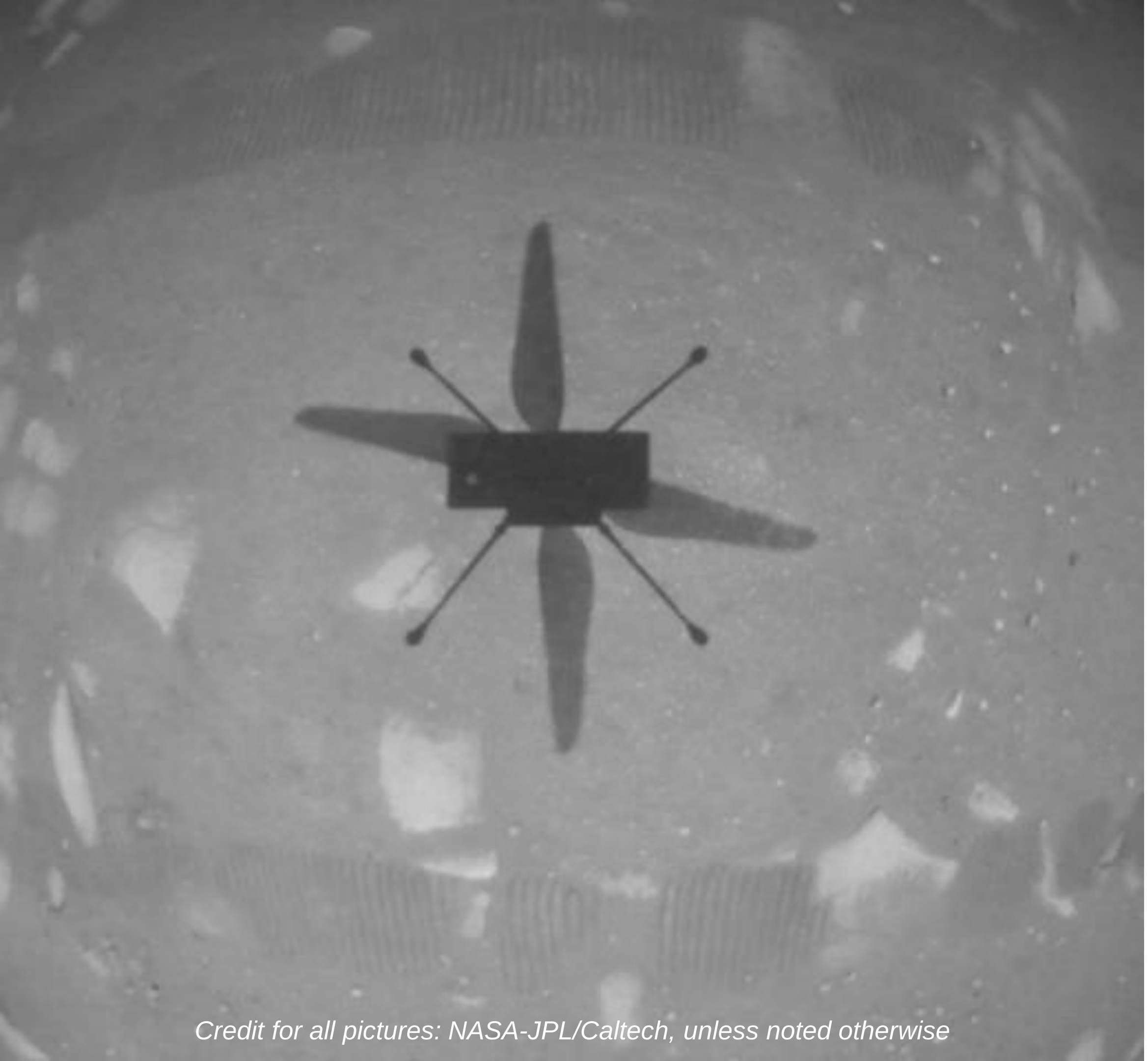

Credit for all pictures: NASA-JPL/Caltech, unless noted otherwise

ETH-UZH

Dec 2, 2021

Vision-Based Navigation for Mars Helicopters

Ingenuity & Mars Science Helicopter

Jeff Delaune, Ph.D.

Robotics Technologist – Aerial Mobility Group

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Jet Propulsion Laboratory
California Institute of Technology

The research described in this presentation was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004). © 2019 California Institute of Technology. Government sponsorship acknowledged.


The Ingenuity Team
ECOSTRESS
InSight
180
NASA JPL + NASA Ames + Aerovironment + NASA Langley

Your speaker

- Born in , with an  dream

- Education:
  - B.S. in Engineering
    - Ecole Centrale de Nantes (FR)
  - MS in Space System Engineering
    - Cranfield University (UK)
  - Ph.D in Visual Navigation / Robotics
    - Institut Superieur de l’Aeronautique et de l’Espace (FR)
    - European Space Agency @ ESTEC (NL)
    - Airbus (FR)

Your speaker (continued)

- At JPL since 2015:
  - Ingenuity: 1st flight project
    - Member of Operations Team
    - Member of the Guidance, Navigation and Control Team
    - Sensor Alignment Lead
    - Director for Navigation Field Tests
  - Research: PI, Co-I
    - Visual Navigation
      - State estimation
      - Sensor fusion: thermal, events, range,…
    - Entry, descent and landing
    - Future Mars rotorcraft

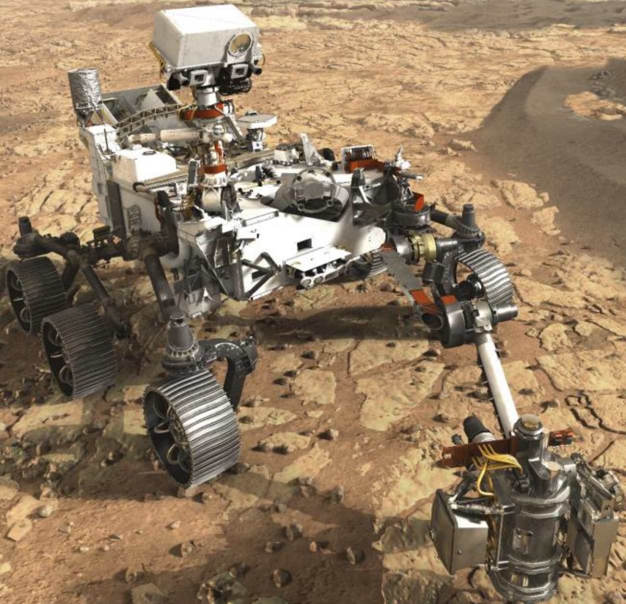
Plan

1. Ingenuity Mission Brief & Status Update
2. Ingenuity Navigation System
3. Mars Science Helicopter Navigation System

1/ Ingenuity Mission Brief & Status Update

Mars 2020 Mission Objectives

In-situ science:
Did life exist on Mars?
Was Mars habitable?

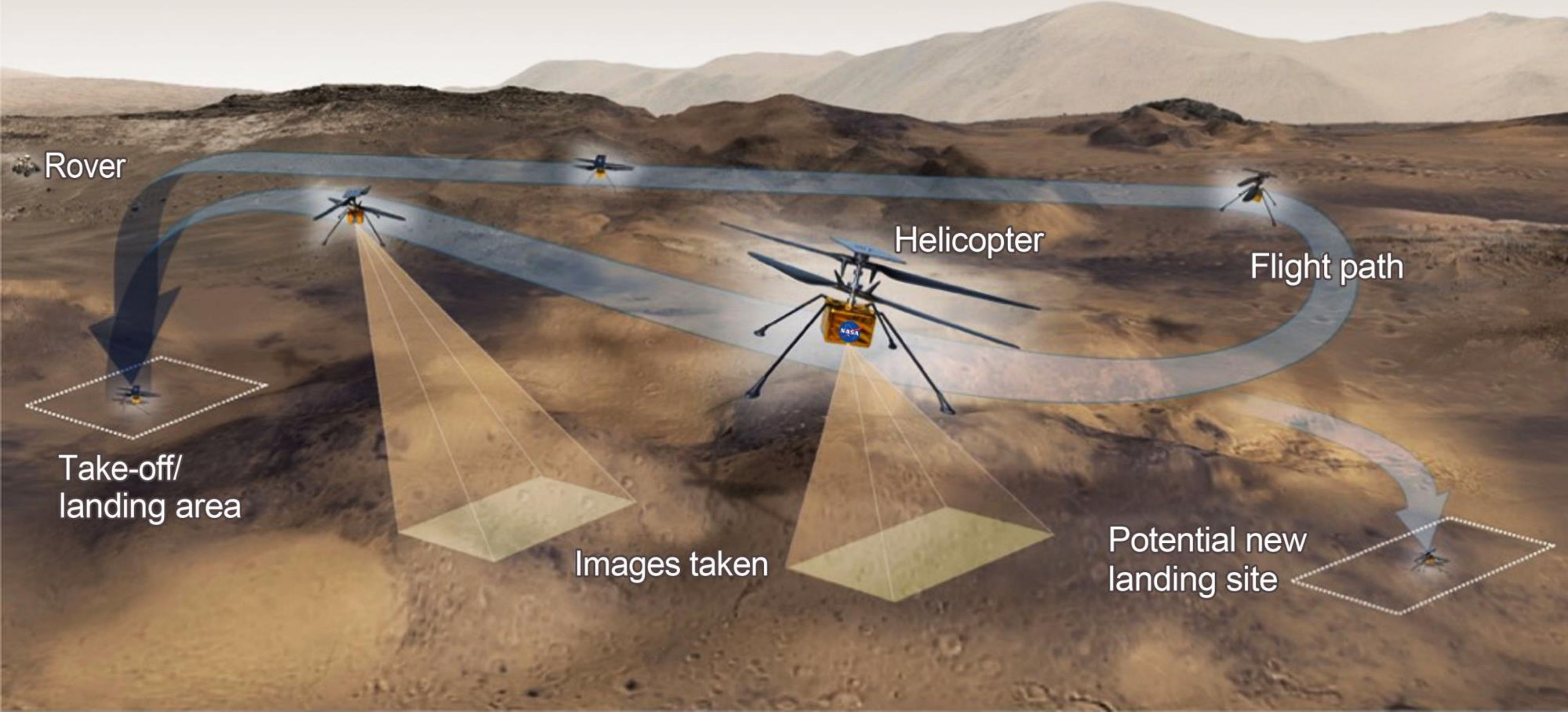


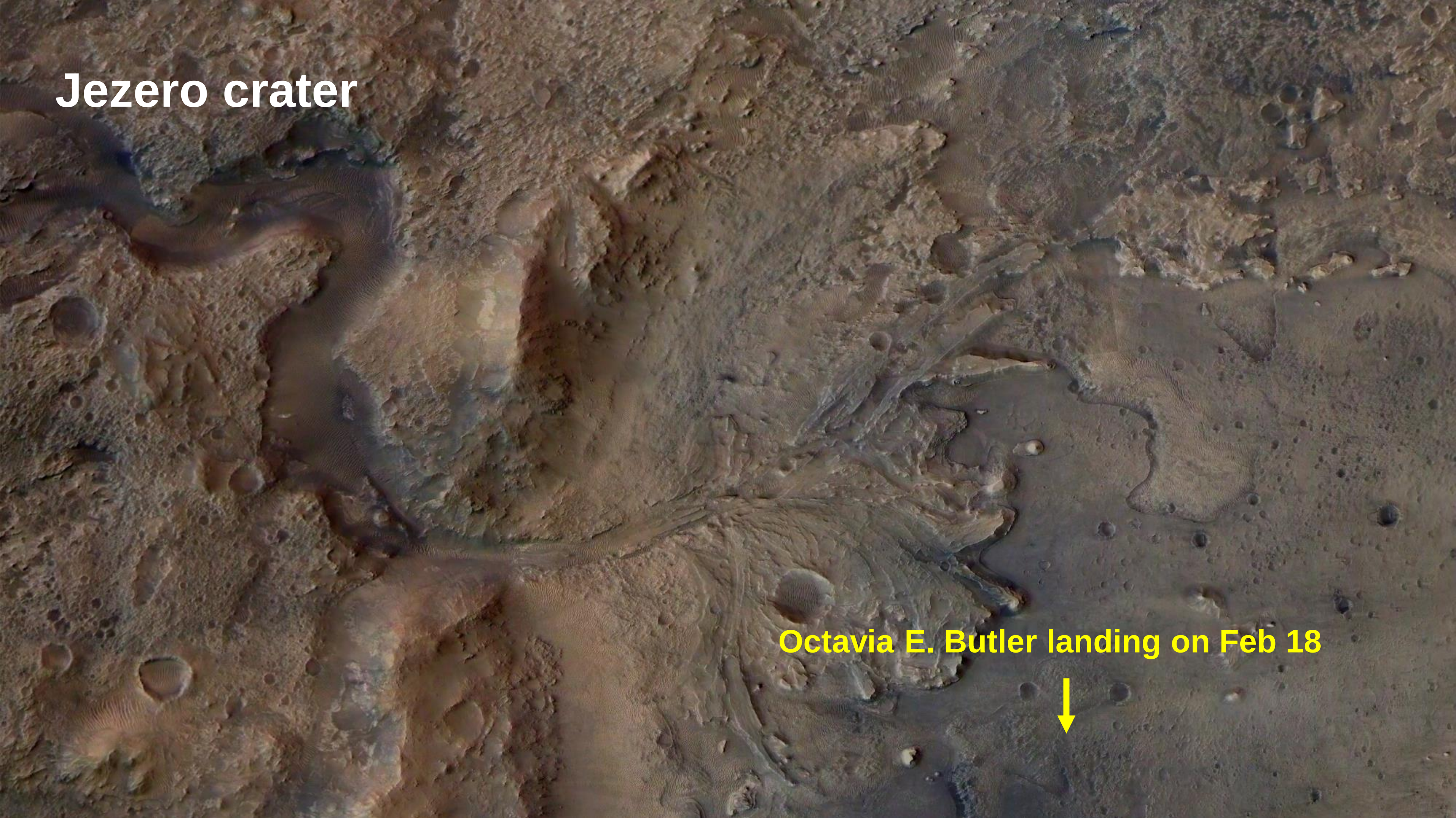
Prepare future missions:
Cache samples
Prepare for humans

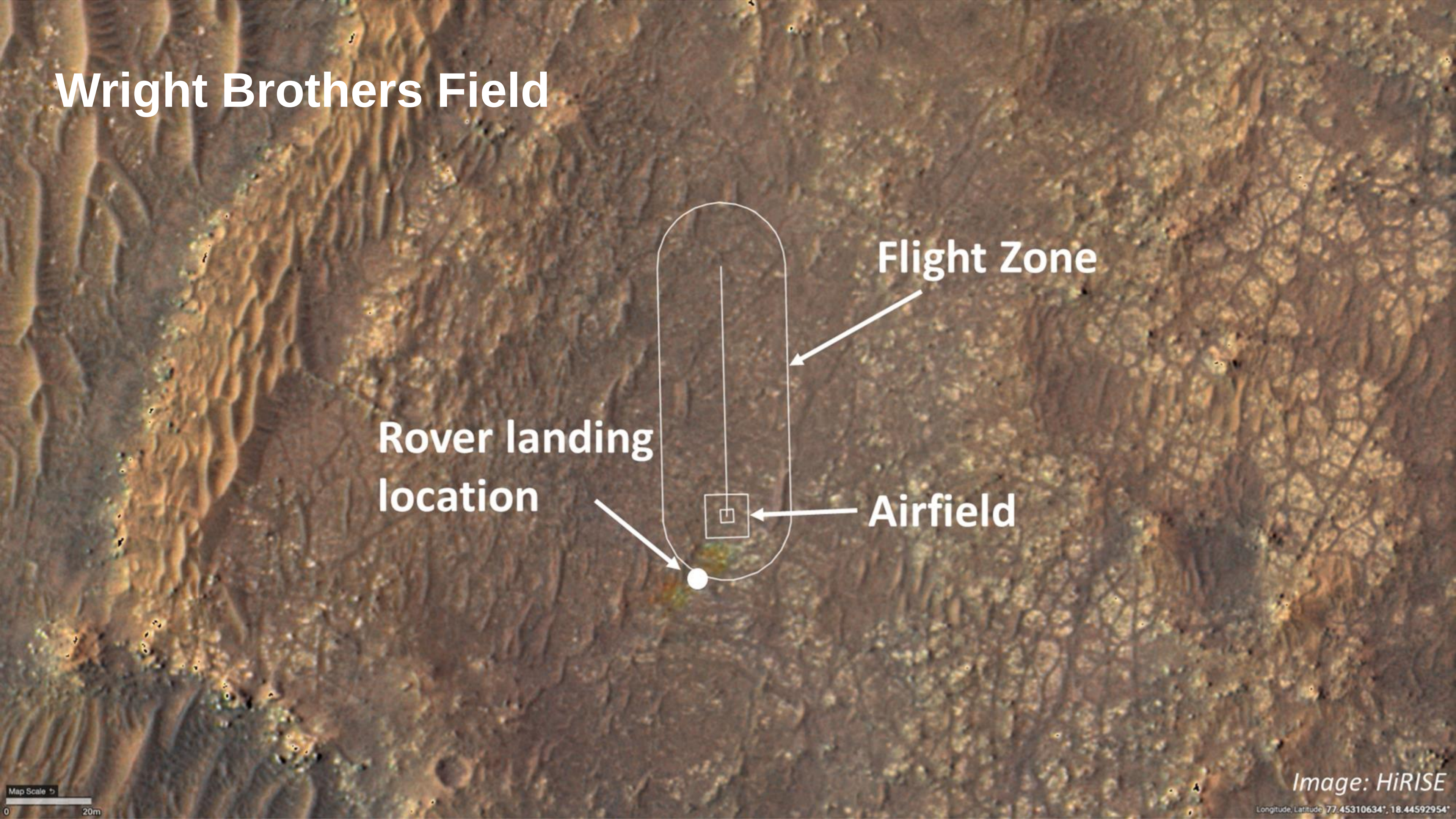
Mars Helicopter Initial Technology Demonstration

- Objective 1: First powered airborne flight on another planet!
- Objective 2: Collect engineering data for future helicopters
- 30-day mission

Design Flight Pattern




Jezero crater
Octavia E. Butler landing on Feb 18


Wright Brothers Field
Flight Zone
Rover landing location
Airfield
Map Scale
0
20m
Image: HiRISE
Longitude, Latitude 77.45310634°, 18.44592954°

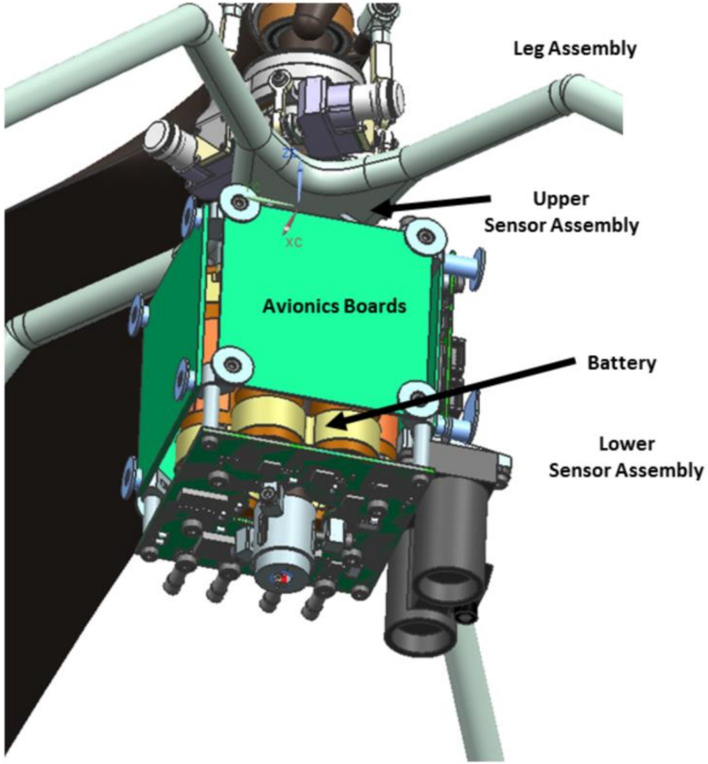
The challenges of flying on Mars

- Generate enough vertical lift in:
  - 1% Earth atmospheric density
  - 1/3 Earth gravity
- No remote control:
  - 180 millions miles away ~ 15 min communication one way
- Survive Mars: as low as -90 C ambient temperature
- Survive launch, cruise end EDL

Meet Ingenuity

- 1.8 kg / 4 lbs
- 1.2 m / 4 ft rotor diameter
- Flights designed up to
  - 5 m / 15 ft high
  - 300 m / 1000 ft long
  - 90 s duration
- Fully autonomous
- Solar panel charging
- Rover comms
- Li-Ion batteries
- Smartphone processors

Meet Ingenuity (on the inside)



(figure: Balaram, 2018)

- 1.8 kg / 4 lbs
- 1.2 m / 4 ft rotor diameter
- Flights designed up to
  - 5 m / 15 ft high
  - 300 m / 1000 ft long
  - 90 s duration
- Fully autonomous
- Solar panel charging
- Rover comms
- Li-Ion batteries
- Smartphone processors

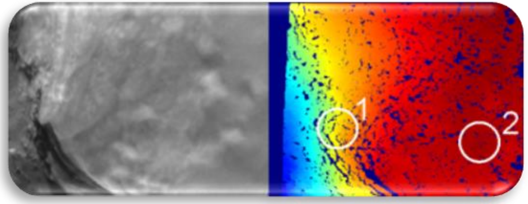
First Flight on Another Planet

What Ingenuity is doing now

- **Active operating alongside Perseverance rovers for 6+ months post tech demo**

- **Scouting ahead**
  - Identify / confirm rover science targets
  - Identify safe rover paths

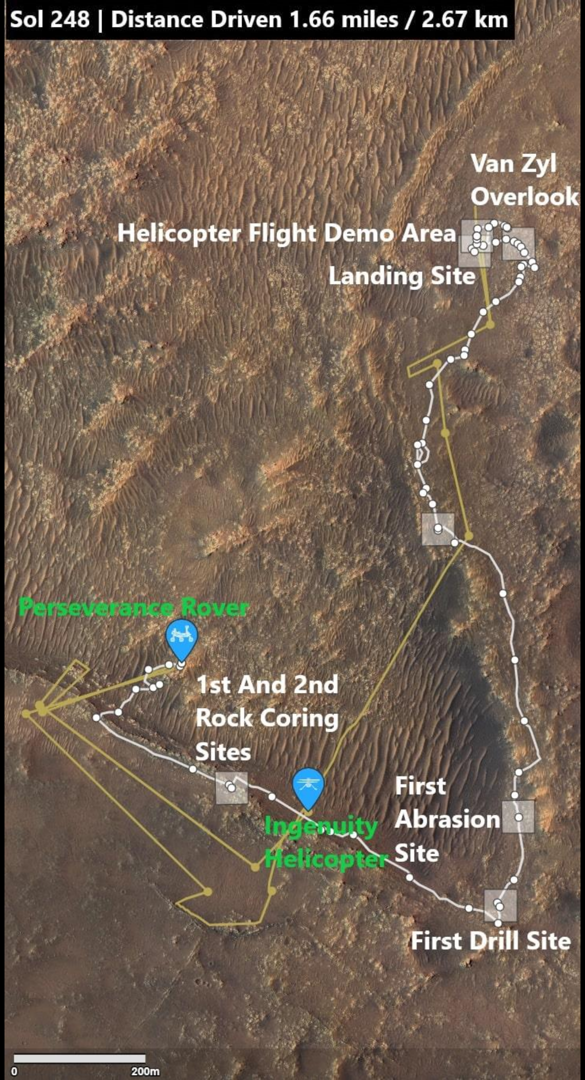
- **Provide unique aerial perspective**
  - High-resolution images (1 cm/pixel)
  - 3D data products (hazards)



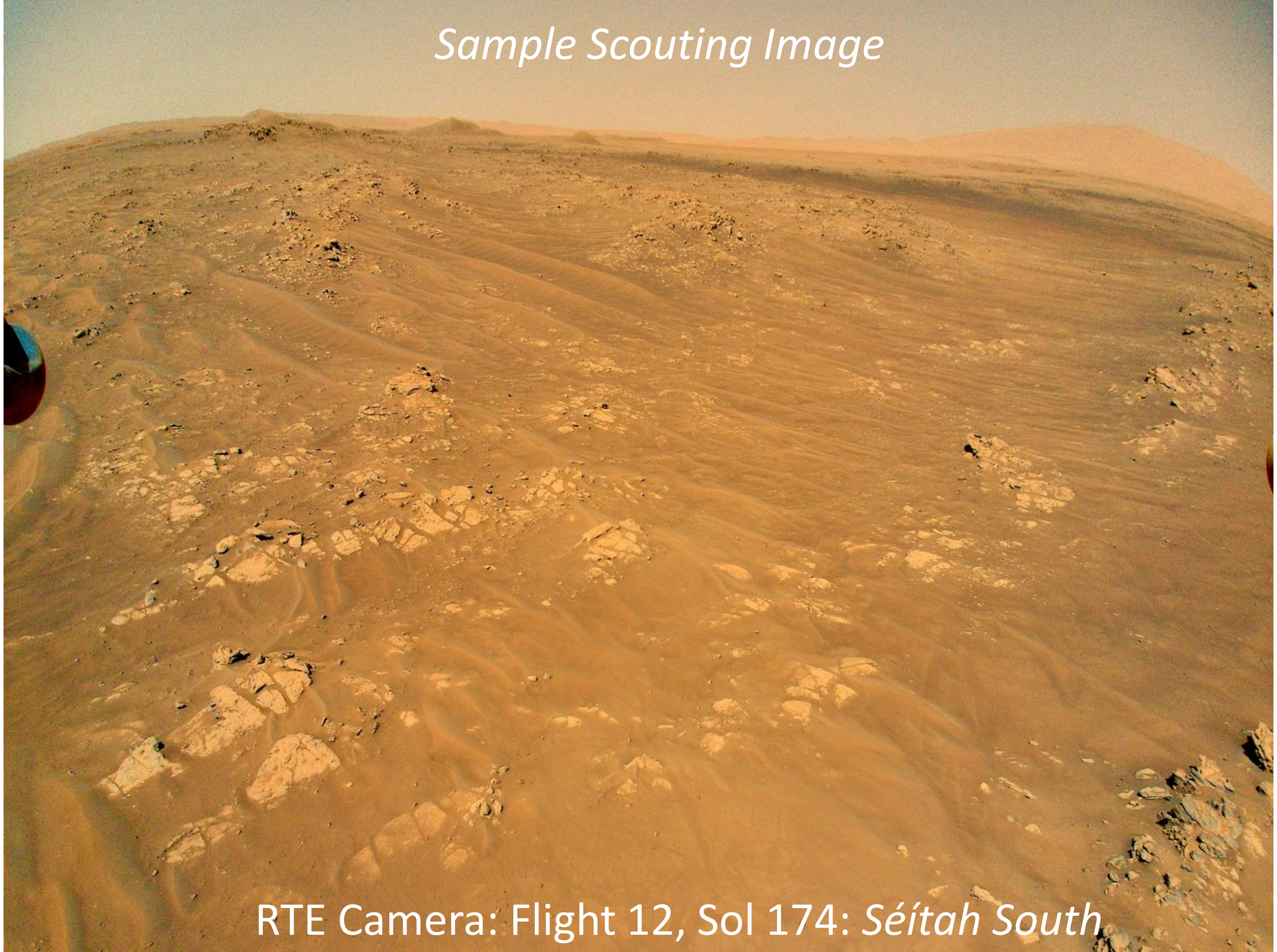
(figure: Brockers, 2021)

Design vs. Performance: The Power of Margins

Variable	Design	Actual
Number of Flights	5	16
Flight Height Above Ground [m]	5	12
Flight Range [m]	300	625
Flight Max Duration [s]	90	170

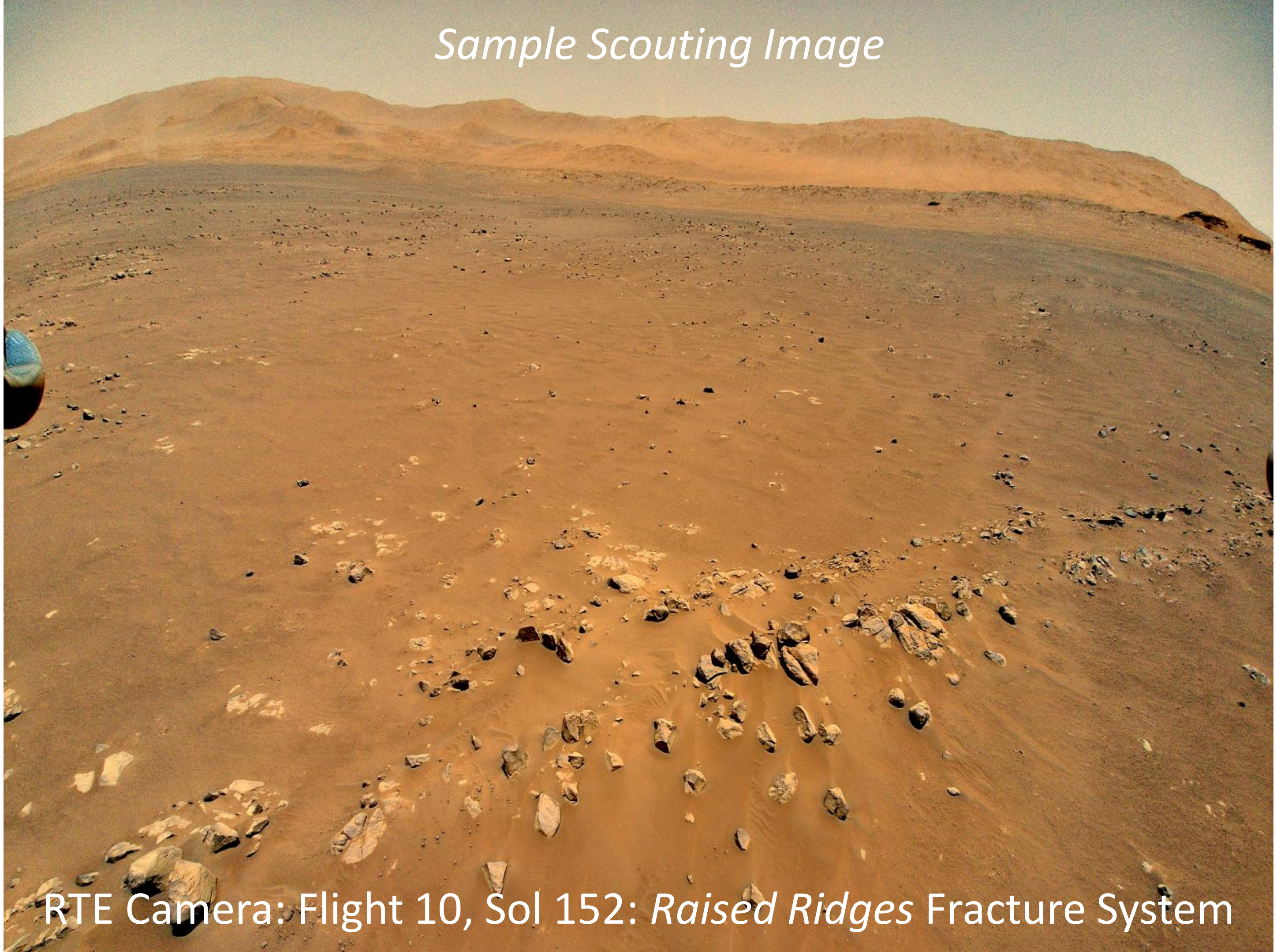


Sol 248 | Distance Driven 1.66 miles / 2.67 km
Van Zyl Overlook
Helicopter Flight Demo Area
Landing Site
Perseverance Rover
1st And 2nd Rock Coring Sites
Ingenuity Helicopter
First Abrasion Site
First Drill Site
0
200m


Sample Scouting Image

RTE Camera: Flight 12, Sol 174: *Séítah South*

Sample Scouting Image



RTE Camera: Flight 10, Sol 152: *Raised Ridges* Fracture System


Sample Scouting Image
RTE Camera: Flight 13, Sol 193: *Faillefeu* outcrop

Reference

AIAA SciTech Forum
8–12 January 2018, Kissimmee, Florida
2018 AIAA Atmospheric Flight Mechanics Conference

Mars Helicopter Technology Demonstrator

J. (Bob) Balaram[★, *],
Timothy Canham[★,†], Courtney Duncan[★,‡], Matt Golombek[★,§], Håvard Fjær Grip[★,¶], Wayne Johnson[★★,‖], Justin Maki[★,**], Amelia Quon[★,††], Ryan Stern[★,‡‡], and David Zhu[★,§§]

[★] *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109*
[★★] *NASA Ames Research Center, Moffet Field, CA 94035*

We describe a helicopter that is being developed as a technology demonstrator of Mars aerial mobility. The key design features of the helicopter, associated test infrastructure, and results from a full-scale prototype are briefly described.

2/ Ingenuity Navigation System

(slide material courtesy of Dr. David Bayard)

Ingenuity Navigation Team

Navigation Development Team
David Bayard (Lead)
Dylan Conway
Roland Brockers
Jeff Delaune
Havard Grip
Larry Matthies

Extended Navigation Team
Gene Merewether
Travis Brown
Johnny Lam
Brent Tweddle
Nuno Filipe
A. Miguel San Martin

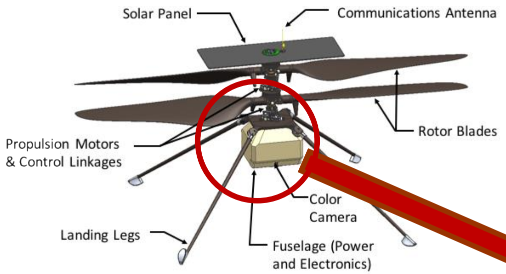
Helicopter Navigation Testing
Fernando Mier-Hicks
Gerik Kubiak
Lucas Leach
Russell Smith

Mars Helicopter Project
MiMi Aung (Project Lead)
Bob Balaram (Chief Engineer)
Teddy Tzanetos (Tactical Lead)

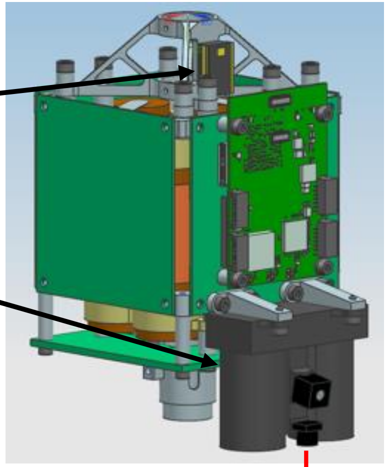
And many others ….

Ingenuity’s Navigation Sensors (cont’d)

SENSORS
- Camera
- IMU
- Lidar Altimeter
- Inclinometer (for pre-flight cal only)



Electronic Control Module (ECM)



- IMU
- Inclinometer

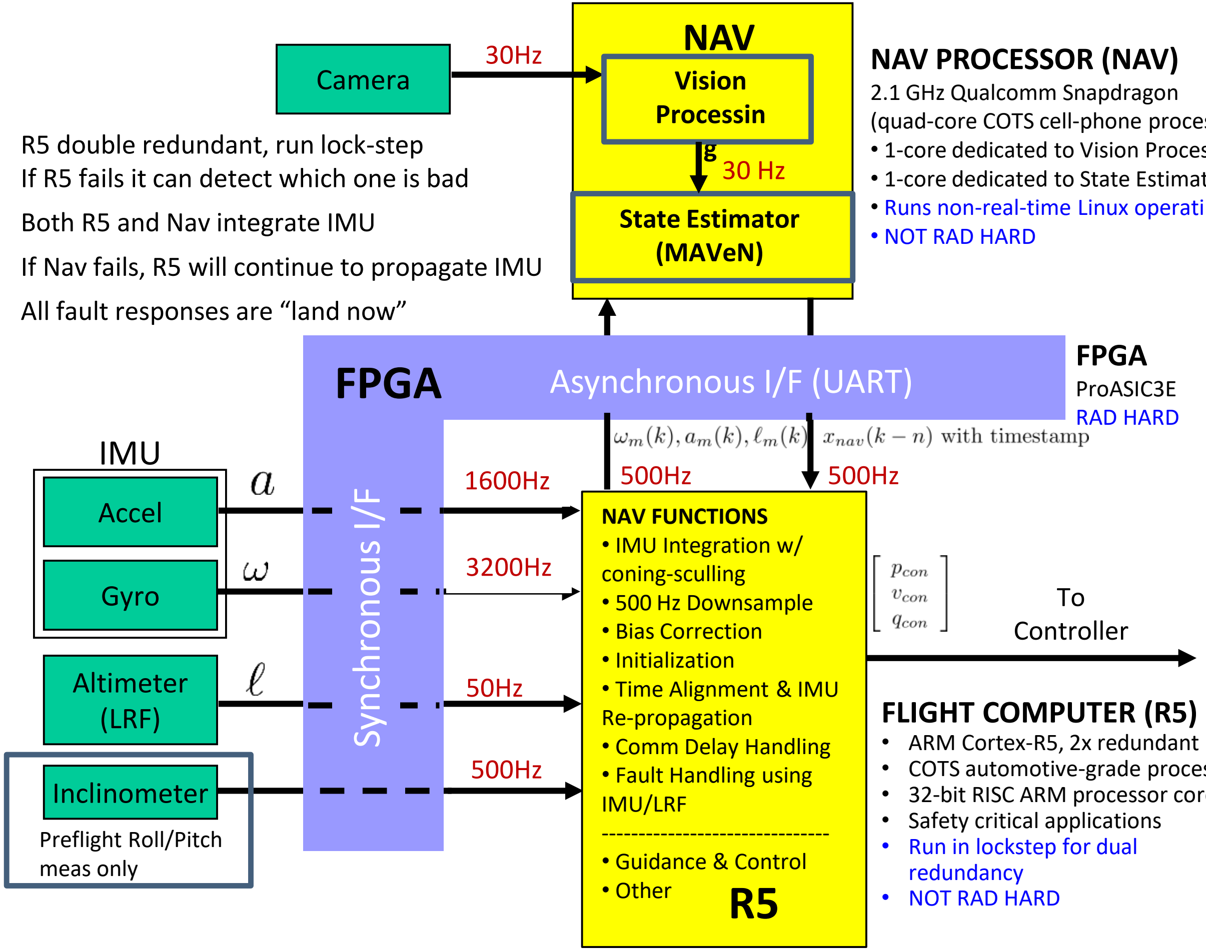
- Lidar Altimeter
- Camera

Nadir Pointed Camera and Altimeter

- Nav Camera: Intrinsyc OmniVision OV7251
  - FOV 133x100 deg, Nadir Pointed
  - Pixels 640x480 ; pixel size 3.6 mrad
  - Frame Rate: >30 Hz

Navigation Architecture Block Diagram

- R5 double redundant, run lock-step
- If R5 fails it can detect which one is bad
- Both R5 and Nav integrate IMU
- If Nav fails, R5 will continue to propagate IMU
- All fault responses are “land now”



NAV PROCESSOR (NAV)

2.1 GHz Qualcomm Snapdragon (quad-core COTS cell-phone processor)

- 1-core dedicated to Vision Processing
- 1-core dedicated to State Estimator
- Runs non-real-time Linux operating system
- NOT RAD HARD

FPGA

ProASIC3E

RAD HARD

FLIGHT COMPUTER (R5)

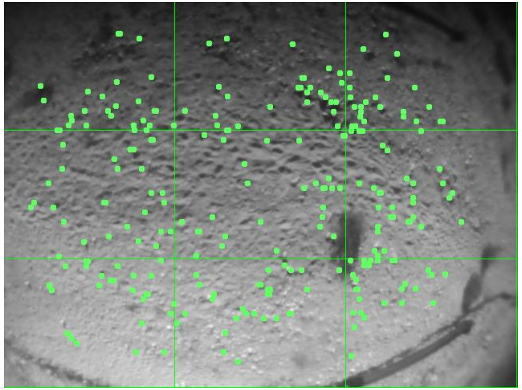
- ARM Cortex-R5, 2x redundant
- COTS automotive-grade processor
- 32-bit RISC ARM processor core
- Safety critical applications
- Run in lockstep for dual redundancy
- NOT RAD HARD

Vision Processing

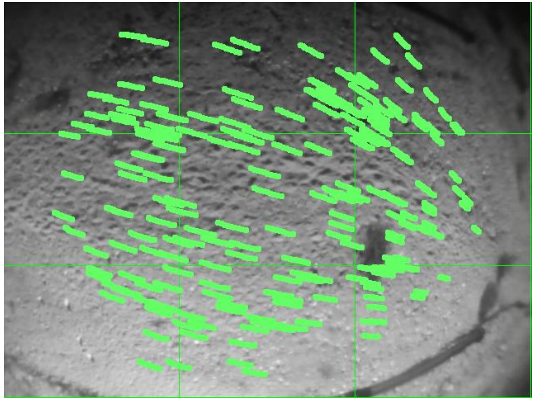
- **FEATURE DETECTION APPROACH**
  - FAST Algorithm: Selects corner-like features
  - Forms feature template using center pixel and square area surrounding it
  - Non-maximum suppression to reduce concentrations of features in high contrast regions
  - Keeps the 28 highest contrast features in each of 9 tiles (3x3 grid of tiles)

- **FEATURE TRACKING APPROACH**
  - KLT Algorithm (Kanade-Lucas-Tomasi)
  - 30 Hz images
  - Estimates image-space displacement of template from one image to the next
  - Iterative gradient-descent search based on pixel intensity
  - Window size of 11x11 pixels
  - Tracks using 3-level image pyramid (full, 1/2, 1/4/, 1/8 resolutions of same image)
    -- extends KLT radius of convergence
  - Augmented with gyro-based derotation to overcome large attitude motion
  - Forces new Base frame every 1/3 second which desensitizes MAVeN to ground slopes

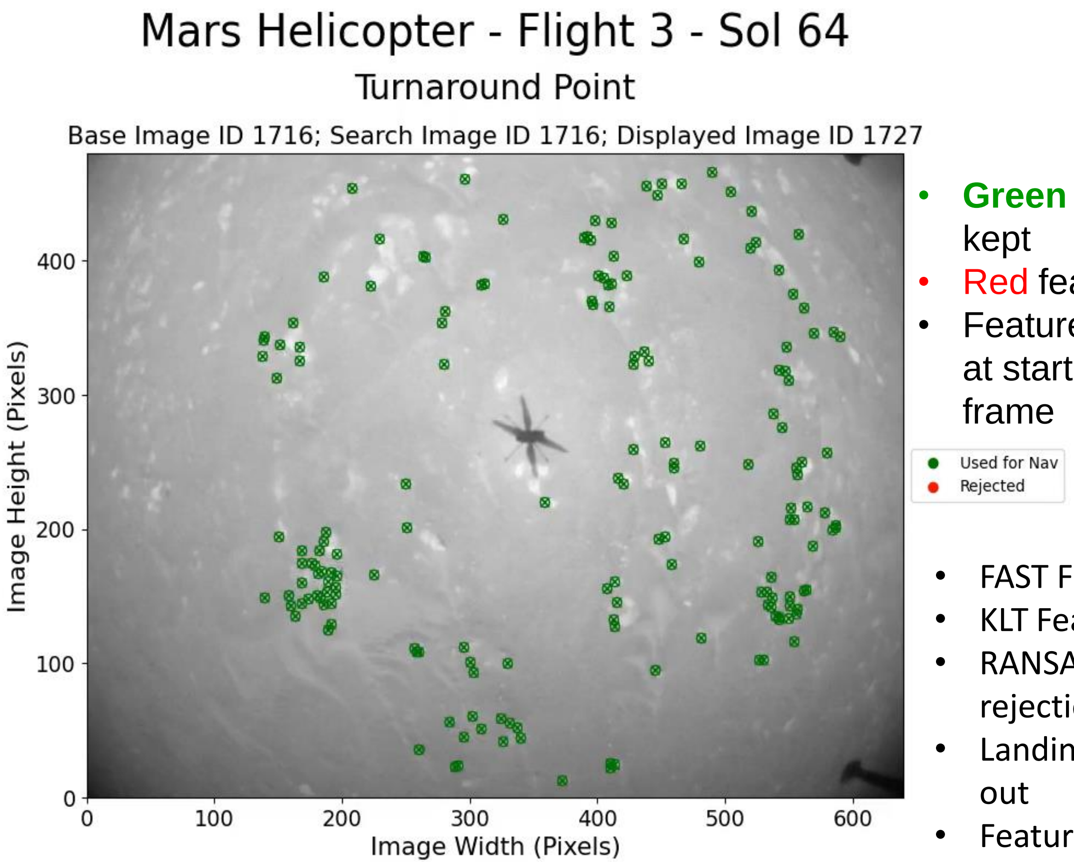
Feature Detection (3x3 grid)



Feature Tracking (ex: track length =10)



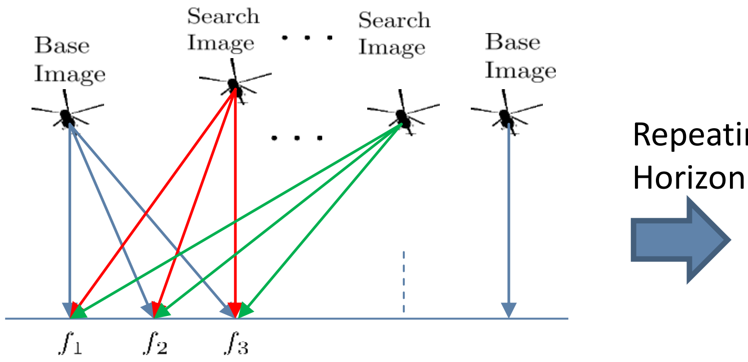
Vision Processing (cont'd)



- **Green** features are kept
- Red features rejected
- Features tracks reset at start of each Base frame

- FAST Feature Detection
- KLT Feature Tracking
- RANSAC outlier rejection
- Landing legs masked out
- Features on shadow removed by RANSAC

MAVeN Base and Search Images



[1] Identify the first image as a Base image

[2] Use the current estimate of Base pose p_B, q_B to map features in the Base image onto the planar ground to give **pseudo-landmarks** f_1, f_2, f_3.

[3] Identify the next image as a Search image. Match Search image features to the pseudo-landmarks f_1, f_2, f_3.

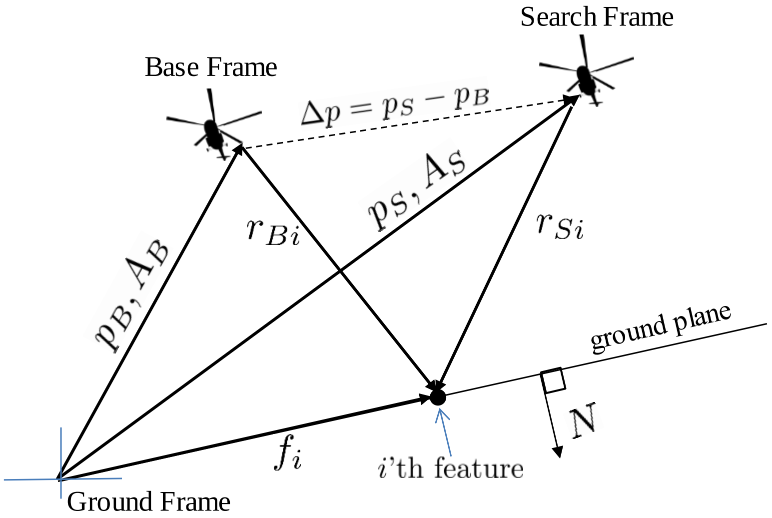
[4] Combine the m pseudo-landmark matches with current geometry to form a measurement that is a function of both the current Base and Search states,

$$y_i = h_i(p_S, q_S, p_B, q_B) + v_i$$

Perform Kalman filter measurement and time updates.

[5] If the number of matched features drops below a threshold, declare the next image as a new Base image and go to [1]. Otherwise declare the next image as a Search image and go to [3]

Ingenuity Navigation Filter Definitions



$$x = \begin{bmatrix} p_S \\ v_S \\ A_S \\ -- \\ b_a \\ b_g \\ -- \\ p_B \\ A_B \end{bmatrix}$$

(7x3 =21 states)

p_S, v_S, q_S - Search state position, velocity and attitude quaternion

p_B, q_B - Base State position and attitude quaternion

b_a, b_g - bias states for the accelerometer and gyro

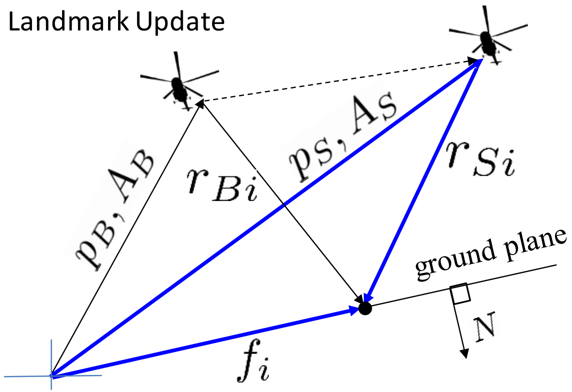
- Base states (i.e., clone states), are copied from Search states at Base times t_B

  $p_B(t_B) = p_S(t_B)$, and $q_B(t_B) = q_S(t_B)$

- Base states propagate with constant dynamics between Base images

  $\dot{p}_B = 0, \dot{q}_B = 0$

Background: Nav with Mapped Landmark Update



Mapped Landmarks: Assume f_i is known and use BLUE triangle

$$r_{S_i} = A_S f_i - A_S p_S$$

For an arbitrary line-of-sight vector $r = [r_x, r_y, r_z]^T$ a pin-hole projection operator is defined as

$$\pi[r] = \begin{bmatrix} r_x/r_z \\ r_y/r_z \end{bmatrix}$$

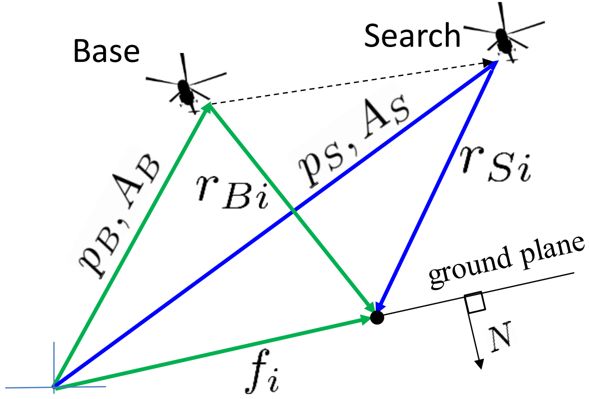
Applying pin-hole operator gives measurement

$$y = \pi(r_{S_i}) = \pi(A_S f_i - A_S p_S) = h(p_S, A_S, f_i)$$

Measurement has desired form

$$y = h(x), \quad \text{where} \quad x = \begin{bmatrix} p_S \\ A_S \end{bmatrix}$$

Ingenuity EKF Measurement Update



- Vector Decomposition

$$r_{B_i} = d_i \; m(\alpha_i, \beta_i)$$

d_i	–	depth (scalar)
$m(\alpha_i, \beta_i)$	–	unit vector
α_i, β_i	–	bearing angles

- Solve for d_i (assumes planar ground)

$$d_i = \frac{N^T p_B}{N^T A_B^T m(\alpha_i, \beta_i)}$$

From BLUE triangle $y \triangleq \pi(r_{Si}) = h(p_S, A_S, f_i)$

MAVeN: Replace unknown f_i by a function of state $f_i(x)$ using GREEN triangle

$$f_i = p_B + A_B^T r_{B_i} = p_B + A_B^T d_i m(\alpha_i, \beta_i) = f_i(p_B, A_B, \alpha_i, \beta_i, N)$$

Substituting gives measurement in desired form

$$y_i = h(\underbrace{p_S, A_S, p_B, A_B}_{x}, \alpha_i, \beta_i, N) \Rightarrow \qquad y_i = h(x) \text{ where } \quad x = \begin{bmatrix} p_S \\ v_S \\ A_S \\ p_B \\ A_B \end{bmatrix} \in R^{15}$$

- Assumptions: (1) Known ground plane with normal N; (2) Base frame bearing angle measurements α_i, β_i are noiseless

- The MAVeN state is not augmented by feature vector

Navigation Performance during Tech Demo

COMMANDED					NAVIGATION LANDING ERRORS*				
FLT	Time	Total Dist	Max Alt	Max Speed	Heading Error	Position Error	Attitude Error	Cross-Track Error	% Drift
#	sec	m	m	m/s	deg	m	deg	m	%
1	40	0	3	0	-0.16	0.27	0.01	0.01	-
2	52	4	5	0.5	1.25	0.31	0	0.15	-
3	80	100	5	2	0.85	0.27	0.04	-0.05	0.3%
4	117	266	5	3.5	4.16	5.69	-1.04	-5.58	2.1%
5	108	129	10	2	1.43	1.89	-1.69	0.8	1.5%

*Post-flight landing error reconstruction

- From HIRISE Images errors

Summary: <u>Tech Demos (TD)</u>

- Drift error ~ 1-2 percent

Navigation Performance post Tech Demo

COMMANDED					NAVIGATION LANDING ERRORS				
FL T	Time	Total Dist	Max Alt	Max Spee d	Heading Error	Position Error	Attitude Error	Cross-Track Error	% Drift
#	sec	m	m	m/s	deg	m	deg	m	%
6	140	215	10	4	7.18	6.04	3.78	-4.72	2.8%
7	63	106	10	4	1.84	1.83	-0.22	-1.79	1.7%
8	77	160	10	4	1.49	2.28	-0.31	-2.24	1.4%
9	166	625	10	5	7.8	38.51	5.26	-38.15	6.2%
10	165	244	12	5	5.29	4.23	-3.26	-2.68	1.7%
11	131	385	12	5	4.99	20.2	-5.12	-19.54	5.2%
12	170	450	10	4.3	10.9	15.73	-2.08	11.74	3.5%
13	161	210	8	3.3	3.4	0.65	0.16	-0.55	0.31

Summary: Scouting Demos (more challenging)

- Drift error ~ 2-6% percent
- Worst-case 6% drift due to Flight 9 over ancient lake bed (sharp slopes)
  - Main drift in cross-track direction due to heading error
- Velocities remained accurate for good flight control (smooth flight)

Reference

AIAA SciTech Forum
7-11 January 2019, San Diego, California
AIAA Scitech 2019 Forum

Vision-Based Navigation for the NASA Mars Helicopter

David S. Bayard* Dylan T. Conway† Roland Brockers‡ Jeff Delaune§ Larry Matthies¶

Håvard F. Grip‖ Gene Merewether** Travis Brown†† A. Miguel San Martin‡‡

Jet Propulsion Laboratory, California Institute of Technology, 91109

A small helicopter has recently been approved by NASA as an addition to the Mars 2020 rover mission. The helicopter will be deployed by the rover after landing on Mars, and operate independently thereafter. The main goal is to verify the feasibility of using helicopters for future Mars exploration missions through a series of fully autonomous flight demonstrations. In addition to the sophisticated dynamics and control functions needed to fly the helicopter in a thin Mars atmosphere, a key supporting function is the capability for autonomous navigation. Specifically, the navigation system must be reliable, fully self-contained, and operate without human intervention. This paper provides an overview of the Mars Helicopter navigation system, architecture, sensors, vision processing and state estimation algorithms. Special attention is given to the design choices to address unique constraints arising when flying autonomously on Mars. Flight test results indicate navigation performance is sufficient to support Mars flight operations.

3/ Mars Science Helicopter Navigation System

Mars Science Helicopter Program

- Mars Science Helicopter concept (MSH, JPL R&D)
  - Goal: Enable science return from a Mars helicopter
    - Region-wide in-situ exploration (range > 1 km/sol)
    - Areas inaccessible to rovers
  - Main challenge:
    - System design to accommodate 5-kg payload
    - Autonomous perception:
      - Navigation
      - Landing site detection
      - Map registration
    - Mission profile: horizontal traverses over 3D terrains (> 1km)

Mars Science Helicopter Concept
(Ames, Univ. of Maryland, JPL)

Literature Review

- Visual-Inertial Odometry (VIO):
  - Loosely-coupled
    - Measurement: unscaled pose in local visual frame
    - ORB-SLAM, SVO, PTAM
  - Tightly-coupled
    - Measurement:
      - Image coordinates (*feature-based*)
      - Image intensities (*direct*)
    - MSCKF, ROVIO, OKVIS

Accurate

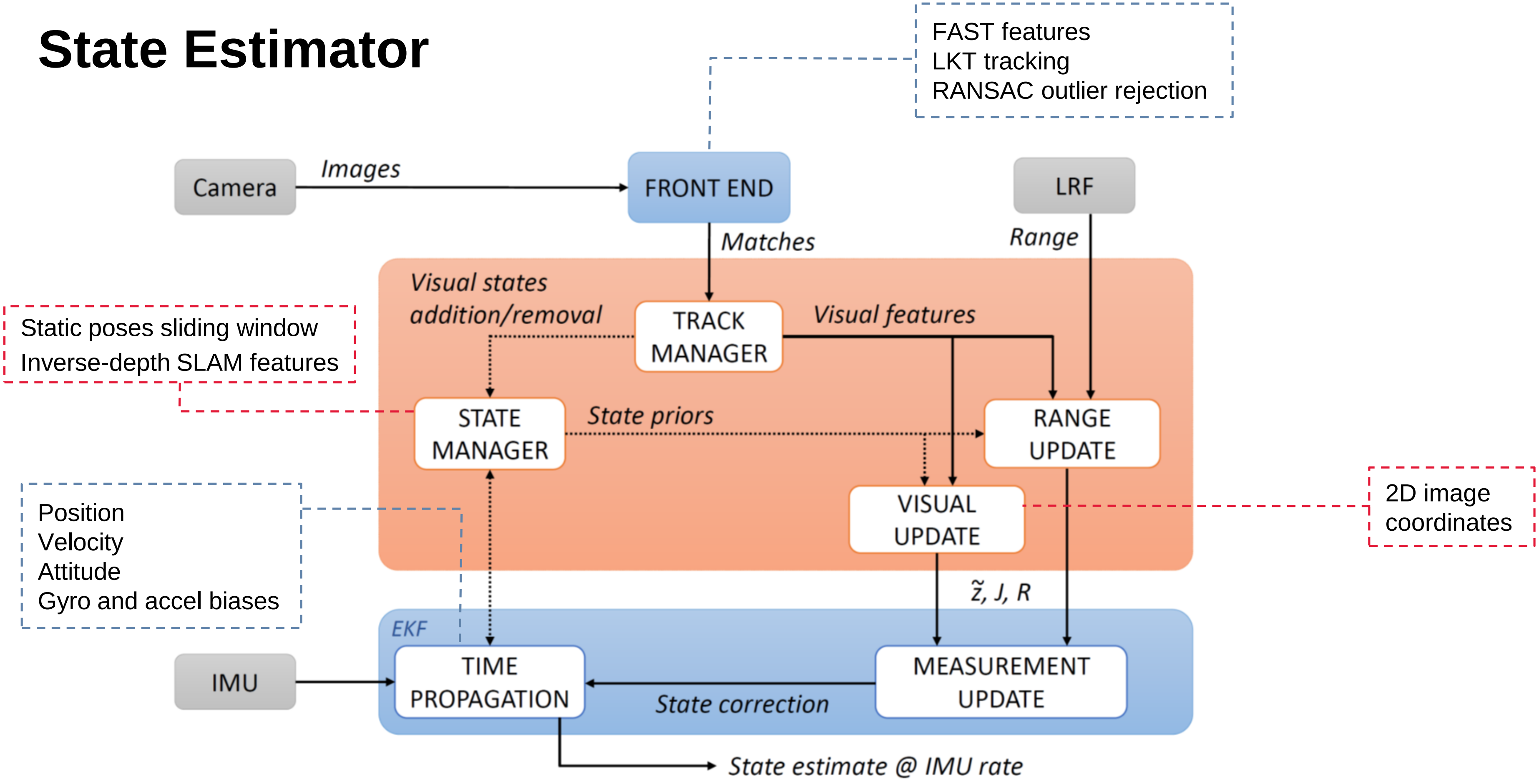
Robust

Large drift due to unobservable:
- scale (w/o excitation)
- heading

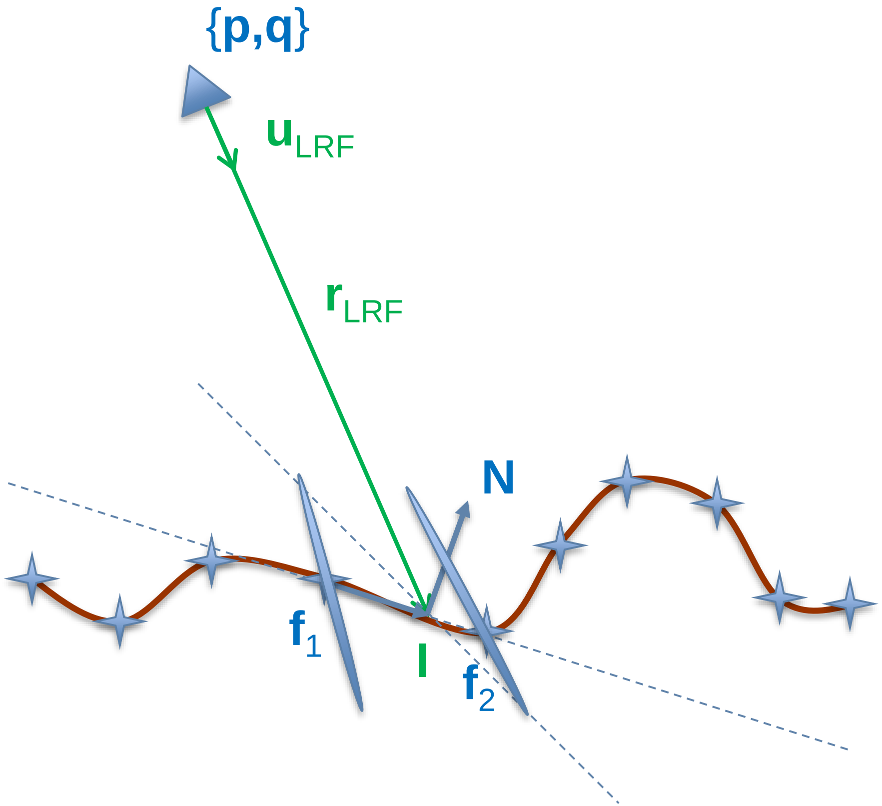
- VIO drift mitigation:
  - Scale:
    - LRF + globally-flat terrain [Bayard, 2019]
    - Ultrasonic sensing + equidistant large terrain patch [Urzua, 2017]
  - Heading (w/o magnetometer):
    - VO + sun sensor [Lambert, 2011]
    - Sun sensing widely used in space

- No range-VIO for 3D terrains
- No solar-VIO

State Estimator



Ranged Facet Update



- Form a triangle with 3 neighboring features:
  - $\boldsymbol{N} = (\boldsymbol{f}_2 - \boldsymbol{f}_1) \times (\boldsymbol{f}_3 - \boldsymbol{f}_1)$
- Assumption: Local planar facet
  - Constraint:

    $$(\boldsymbol{I} - \boldsymbol{f}_1)^T \boldsymbol{N} = 0$$

  - $$\boldsymbol{r}_{LRF} = r_{LRF}\boldsymbol{u}_{LRF}$$

    $$\boldsymbol{r}_{LRF}{}^T \boldsymbol{N} = r_{LRF}\boldsymbol{u}_{LRF}{}^T \boldsymbol{N}$$

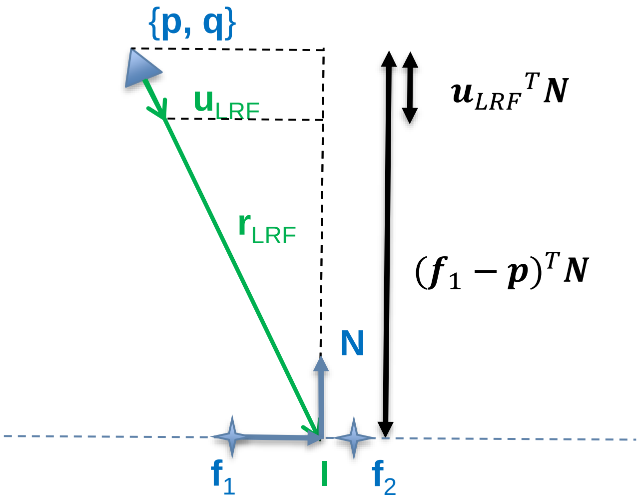
    $$r_{LRF} = \frac{(\boldsymbol{f}_1 - \boldsymbol{p})^T \boldsymbol{N}}{\boldsymbol{u}_{LRF}{}^T \boldsymbol{N}}$$

    $$= h(\boldsymbol{x})$$

  - Integrates depth uncertainty

Ranged Facet Update (cont'd)

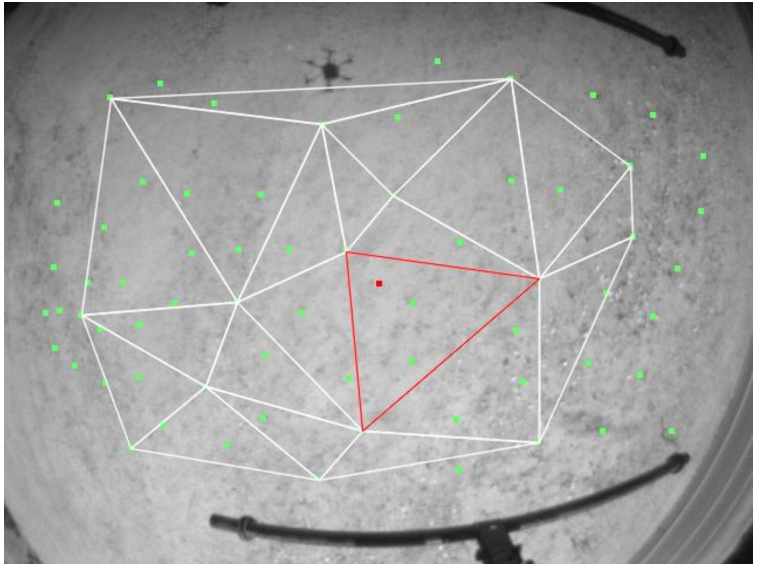
Projection



$$r_{LRF} = \frac{(\boldsymbol{f}_1 - \boldsymbol{p})^T\boldsymbol{N}}{\boldsymbol{u}_{LRF}{}^T\boldsymbol{N}}$$

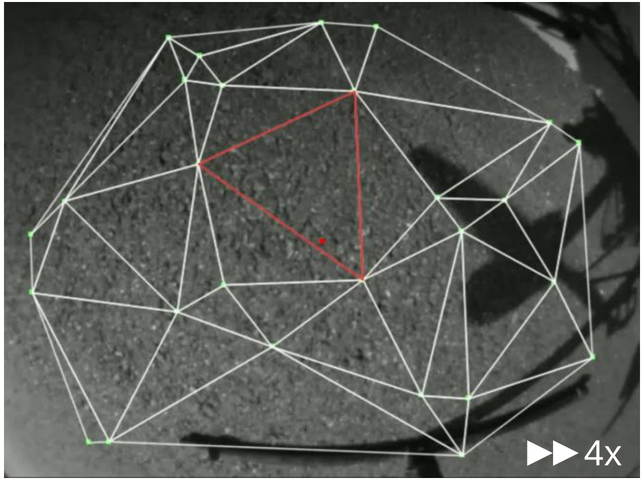
$$(\boldsymbol{N} = \boldsymbol{N}(x))$$

Delaunay image triangulation



Maximizes smallest angle of all triangulations

State Estimator Outdoor Flight Test



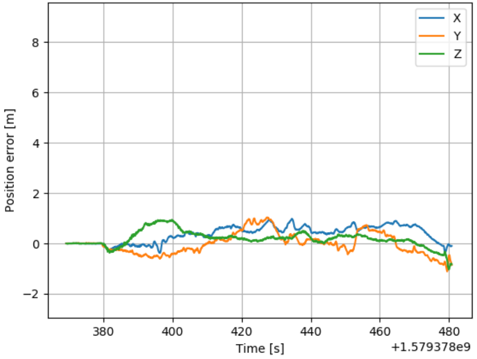
Range-VIO forms triangular facets between SLAM features to construct range constraints

Works over arbitrary structures: flat or 3D

Enables scale observability in the absence of excitation (e.g. constant speed)

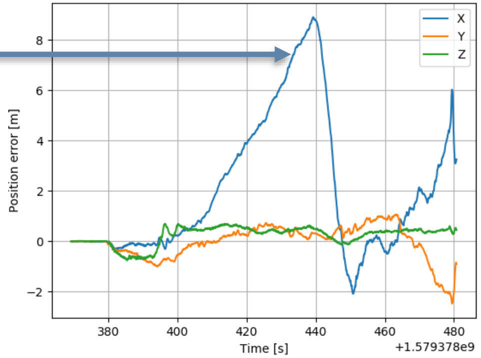
Theoretical demonstration for the linearized system in the paper.

30 Hz update on 1 core of QC Snapdragon 820



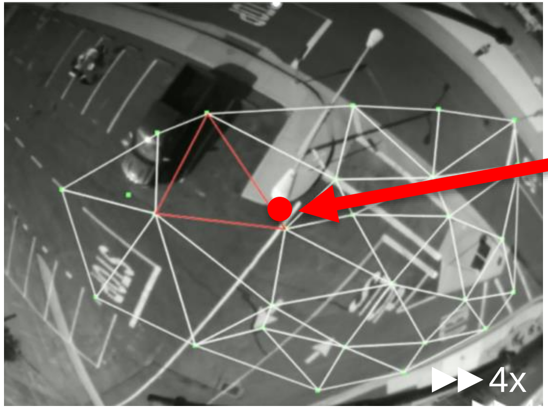
VIO scale drift

Range-VIO



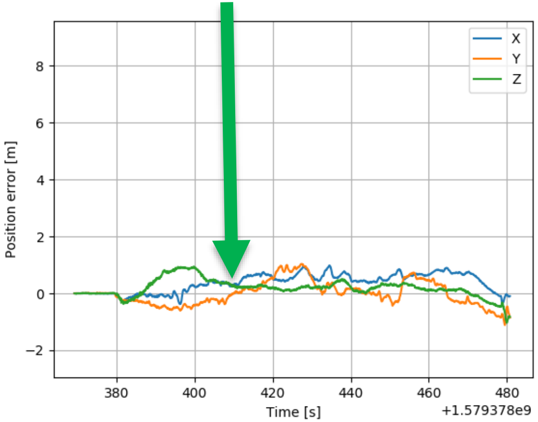
jpl.nasa.gov

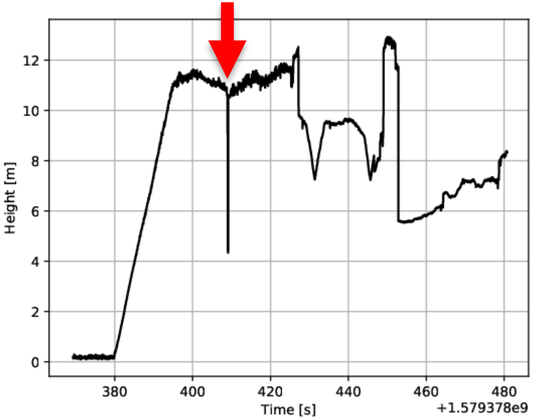
Range outlier rejection



The range finder hits a 7-m high street light

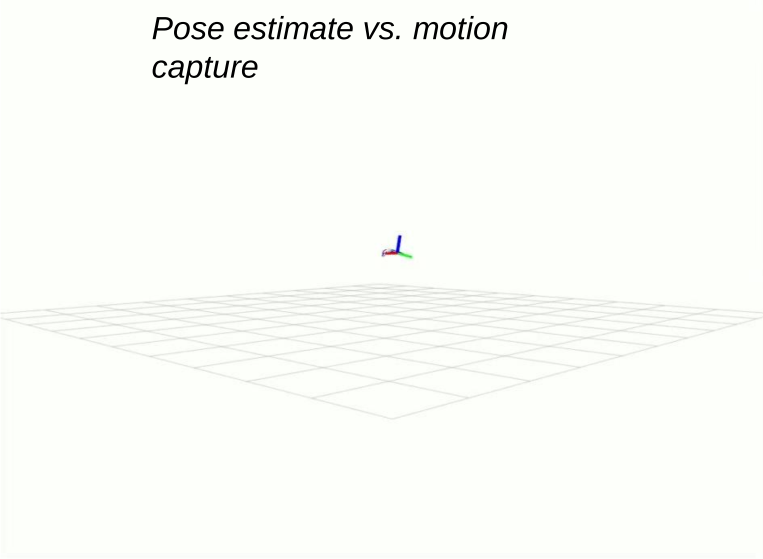
The Mahalanobis gating catches it and shows no impact on range-VIO

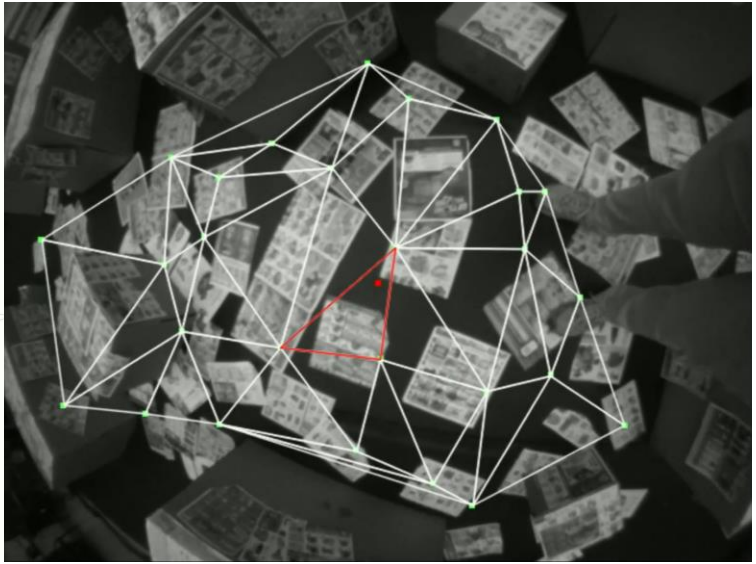




jpl.nasa.gov

State Estimator Indoor stress case





Inertial excitation

Strong accelerations

Fast rates

Close-up passes over 3D structure

Reference 1/2

Extended Navigation Capabilities for a Future Mars Science Helicopter Concept

Jeff Delaune, Roland Brockers, David S. Bayard, Harel Dor, Robert Hewitt, Jacek Sawoniewicz,
Gerik Kubiak, Theodore Tzanetos, Larry Matthies and J. (Bob) Balaram
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California Institute of Technology
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Pasadena, CA 91109
{jeff.h.delaune, roland.brockers, david.s.bayard, harel.dor, robert.a.hewitt, jacek.m.sawoniewicz,
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***Abstract*—This paper introduces an autonomous navigation system suitable for supporting a future Mars Science Helicopter concept. This mission concept requires low-drift localization to reach science targets far apart from each other on the surface of Mars. Our modular state estimator achieves this through range, solar and Visual-Inertial Odometry (VIO). We propose a novel range update model to constrain visual-inertial scale drift using a single-point static laser range finder, that is designed to work over unknown terrain topography. We also develop a sun sensor measurement model to constrain VIO yaw drift. Solar VIO performance is evaluated in a simulation environment in a Monte Carlo analysis. Range-VIO is demonstrated in flight in real time on 1 core of a Qualcomm Snapdragon 820 processor, which is the successor of the NASA's Mars Helicopter flight processor.**

time-delays for communication to Mars and the highly dynamic and uncertain flight environment. MSH will extend the MH2020 capabilities in real-time onboard navigation to estimate position, attitude and velocity in flight over rough, highly-sloped and even discontinuous terrain. To enable this, the global planar ground assumption of the MH2020 navigation algorithm [3] will be relaxed to allow the science helicopter to operate over such challenging terrains.

For robustness and accuracy, the state vector maintained in the on-board estimates is required to provide low-drifting state estimates under all expected motion conditions, including uniform-velocity translations which are not observable by visual-inertial state estimators typically used in robotics

IEEE Aerospace, 2020)

Reference 2/2

Range-Visual-Inertial Odometry: Scale Observability Without Excitation

Jeff Delaune, David S. Bayard and Roland Brockers

***Abstract*—Traveling at constant velocity is the most efficient trajectory for most robotics applications. Unfortunately without accelerometer excitation, monocular Visual-Inertial Odometry (VIO) cannot observe scale and suffers severe error drift. This was the main motivation for incorporating a 1D laser range finder in the navigation system for NASA's *Ingenuity* Mars Helicopter. However, *Ingenuity*'s simplified approach was limited to flat terrains. The current paper introduces a novel range measurement update model based on using facet constraints. The resulting range-VIO approach is no longer limited to flat scenes, but extends to any arbitrary structure for generic robotic applications. An important theoretical result shows that scale is no longer in the right nullspace of the observability matrix for zero or constant acceleration motion. In practical terms, this means that scale becomes observable under constant-velocity motion, which enables simple and robust autonomous operations over arbitrary terrain. Due to the small range finder footprint, range-VIO retains the minimal size, weight, and power attributes of VIO, with similar runtime. The benefits are evaluated on real flight data representative of common aerial robotics scenarios. Robustness is demonstrated using indoor stress data and full-state ground truth. We release our software framework, called xVIO, as open source.**

***Index Terms*—Visual-Inertial SLAM, Aerial Systems: Perception and Autonomy, Observability, Inertial Excitation, Mars Helicopter.**

in general; as well as indoor or underground traverses along a straight corridor or tunnel.

Our novel range-visual-inertial odometry algorithm can observe scale even under zero or constant-acceleration trajectories. It uses a 1D Laser Range Finder (LRF) that keeps the sensor suite lightweight, while efficiently leveraging VIO sparse structure estimates. Our main contributions are:

- a range measurement model which prevents VIO scale drift and adapts to any scene structure,
- a linearized range-VIO observability analysis, showing scale is observable without excitation,
- outdoor demonstration on a realistic dataset,
- indoor stress case analysis with full-state ground truth,
- an open-source C++ implementation.

In [1], a range-VIO method was presented that navigates over relatively flat terrain while supporting a stable motionless hover needed for demonstrating NASA's *Ingenuity* Mars Helicopter. The current paper extends these range-VIO results with a new method that makes scale observable for 3D terrain without requiring any inertial excitation. This generalization

Safe Landing Site Detection

Multi-step keyframe-based process:

1. Keyframe selection (baseline-based)
2. Bundle adjustment of VIO poses
3. Stereo rectification
4. Dense Depth Estimation
5. Multi-Resolution Elevation Map Depth Filtering
6. Site selection: slopes, roughness, map confidence

Reference:

Autonomous Safe Landing Site Detection for a Future Mars Science Helicopter

Roland Brockers, Jeff Delaune, Pedro Proença, Pascal Schoppmann, Matthias Domnik, Gerik Kubiak, and Theodore Tzanetos

(IEEE Aerospace, 2021)

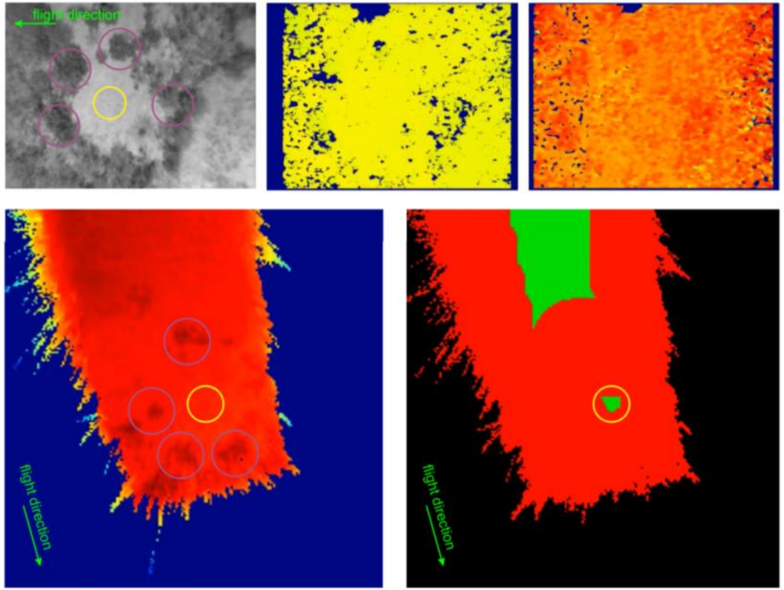


Figure 12. Landing site detection with UAS flight data: Top row: Left: Reference view (rectified); Middle: stereo disparity map; Right: height from range image. Bottom left: aggregated elevation map; Bottom right: landing site map (green: safe landing site, red: landing hazard). Purple circles label selected landing hazards for visualization. Yellow circle depicts suitable landing site on sand patch in input image.

Background: Map-Based Localization for M2020 EDL

- Patch correlation-based
- 2 orbital maps (HiRISE instrument on MRO):
  1. Low resolution (12 m/pix)

     => 1st loc.
  2. High-resolution => High accuracy
- Flown successfully on M2020 EDL, for hazard avoidance purposes
- Reference:

THE LANDER VISION SYSTEM FOR MARS 2020 ENTRY DESCENT AND LANDING*

Andrew Johnson, Seth Aaron, Johnny Chang, Yang Cheng, James Montgomery, Swati Mohan, Steven Schroeder, Brent Tweddle, Nikolas Trawny and Jason Zheng†

(AAS GNC Conference, 2017)

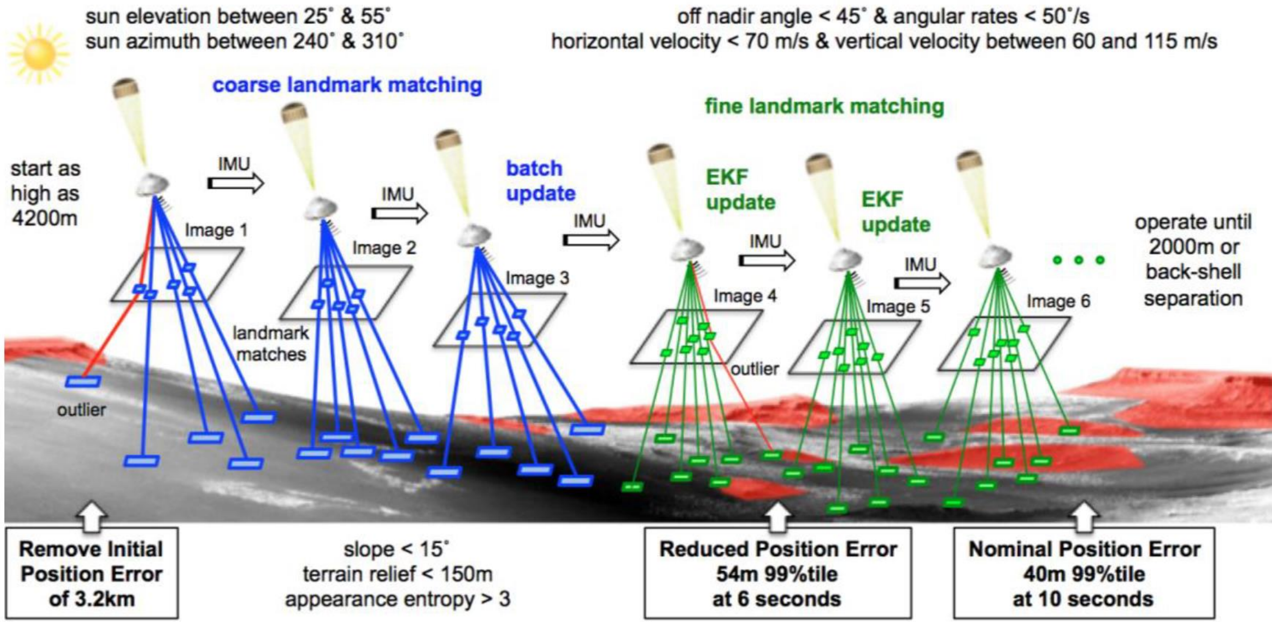


Figure courtesy of Andrew Johnson

Map-Based Localization for MSH

- Compared SOTA detectors / descriptors on simulated Mars data and terrestrial flight data
  - SuperPoint, SIFT, SURF, ORB, patch correlation,..
- Also test on M2020 EDL images
- SIFT presented best performance in accuracy, robustness trades
  - Illumination, view angle, altitude
- Uses heli VIO pose prior

Reference:

On-board Absolute Localization Based on Orbital Imagery for a Future Mars Science Helicopter

Roland Brockers, Pedro Proença, Jeff Delaune, Jessica Todd
Larry Matthies, Theodore Tzanetos, and J. (Bob) Balaram

(Accepted in IEEE Aerospace, 2022)

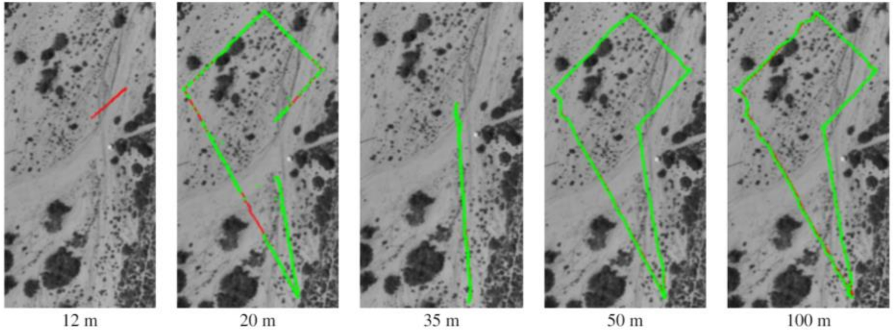


Figure 13. Localization during UAS flights at different altitudes: Map detail with overlaid UAS trajectory. Red: GPS positions; Green: Localization results on top of GPS positions (matching with exhaustive search).

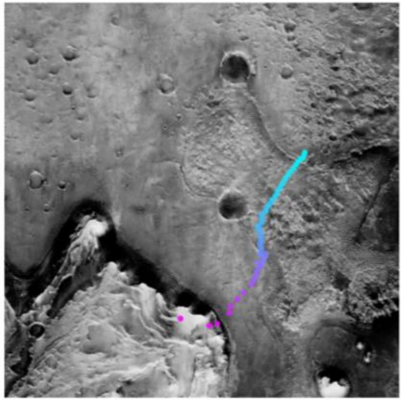
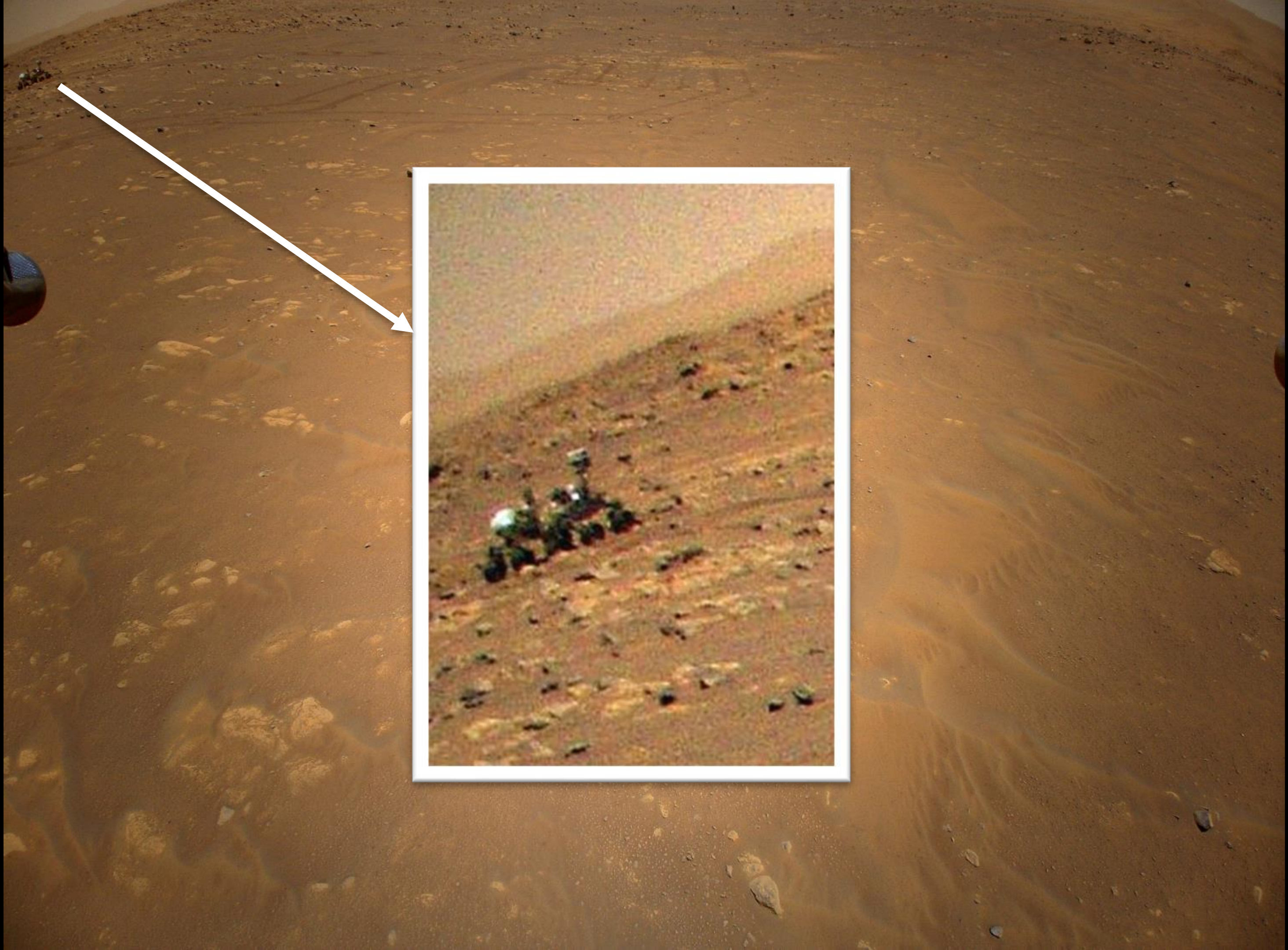


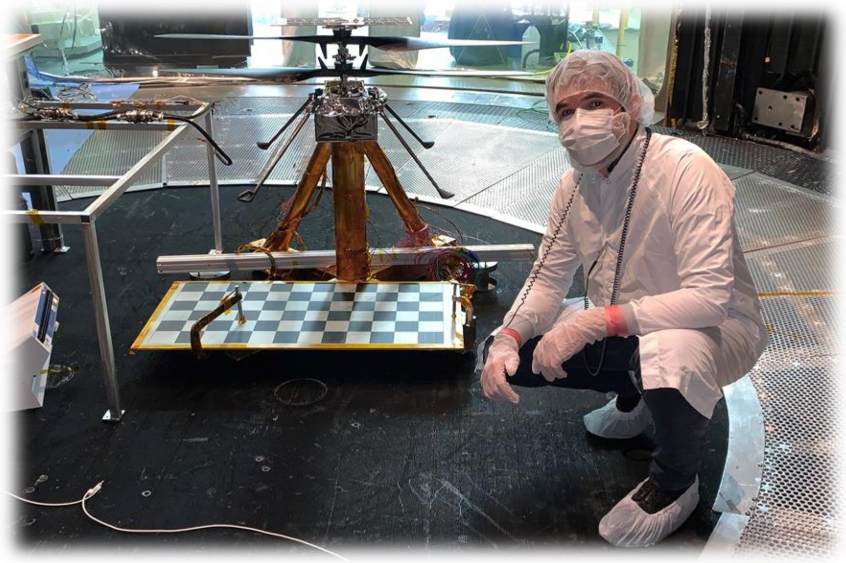
Figure 1. Estimated trajectory of the Mars 2020 landing approach overlaid on HiRISE image map. Each dot corresponds to the estimated position of the LVS camera during descent. The dot color codes the estimated altitude [violet: 7 km - light blue: ~110 m].

Summary

Summary

- Ingenuity keeps pushing the flight envelope on Mars: 16 flights and counting.
  - New software upgrade considered after flight 17
- Navigation system performed reliably and supported a successful Ingenuity flight demonstration
  - 1-2% position drift
  - Simple 21-state filter
  - Stable hover
- Next-gen Mars Science Helicopter research work focuses on:
  - 3D-compatible range-VIO: scale observability w/o excitation
  - Landing site detection: temporal filtering of stereo-from-motion depth
  - Map-based localization: SIFT using VIO pose prior
  - Open-source C++ implementation: https://github.com/jpl-x

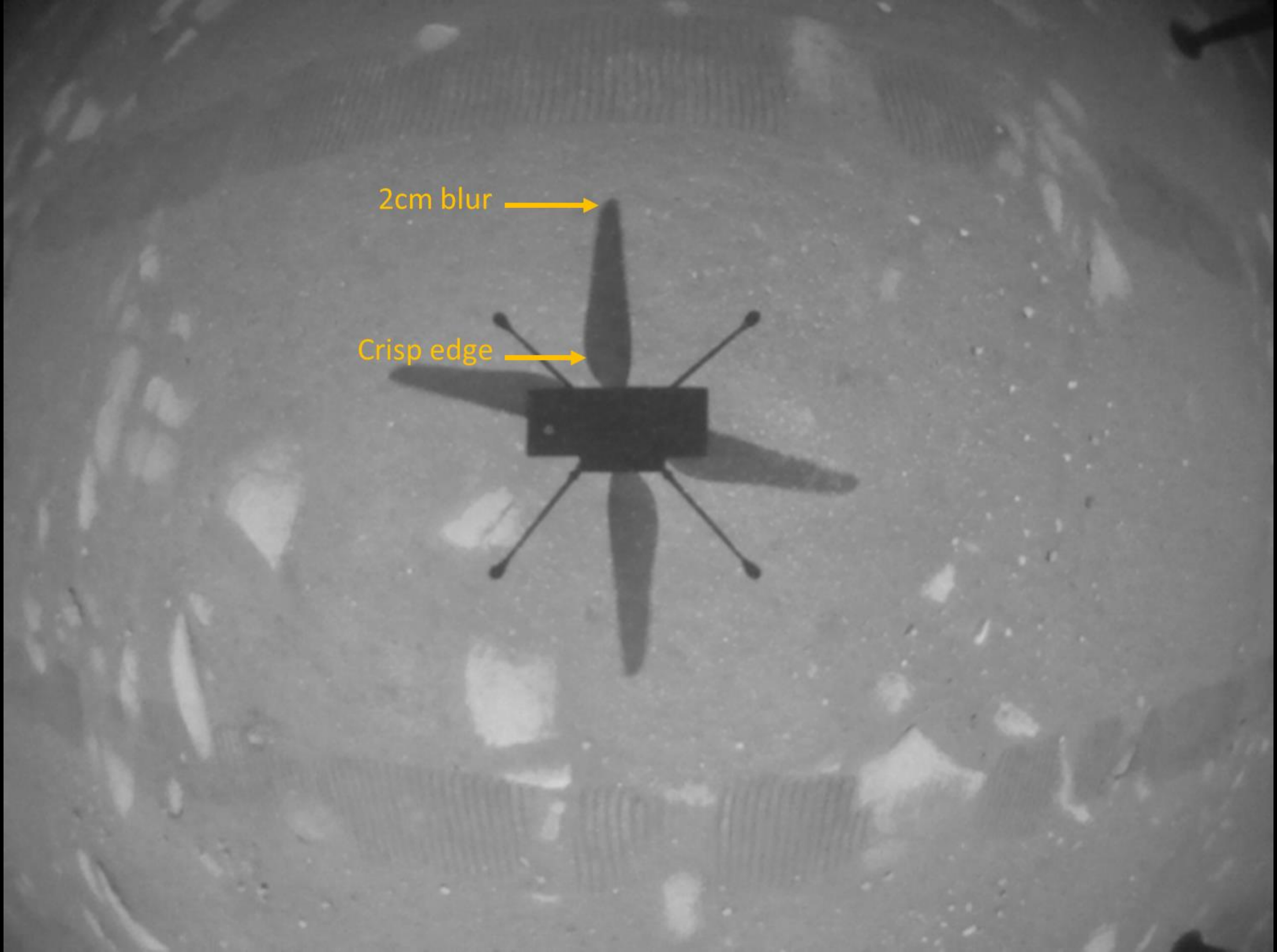


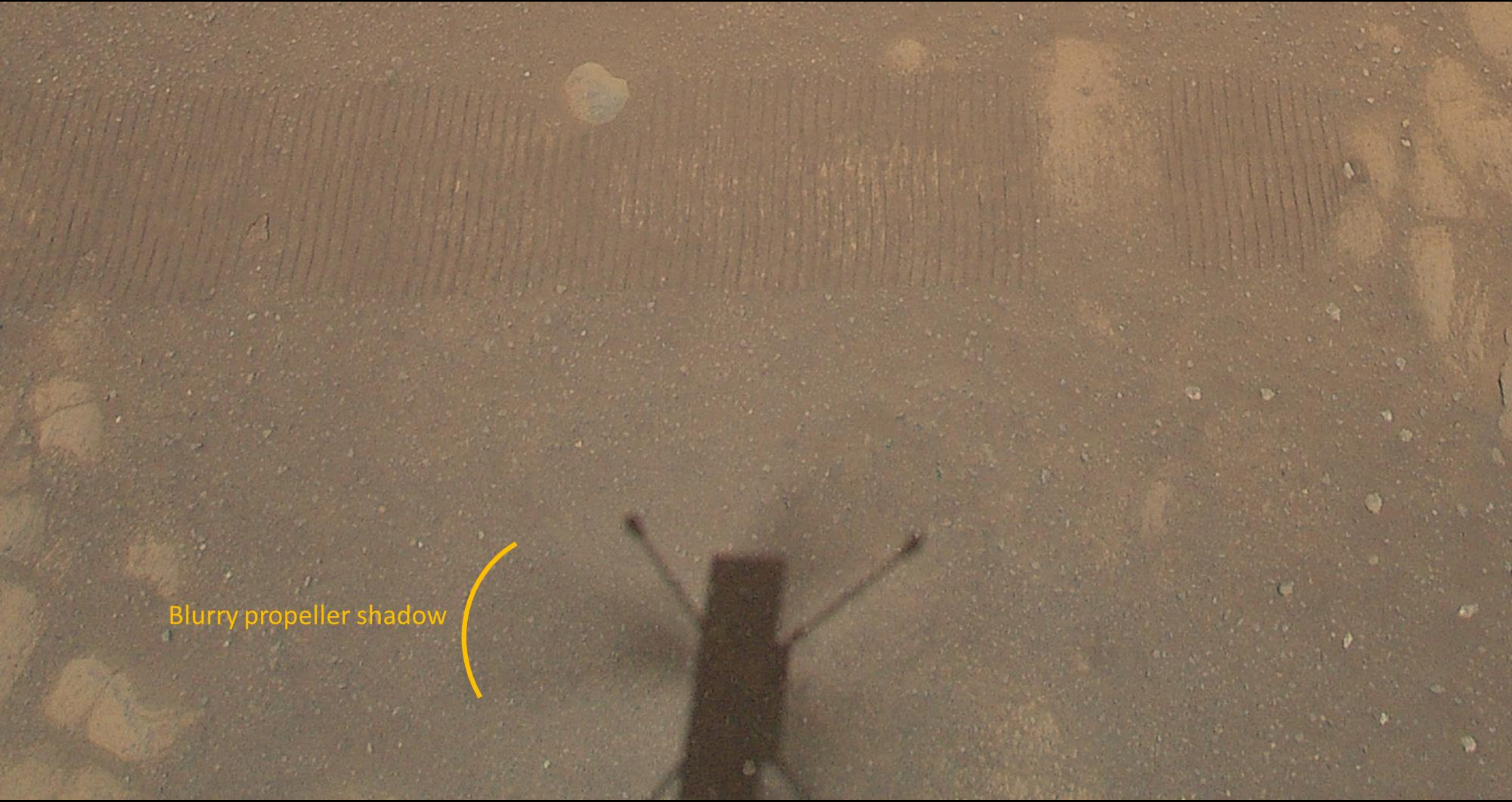


Jet Propulsion Laboratory
California Institute of Technology

Thank you!

BACK-UP


2cm blur
Crisp edge


Blurry propeller shadow

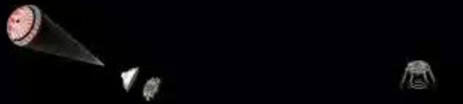
Flight 6 Anomaly

(Very) First Controlled Flights

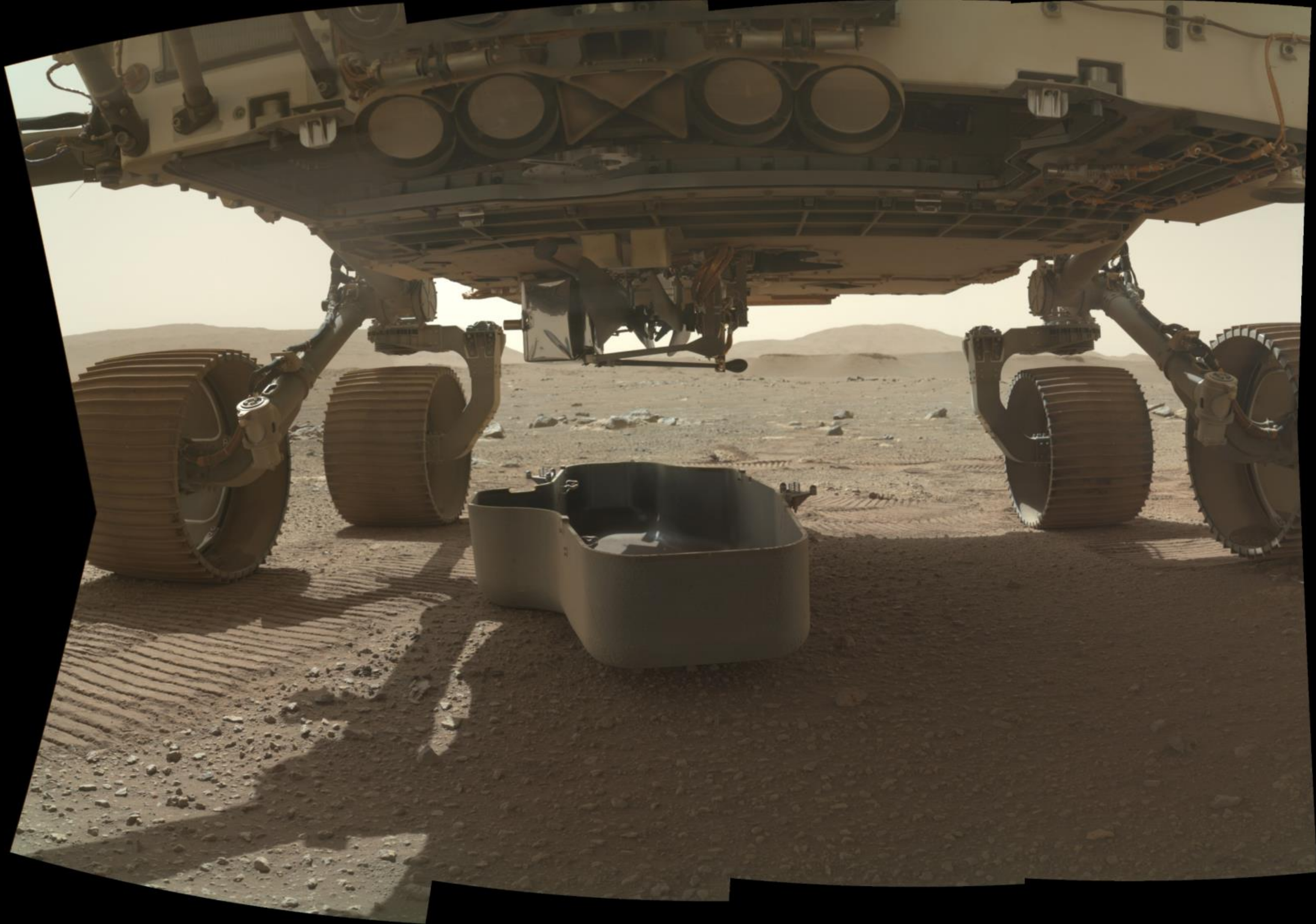
Early Helicopter Prototype Testing
Dec. 19, 2014
25-Foot Space Simulator - JPL


Surviving Launch, Cruise & EDL

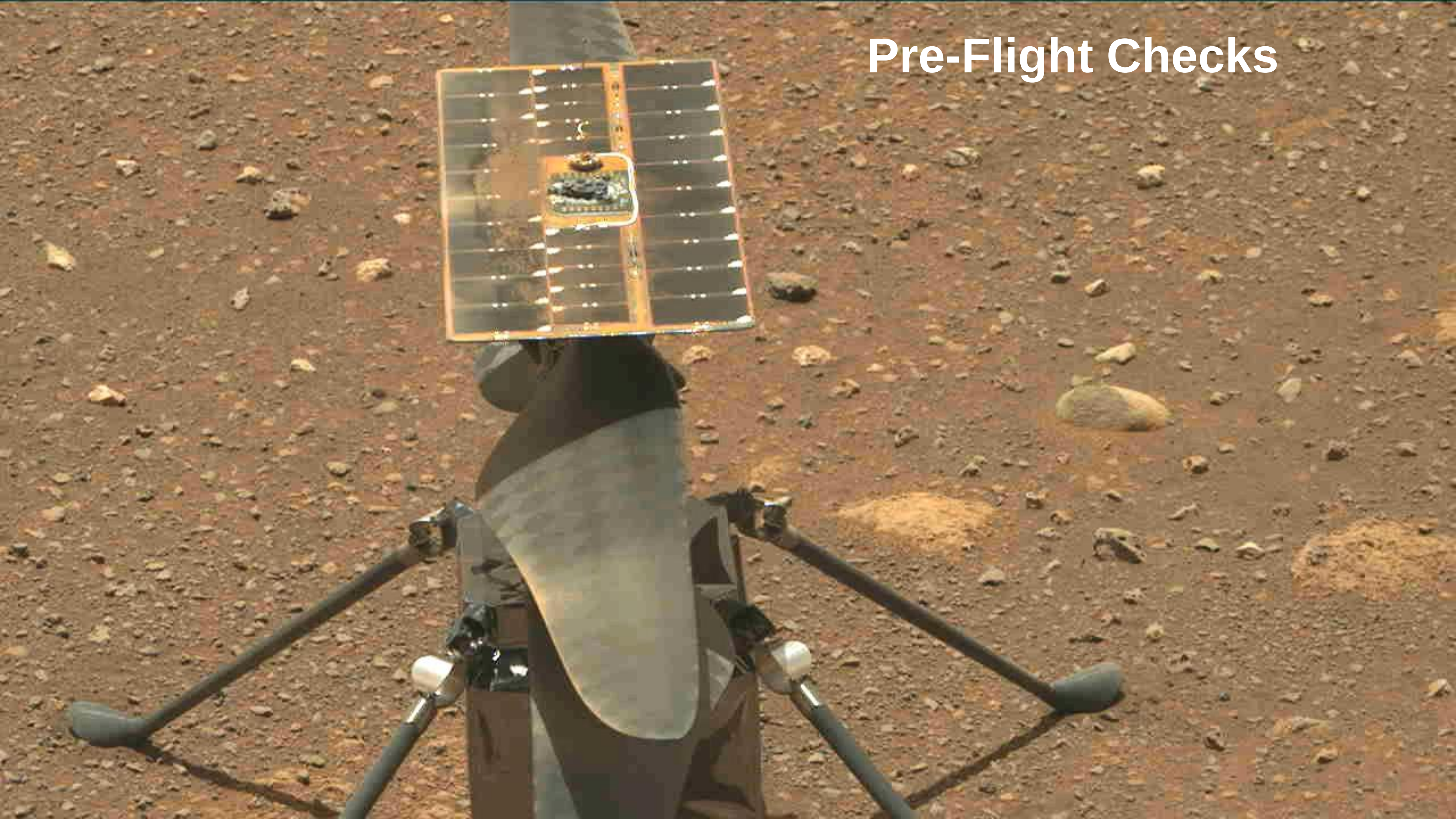
Surviving Launch, Cruise & EDL



Ingenuity deployment



Pre-Flight Checks

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OPTER
DARE MIGHTY THINGS
292-2