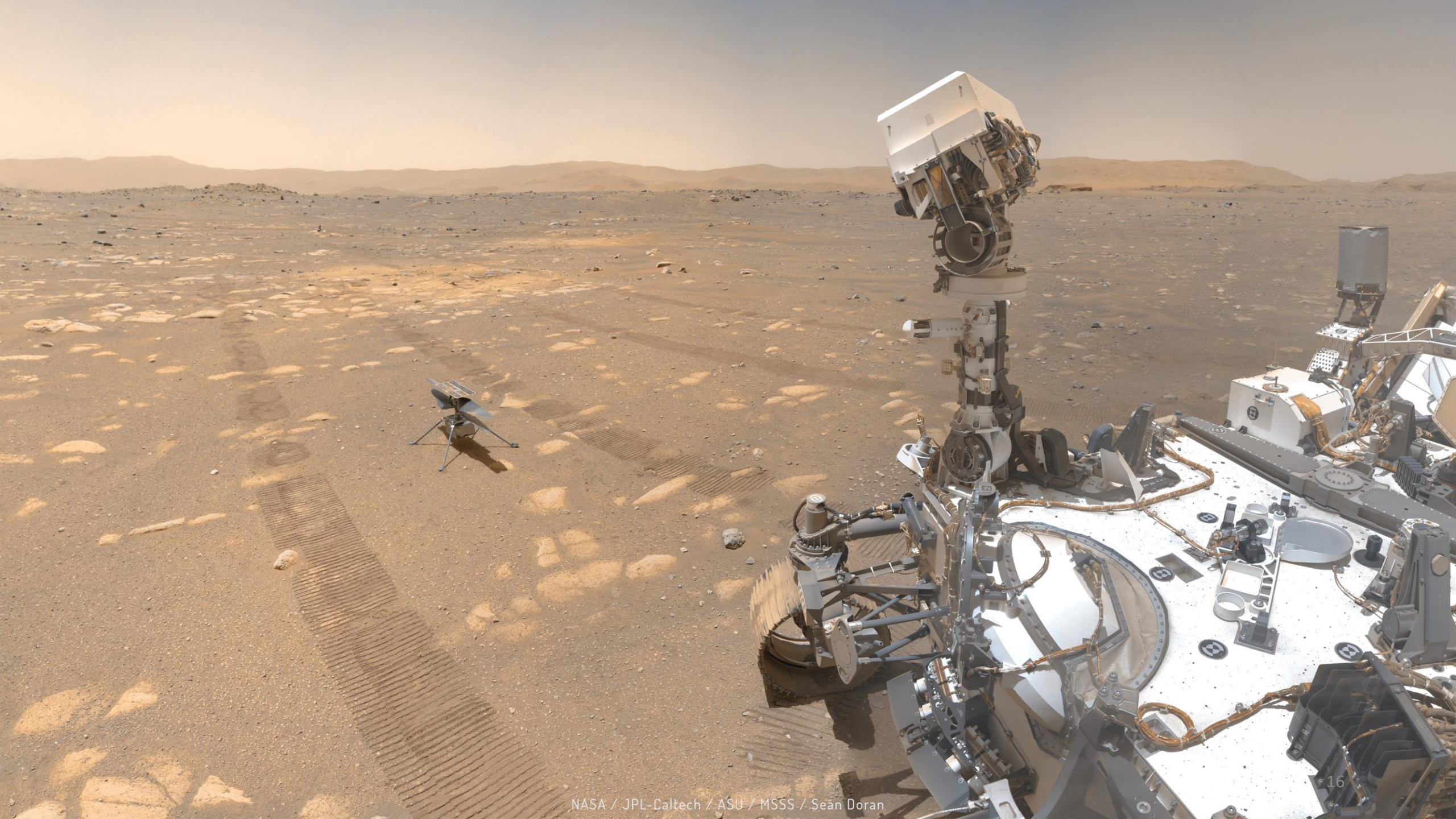
5 flights
90 seconds
180 meters

MARS HELICOPTER INGENUITY

“Kick-off” Meeting at Ames in 2015



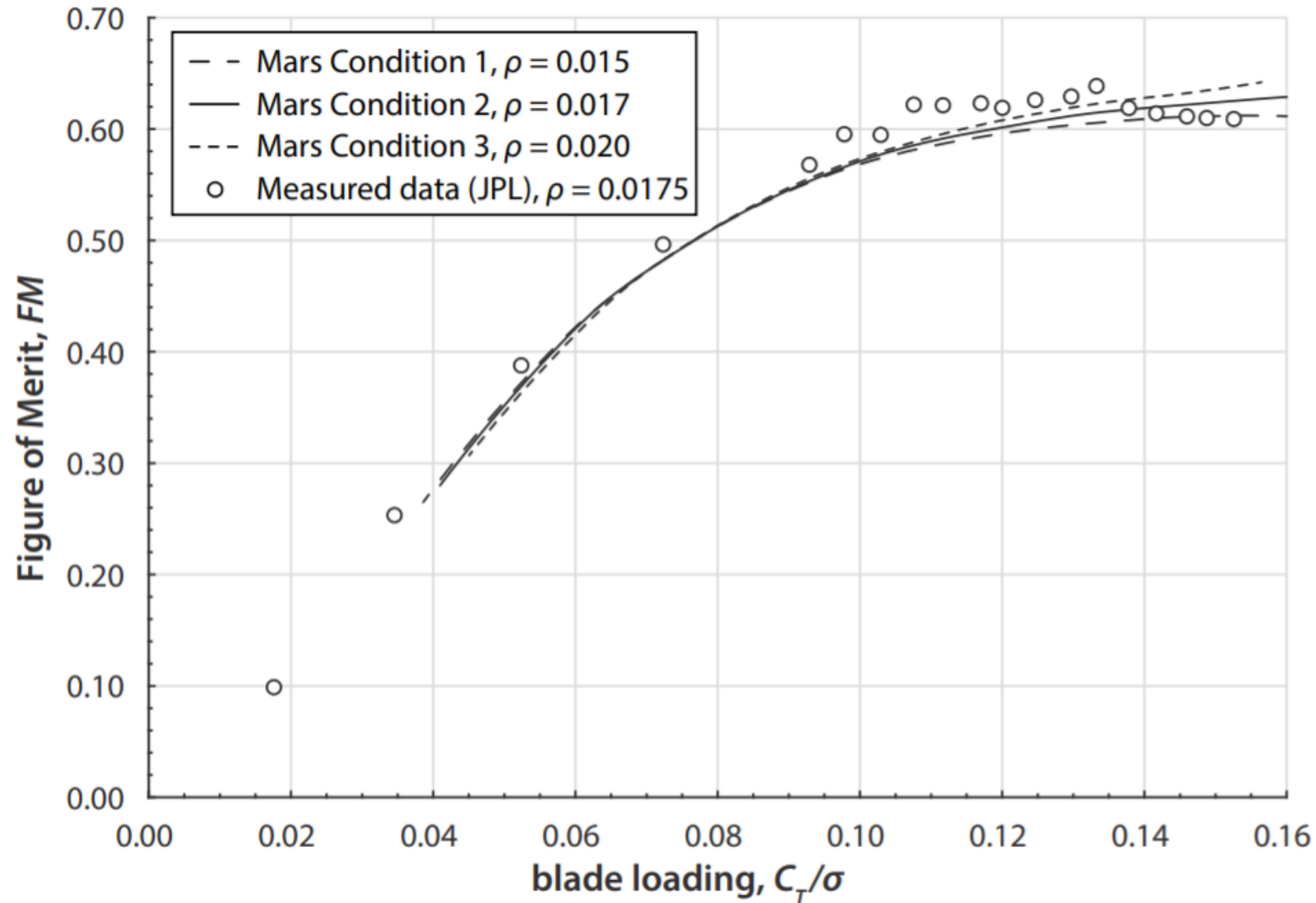




Ames Tasks in Support of Ingenuity: Aeroperformance

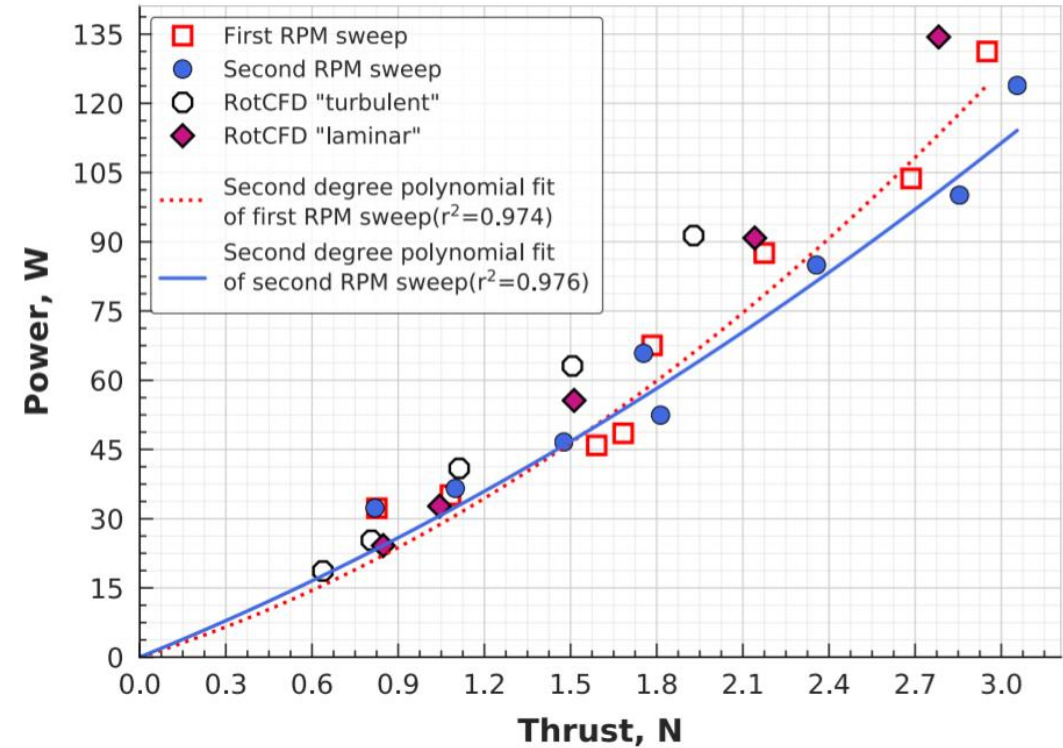
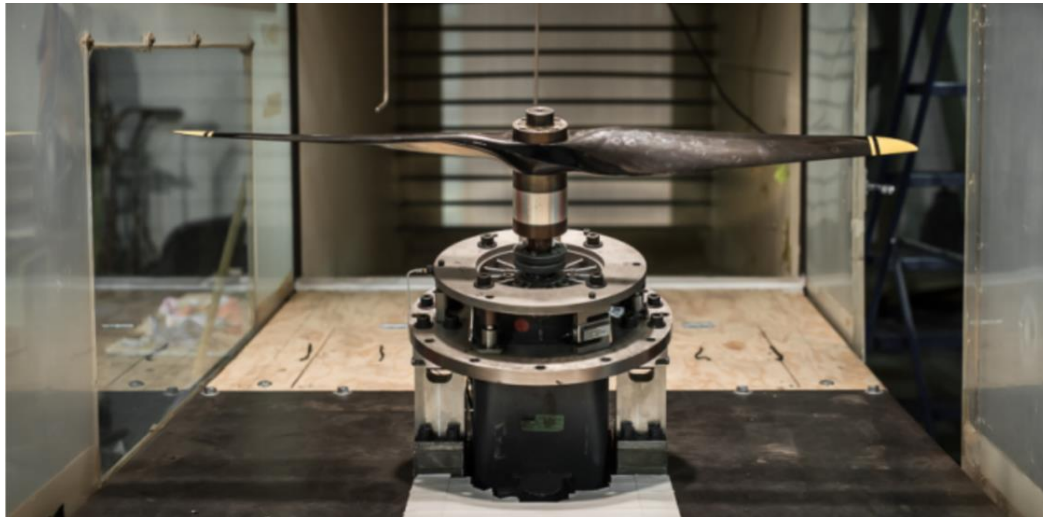
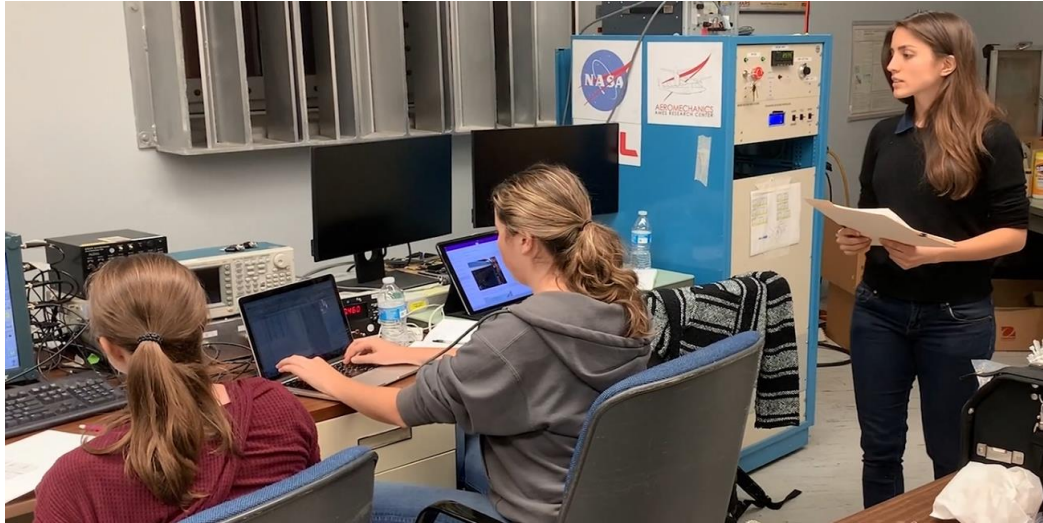
- Rotor design- and peer-review support
- Airfoil characteristics 2D CFD modeling
- Comprehensive rotorcraft analysis performance modeling for hover and forward flight
- Solar array aero interaction and sizing analysis in hover
- In-parallel inhouse “first ever” surrogate Mars rotor edgewise forward flight testing in the Mars wind tunnel in Ames N242 large low-pressure chamber; correlation of experimental results with CFD predictions

Comprehensive Rotorcraft Analysis Correlation Studies



Source: Koning, W. J. F.,
Johnson, W., Grip, H.,
"Improved Mars Helicopter
Aerodynamic Rotor Model for
Comprehensive Analyses,"
Presented at the 44th
European Rotorcraft Forum,
Delft, the Netherlands, 18-21
September, 2018.

Surrogate Rotor Experimental Testing and Validation

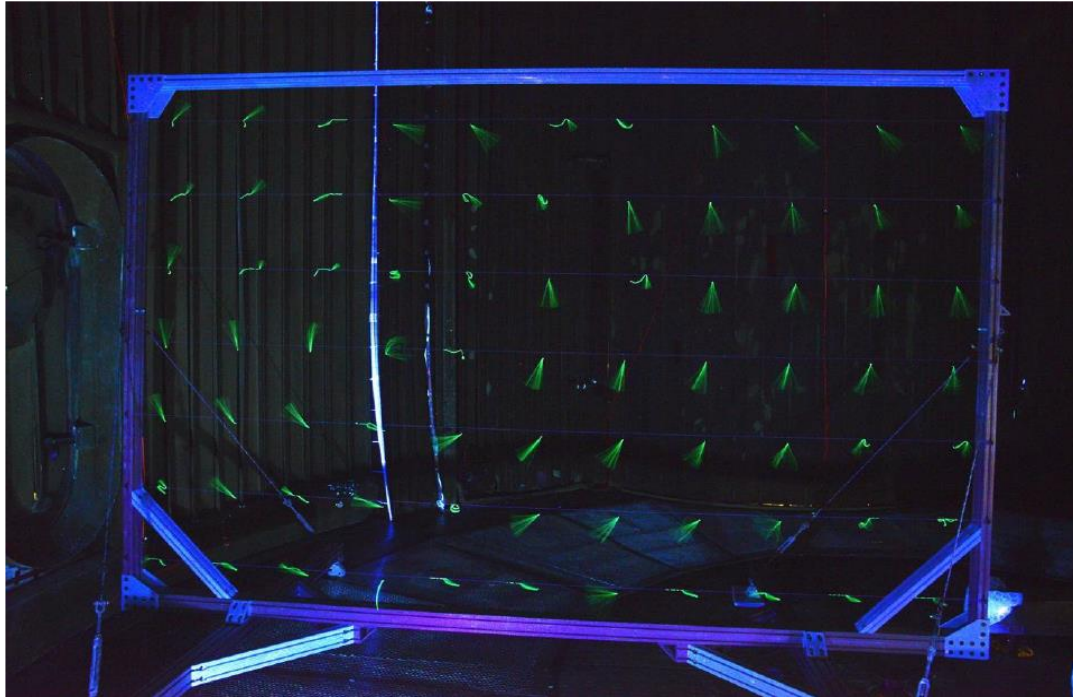


Source: Perez Perez, B.N., "Forward Flight Rotor Performance at Martian Atmospheric Densities and Sensitivity to Low Reynolds Numbers," Presented at the VFS Aeromechanics for Advanced Vertical Flight Technical Meeting, San Jose, CA, January 21–23, 2020

Facility Aero Interference Effects

- Analytical/CFD study of flow recirculation of rotor systems in JPL 25-ft Space Simulator and other NASA large vacuum chambers
- Experimental study of flow recirculation of rotor systems in JPL 25-ft Space Simulator
- Development of a time-dependent analytical (tuned with CFD results) "wind" model

Ames Conducted Experimental Evaluation of JPL 25-ft Space Simulator



Sys-ID Analysis and Flight Control Efforts

- Sys-ID analysis/support of hover characteristics using 'swing arm' for full-scale prototype and engineering development model (EDM-1)
- Sys-ID forward flight testing using JPL/Caltech ducted-fan array of flight model

Ingenuity Mars Helicopter Development Team

- NASA JPL
 - MiMi Aung, Bob Balaram, Havard Grip, Daniel Scharf, Joe Melko, Amiee Quon, Teddy Tzanetos...
- NASA Ames
 - William Warmbrodt, Wayne Johnson, Larry Young, Carlos Malpica, Alan Wadcock, Michelle Dominguez, Natasha Schatzman, Geoffrey Ament, Eduardo Solis, Witold Koning, Natalia Perez Perez, Shannah Withrow-Maser, Farid Haddad, J. Ken Smith...
- NASA Langley
 - Susan Gorton (Revolutionary Vertical Lift Technology Project), Brian Allan, Norm Schaeffler...
- AeroVironment
 - Ben Pipenberg, Matt Keennon, Chris Bang...



Rotor Optimization for the Advancement of Mars eXploration (ROAMX)

Early Career Team



Haley Cummings
Principal Investigator



Witold Koning
Computational Lead



Natalia Perez Perez
Experimental Lead



Shannah Withrow-Maser
Mars Science Helicopter Vehicle
Systems Lead

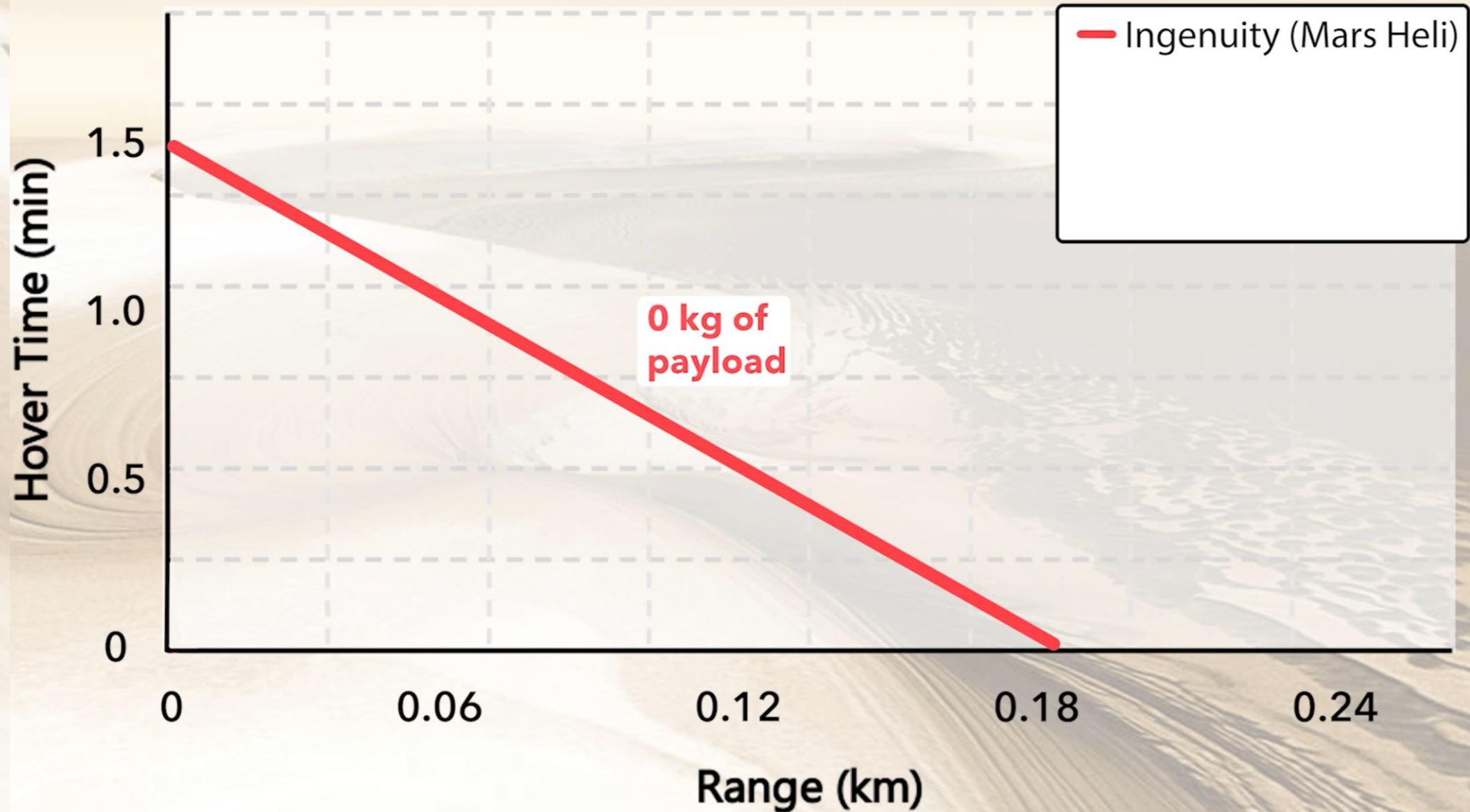


Joshua Bowman
Experimental Team

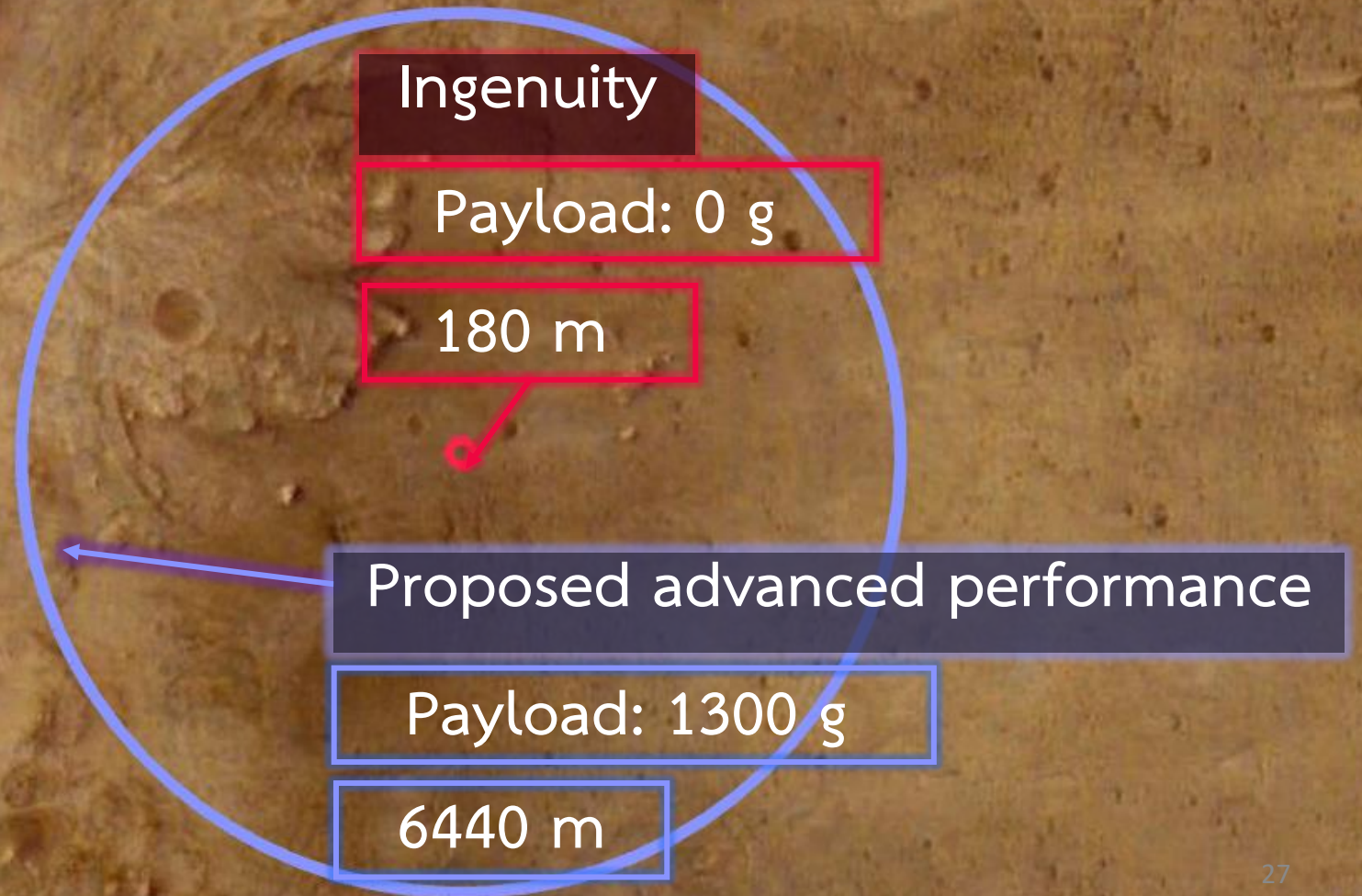


Lauren Wagner
Experimental Team

Mission Capabilities Enabled by ROAMX Work



Range Increase with ROAMX Blade





Belva

Perseverance
Sol Range: 0.1 km

Three Forks

★ Octavia E. Butler Landing Site

Seitah-N

Seitah-S

CF-Fr

Raised Ridges

Advanced Mars Helicopter
Sortie Range: 4 km
2 min
hover
1.3 kg
payload

Perseverance
Science Mission #1
Perseverance
Science Mission #2

Scale
500m 1000m 2km

Longitude, Latitude 77.46542491°, 18.44684159°

JE

28

Enabled Science

- Mapping of Mars
- Polar Science
- Atmospheric Science
- Subsurface Geophysics



Examples of Science Instruments	Weight (g)
VNIR spectrometer	500
Tunable spectrometer	300
Magnetometer	20
Environment sensors (temp, humidity, wind, etc)	100
Camera for imaging	250
Soil sensors	100



Dragonfly $Re_c = 5,000$



Cambered plate $Re_c \sim 10^3 - 10^4$



Pigeon $Re_c = 50,000$



Preliminary ROAMX $Re_c \sim 10^3 - 10^4$

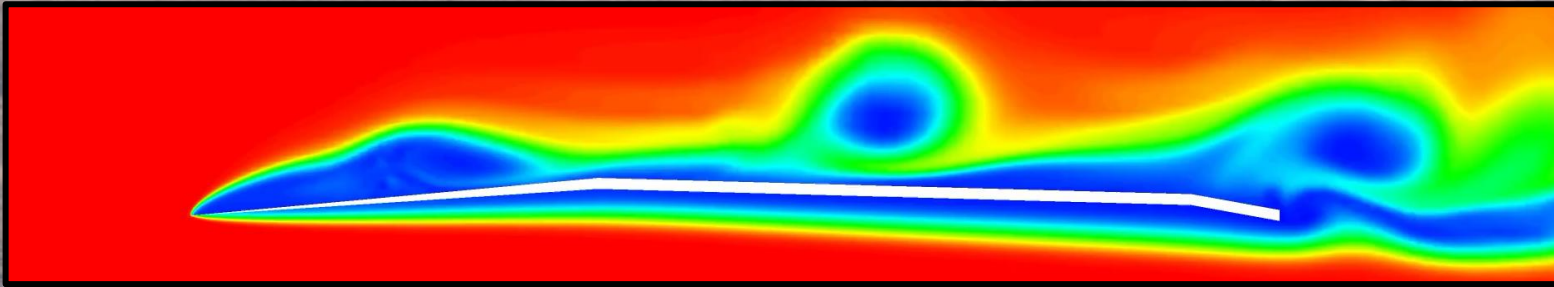


Ingenuity (outboard) $Re_c \sim 10^4$

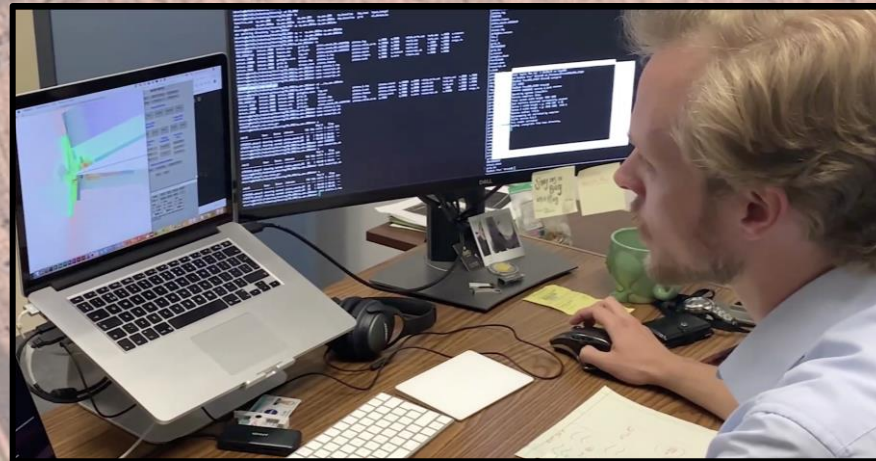
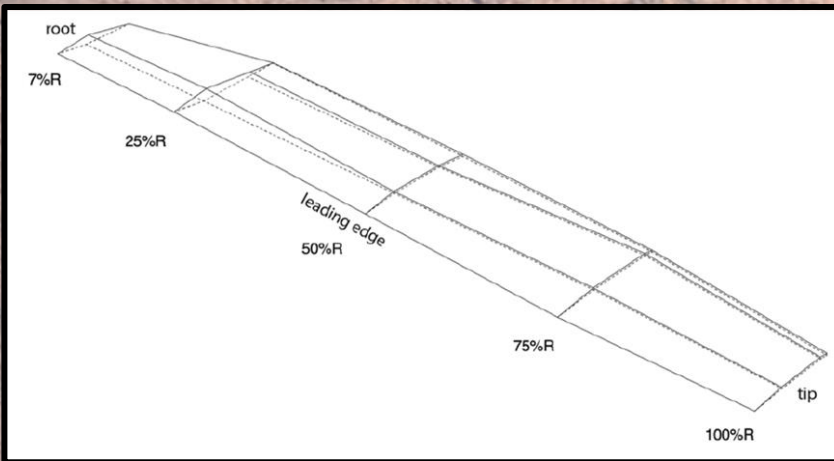


Eppler 193 $Re_c = 100,000$

Computational Rotor Optimization



- Develop optimized airfoils for different radial stations.
- Optimize blade planform.
- Generate 3D CFD model to compare with experiments.



Computational Rotor Optimization

- Airfoil optimization code completed:

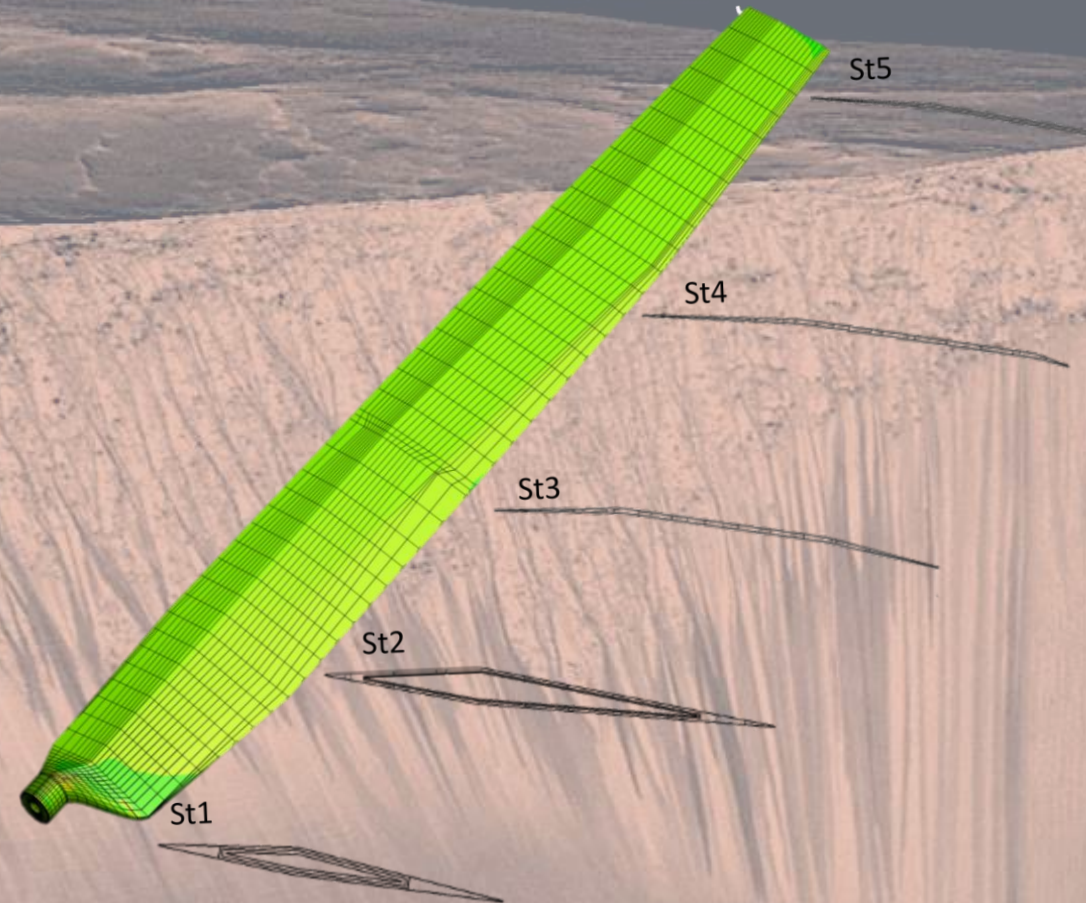
Performance increase compared against Ingenuity	
Key Performance Parameters (KPP)	Change (%)
Design CT/σ	+20
FM at design CT/σ	+7
Design M_{tip}	+15
Power at $M_{tip}=0.8$ and 30 m/s cruise speed**	-16
Airfoil $(Cl/Cd)_{0.75R}$	+25

Current results show >30% drag reduction at equal lift

- Dual objective mode: maximize lift, minimize drag
- Triple objective mode: maximize lift, minimize drag, maximize structural property of choice

Computational Rotor Optimization

- Write code to use optimized families of airfoils to optimize rotor:
 - Vary airfoil choice, blade planform, and blade twist
 - Optimize for thrust and power simultaneously
- Compare comprehensive analysis with full 3D high-fidelity CFD:



Experimental Validation



~1% Earth's
atmospheric density

- Validate simulations through experimentation
- Simulate Mars flight conditions
- Test in a vacuum chamber
- Match Re and M number

Credit: Google Earth

Experimental Validation

For the experiment:

- Rotor diameter: 1.2 meters
- Tip Mach number 0.7 to 0.95
- Hover flight
- Vary collective angle

Rotor performance: thrust, torque, RPM, collective angle and atmospheric conditions



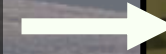
Sensors, motor, controllers, and hardware



Hover stand design



Rotors



Structural analysis

ROAMX Outcomes and Contributions

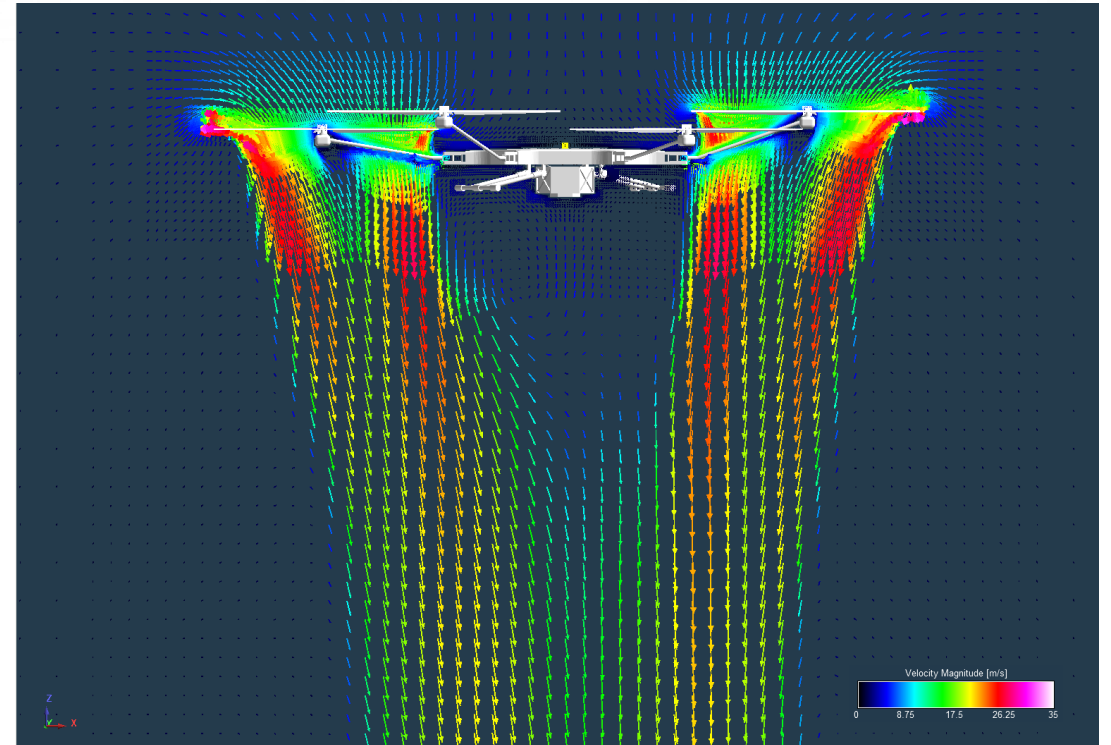
- Understanding of low-Re aerodynamics
- Optimized rotor
- Design methodology

Performance Parameter	Ingenuity (Design)	Advanced Vehicle
Range	180 m	6000 m
Scientific Payload	-	1.2 kg
Hover Time	1.5 min	3 min



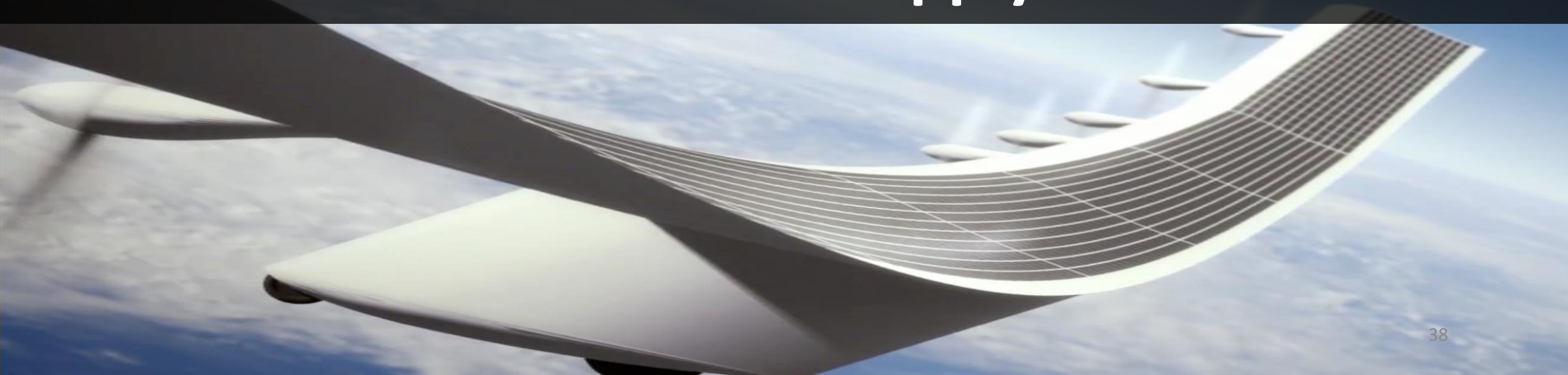
What's Next?

- Mars Science Helicopter
 - Controls design
 - Adapting reference vehicles to more specific missions
 - Test flight of Earth-based demonstrator
 - Lessons learned from Ingenuity
- The community
 - Dragonfly (2027)
 - Human presence on Mars
 - Developing technologies: batteries, swarms, processing power, solar cells
 - Other flight configurations
 - Application of Earth for high altitude flight and micro-UAVs





Terrestrial Applications where Similar Aerodynamic Conditions Apply





The Next Generation



ROAMX Contributors

- NASA Science Technology Mission Directorate
- NASA Ames: Rotorcraft Aeromechanics Branch, Code TS
- NASA Langley
- NASA Jet Propulsion Laboratory
- University of Maryland
- AeroVironment, Inc
- Tohoku University



Questions

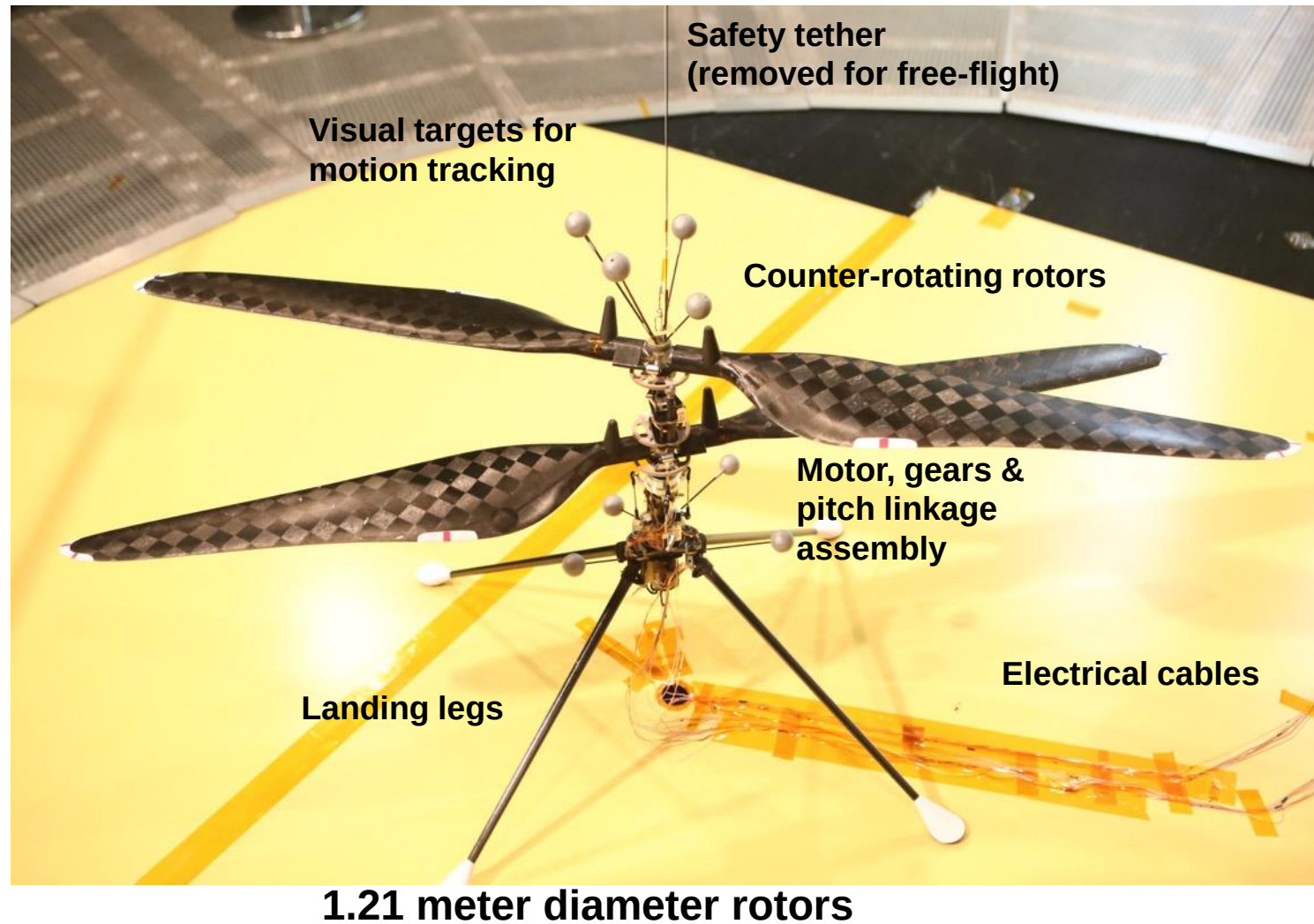


Backup Slides

Demonstration of Lift



Full-sized Rotor Mars Helicopter Prototype



Free Flight

Free Flight Demonstration
May 31, 2016