THE COMPLETE ORTHOPHOTOMOSAIC OF INGENUITY NAVCAM IMAGES. A. E. Zubarev[1], N. A. Slodarzh[1] and I. E. Nadezhdina[1], Moscow State University of Geodesy and Cartography (MIIGAiK), 105064, Gorokhovsky per, 4, Moscow, Russia (mexlab@miigaik.ru)

Introduction: The Mars 2020 Ingenuity mission came to its end in January 2024. The first Martian helicopter completed a total of 72 flights and flew over 17 km. Total of 14,553 images, including 13,945 images from a greyscale navigational camera (Navcam) and 608 from a high-resolution color camera (RTE), available at (https://mars.nasa.gov/mars2020/multimedia/raw-images). We present the results of a complete photogrammetric procession of Navcam images.

Camera: Navcam is a low-resolution grayscale fisheye nadir camera; RTE is a high-resolution color camera pointed 45° below horizon along track [1].

Table 1. Camera specifications

Item	Navcam	RTE
Sensor	CMOS (OB7251), global shutter	CMOS (IMX214), rolling shutter
Array size, pixels	640 x 480	4208 x 3120
Field of view, °	166.5	102 x 82
Pixel format	Grayscale	RGB color (8 bit Bayer)
Pixel scale, mrad/pixel	3.57	0.53

As no additional camera parameters, necessary for precise image processing, were published, and no navigation information for Ingenuity is available in Martian reference frame, a reference background is required in order to perform a georeferencing for the Ingenuity images. We chose HiRISE imagery in order to construct such background.

Reference data preparation: In the first step, raw tiles of HiRISE [2] images were selected from PDS (pds-imaging.nasa.gov). Each image's tiles were combined into a single image; the brightness and histogram differences were adjusted between tiles; navigation information was converted to RPC [3].

Table 2. HiRISE images used for DTM creation

Image ID	Data	Off-nadir angle, °
PSP_001820_1985_RED	16.12.2006	1.1
PSP_002387_1985_RED	29.01.2007	1.7
ESP_036618_1985_RED	19.05.2014	5.8
ESP_053734_1985_RED	12.01.2018	5.8
ESP_037396_1985_RED	19.07.2014	8.1
PSP_003798_1985_RED	19.05.2007	15.9
ESP_037119_1985_RED	27.06.2014	17.3
ESP_042315_1985_RED	06.08.2015	28.0

In total, ~13,000 tie-points were measured by SIFT algorithm and filtered by RANSAC method. Adjustment and setereopair construction were performed in PHOTOMOD 8.0 software.

In the second step, adjusted images were used to construct a high-quality digital elevation model (DEM) based on stereopairs, covering all of the Ingenuity flight area (~33 km^2). The vertical accuracy of the resulting DEM is 50 cm; the horizontal pixel size is 25 cm/pixel. Ortho mosaic was obtained by orthorectified images and DTM. The images with small off-nadir angle had a higher priority for mosaicing process.

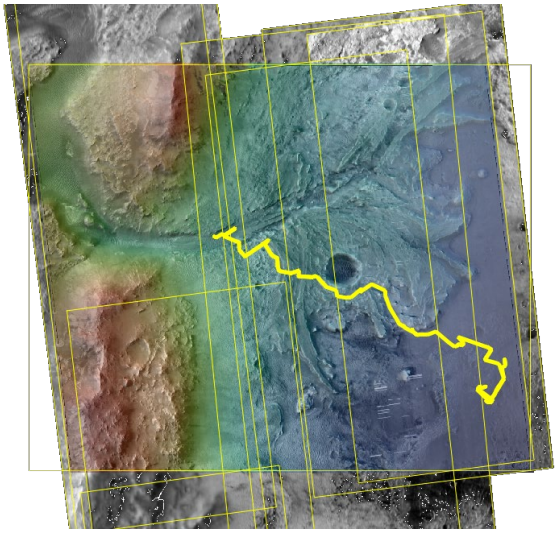

Fig. 1. HiRISE images footprints and DTM

Navcam processing: For the flight 21 (375th sol) the tie-points of the wide-angle Ingenuity camera were measured automatically based on the characteristic features of the relief. The reference points (10 per each flight) were controlled manually simultaneously on HiRISE orthoimages and images from the Ingenuity camera. The accuracy of determining reference points in space was taken to be 0.5 m. Then, self-calibrations Navcam and RTE parameters were determined by the result of bundle-adjustment (see Table 3).

Across all flights 10,030 Navcam images were tied. Only vertical flights were rejected from processing. ~1,231,000 tie-points were adjusted and 148 control points were used to transform models to the Martian reference frame. Tie-points were measured 5,866,974 times, maximum is 250 and average is 5.6 measurements per image. Distortion was applied to whole Ingenuity image dataset (see figure 2).

Table 3. Camera calibration results

Parameter	Value	
	Navcam	RTE
F*, mm	2.1743	12.0243
PPA, mm	0.1070 /-0.0370	-0.2914/-0.7092

Parameter	Value	
	Navcam	RTE
K1	-0.06691966	0.005264416
K2	-0.02679540	-0.0002339622
K3	0.006214104	0.00000408223
K4	-0.001328666	-2.993374e-08
K5	0.00006322423	7.666547e-11
PS**, km	7.2	7.2
P1	-0.005218515	0.000705780
P2	-0.002509209	-0.000352307
P3	0.1073659	0
P4	0.04976130	0
B1	0.004738182	0
B2	-0.001548173	-0.002234866

**F - Focal length, ** PS - Pixel size*

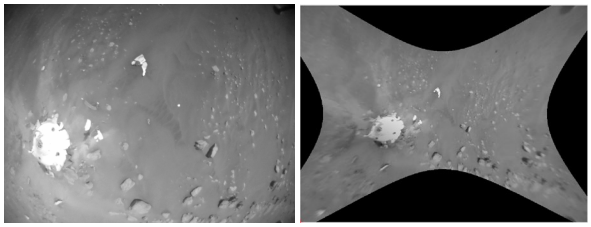

Fig. 2. Example of original and undistorted Navcam image: HNM_0414_0703689953_852ECM_ N0260001HELI03876_0000LUJ03

Based on the obtained accurate data on the position and orientation of the Ingenuity, automatic stereo processing was performed and a highly detailed DEM was obtained for a strip of land 20-32 m across track.

Results: Highly detailed orthomosaics of the flight routes were created from the original images and the resulting DEM. In the process of creating the mosaic, artifacts such as helicopter shadows, contrast spots and image defects were removed. The DEM and mosaics have a pixel size on the ground of 3.8 cm. The actual mosaic resolution is determined by the angular resolution of the camera and the flight altitude. For a typical flight altitude of 10 m, the original pixel is about 3.8 cm in plan (in the middle of the imaged strip) and gradually deteriorates from the nadir to the edges of the strip. The actual spatial resolution of the DEM is somewhat worse. The formal internal accuracy of vertical altitude measurements is 3-6 cm for a helicopter altitude of 10 m near the nadir; the actual noise amplitude visible in the DEM is slightly higher. Nevertheless, Ingenuity data processing provides an actual resolution of images and topographic data an order of magnitude higher than that of the HiRISE camera from orbit. The profile of a small (D = 38 m) crater in Figure 3 according to Navcam data has a depth of 1.2 m with a central peak up to 0.5 m. In HiRISE images, the central peak is not expressed and the DEM has noise, the crater diameter is overestimated.

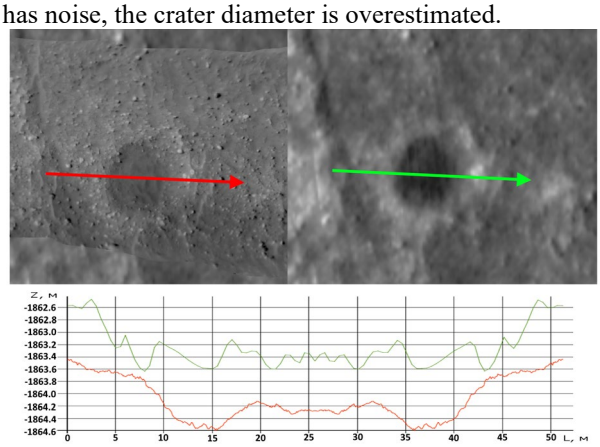

Fig. 3. HiRISE and NAVCam orthomosaics comparison. a) NAVCam, sol 776, flight 52, b) HiRISE, c) vertical profiles

Figure 4 shows small relief details that are poorly readable in HiRISE images. The Navcam orthophoto and DEM profile show the furrow amplitude comparable to the model accuracy. Nevertheless, we can state that the peaks are not model noise (artifacts) and these data can be used for morphometric description of the surface.

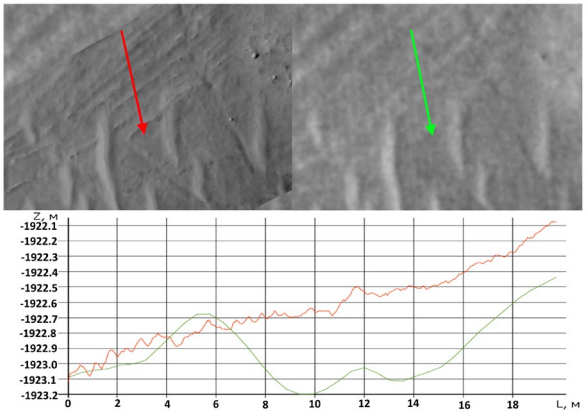

Fig. 4. HiRISE and NAVCam orthomosaics comparison: a) NAVCam, sol 717, flight 46, rad; b) HiRISE, green; c) vertical profiles

The obtained DEMs were referenced to the Martian reference frame with an error of no more than 0.5 m.

Discussion: The complete orthophoto mosaic, as well as the highly detailed DEM, will be available to the general public in 2025.

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References: [1] Balaram et al. (2020), *NASA PDS*. https://doi.org/10.17189/1522845. [2] Delamere A. et al. (2003), *6 IC on Mars*. [3] Brusnikin E.S et al. (2016), *Icarus, V. 278*