INGENUITY MARS HELICOPTER CAMERAS: DESCRIPTION AND RESULTS. J. Maki[1], M. Golombek[1], F. Ayoub[1], R. Deen[1], J. Delaune[1], P. Meras[1], T. Canham[1], J. Ravich[1], M. Cacan[1], N. Williams[1], H. Grip[1], L. Crumpler[2], J. F. Bell III[3], G. Caravaca[4], S. Sholes[1], [1]Jet Propulsion Laboratory/California Institute of Technology, Pasadena, CA (Contact: Justin.N.Maki@jpl.nasa.gov), [2]New Mexico Museum of Natural History, [3]Arizona State University, Tempe, AZ, [4]Université Paul Sabatier Toulouse.

Introduction: The *Ingenuity* Mars Helicopter flew a total of 72 flights on Mars between April 2021 and January 2024 as part of a technology demonstration mission. The goal of *Ingenuity* was to demonstrate powered flight in the thin atmosphere of Mars by conducting five demonstration flights [1]. After successfully accomplishing the first five flights [2], the helicopter began an operations demonstration mission that included 67 additional flights [3], [4].

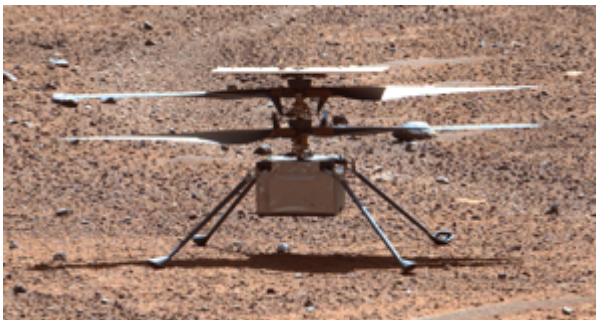

Figure 1. The *Ingenuity* Mars Helicopter on the surface of Mars as imaged by the Mastcam-Z camera [5] on the *Perseverance* rover (Sol 871 , seqID ZCAM05155).

Camera Descriptions: The *Ingenuity* helicopter carried two cameras (Table 1, Figure 2). The first camera, a low-resolution, grayscale camera (Navcam), provided in-flight tracking data for the onboard navigation computer. The second camera, a high-resolution color camera, was originally proposed as a scouting camera (ScoutCam) for the rover. The ScoutCam was later renamed the "Return to Earth" (RTE) camera, to indicate the technology demonstration goal of acquiring a color picture of Mars during flight and returning that image to Earth.

Table 1. Camera specifications

Item	Navcam	RTE
Sensor	CMOS (OV7251), global shutter	CMOS (IMX214), rolling shutter
Lens size	1/7.5" (~2.3 mm diagonal)	1/3.06" (~5.6mm diagonal)
Array size	640 x 480 pixels	4208 x 3120 pixels
Pixel size	3 µm x 3 µm	1.12 µm x 1.12 µm
Sensor size	1.968 mm x 1.488 mm	6.1 mm x 4.524 mm
Field of View	166.5° ±3° (d)	102°(h)x82°(v),125° (d)
Pixel scale	3.57 mrad/pixel	0.53 mrad/pixel
Pixel format	8-bit grayscale	RGB color (8 bit Bayer)

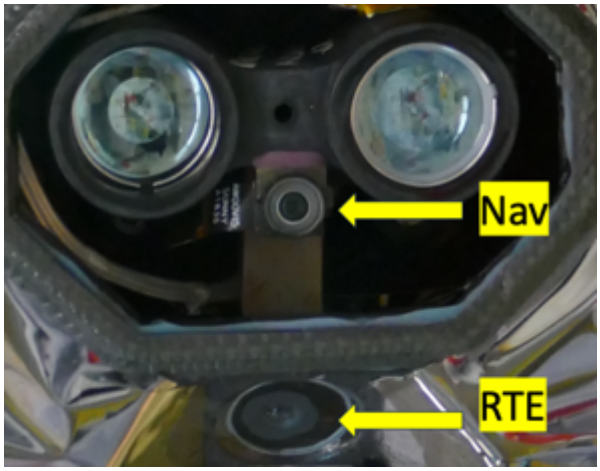

Figure 2. The *Ingenuity* cameras, as viewed from below the helicopter, looking upwards. The Navcam boresight points in the nadir direction (straight down), and the RTE camera boresight points 45° above nadir (e.g., 45° below the horizon). The two large lenses at the top of the images are laser altimeter apertures.

Results: A total of 14,561 images have been returned from *Ingenuity*. Of these images, 13,959 were from the Navcam, and 602 images were from the RTE camera. Navcam images were acquired at 30 Hz during flights for visual-inertial navigation, but a maximum of 200 images per flight were saved in memory for post-flight downlink. RTE images were acquired less frequently and were often targeted based on inputs from the

Figure 3. RTE image acquired on Sol 43 just after helicopter deployment onto the surface.

Perseverance science and operations teams. In addition to acquiring images during flights, landed RTE images were also acquired when on the surface (Figure 3). The angular pixel scale at the center of an RTE image is ~ 0.53 mrad/pixel and ~ 0.33 mrad/pixel at the edges. At the center of a typical landed RTE image (as shown in Figure 3, located ~ 0.2 meters in front of the vehicle) the spatial scale is ~ 0.1 mm/pixel. Most in-flight images were acquired ~ 5-10 meters in altitude. Table 2 lists the spatial resolution for each camera for a range of helicopter altitudes. Once received on Earth, images were processed into a variety of derived image products, including stereo-derived Digital Terrain Models (DTMs) and orthomosaics (Figure 4).

Table 2. Camera spatial scale vs helicopter altitude

Altitude (m)	Spatial Scale (cm/pixel)	
	RTE	Navcam
0.2 (landed)	0.01	0.07
1	0.05	0.36
5	0.27	1.78
10	0.53	3.57
15	0.80	5.35
20	1.06	7.13
25	1.33	8.91

Table 3. Number of *Ingenuity* camera images acquired on Mars, listed by flight # and camera type. Key: # = flight number, N=Navcam, R=RTE, F= acquired during flight or flight activity, L=acquired during landed activity.

#	NF	NL	RF	FL
1	15	0	0	0
2	18	0	3	0
3	24	0	4	0
4	62	0	5	0
5	128	0	6	0
6	106	0	8	0
7	72	0	0	0
8	186	0	0	0
9	193	0	10	0
10	190	0	10	0
11	194	0	10	0
12	197	0	10	0
13	191	9	10	2
14	182	0	0	0
15	191	0	10	1
16	185	0	9	1
17	192	0	10	0
18	184	8	10	2

#	NF	NL	RF	RL
37	146	1	3	1
38	194	0	4	0
39	196	0	6	0
40	192	0	8	0
41	192	0	9	1
42	196	0	13	0
43	10	0	0	0
44	190	0	12	0
45	196	0	14	0
46	192	0	12	0
47	195	0	12	0
48	193	0	13	0
49	191	0	12	0
50	193	0	11	0
51	193	0	12	0
52	195	1	13	1
53	0	0	0	0
54	137	1	1	1

#	NF	NL	RF	RL
19	174	1	9	0
20	192	0	10	1
21	191	0	10	1
22	176	0	9	1
23	191	0	10	2
24	164	0	6	1
25	190	0	10	1
26	190	0	10	0
27	181	0	10	0
28	180	3	10	1
29	183	2	5	4
30	172	0	2	0
31	188	0	4	1
32	185	0	4	0
33	185	2	4	0
34	62	0	1	0
35	162	0	3	0
36	182	0	8	0

#	NF	NL	RF	RL
55	190	0	6	1
56	186	0	6	0
57	185	1	4	1
58	186	0	5	0
59	180	0	5	0
60	185	0	6	2
61	182	0	5	1
62	189	0	7	0
63	196	0	6	29
64	194	0	6	0
65	181	0	2	0
66	90	0	1	23
67	191	0	4	0
68	182	0	6	0
69	182	0	6	1
70	186	0	6	1
71	0	2	1	1
72	3	2375	3	33

All of the raw images from the Ingenuity helicopter have been archived in the NASA Planetary Data System (PDS) [6].

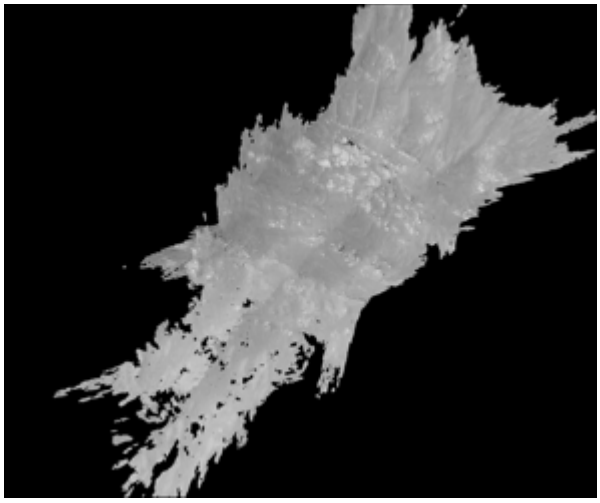

Figure 4. Sol 193 Navcam carpet mosaic (orthographic projection). This mosaic, comprised of 109 individual Navcam images, is 125 meters high by 150 meters wide.

Figure 5. Sol 714 RTE image of Pinestand Mountain, acquired during flight 45 at an altitude of approximately 12 meters.

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References: [1] Balaram et al., SSR 217, 56 (2021), [2] Golombek et al., LPSC 2022, [3] Golombek et al., LPSC 2023, [4] Golombek et al., LPSC 2024, [5] Bell, J.F., Maki, J.N.. et al. SSR 217, 24 (2021). [6] Balaram et al., Mars 2020 Helicopter Camera Suite Bundle. NASA PDS (https://doi.org/10.17189/1522845).