



Ingenuity flights (If) on Mars (oM)

Part 4^{\$\$}: Exploratory Experimental Learning (EEL, If 14-18)

KnowLab

rsr.chem1979

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Conspectus: quadcopter (IQ) flew for the first time on Mars for 39.1 second on April 19, 2021. It rose vertically to a height of 10 feet, hovered and landed at the same point. This is the technical demonstration of

proof-of-concept that a powered, controlled flight on Mars is possible for Hi (Helicopter ingenuity). The helicopter was made of "off the shelf," components commercially available. However, NASA takes cybersecurity very seriously. For this reason, no specifics regarding the cybersecurity of agency assets are open for discussion. Perseverance rover takes care of helicopter's all communications base with controllers on Earth. The little chopper checked off several success boxes during the course of eighteen flights. The status-as-on-to date (31st Dec, 2021) shows Hi flew to higher altitude, farther horizontal distance and at faster speeds than engineers hoped. Henceforth, any flight of IQ could be the last one in the harsh Mars environment. It crossed technology demonstration, operations feasibility and is under Eel (Experimental exploratory learning) cover from tenth flight. The typical outcome of If.14 to If.18 are briefed.

Layout

1.	If-14
2.	If-15
3.	If-16
4.	If-17
5.	If-18
SI	1. Image-gallery 2. Numerical Data

\$\$:K. Somasekhara Rao, R. Sambasiva Rao, Ingenuity flights (If) on Mars (oM),
Part 1 ; Ingenuity flew (If 1-5) on Mars (oM), J.Appl.Chem., 2021, 10 (3): 409-436 ;
Part 2 ; Operations Demonstrations (OD, If 5-9), J.Appl.Chem., 2021, 10 (4):569-589;
Part 3 ; Exploratory Experimental Learning (EEL, If 10-13) J.Appl.Chem., 2021, 10 (5):740-754

Pre-Flight High Spin Test: The high spin test for rotor speed at 2700 rpm was successful on Sep,16,2021, in spite of earlier failure of software transition to flight mode earlier. This certifies right signal for taking up IF.14.

Operations Ingenuity (Hi) test Failure			
Location	Airfield H	18.43268°N	77.43924°E
		Landing spot of 13th flight	
Onboard software	Transition to the flight mode	Failed	

Pre-Flight High Spin Test performed	16th Sep, 2021	Success – Ready for next flight	Sol 204
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Ingenuity flight-Fourteen(IF.14): It is a feasibility test flight at higher rotor speed of 2700 rpm in Mars' summertime. This flight is a short 23-second one at a peak altitude of only 16 feet. This flight-time duration is less than that for first maiden flight (39.1 sec) on April 19, 2021.

Highlights of 14 ingenuity helicopter on Mars (Hi-om) :

- ✓ A higher rotor spin speed of 2700 rpm was successful.
 - + It ensures feasibility of If Om in summer time when density of atmosphere on Mars may fall down to 1% (during the afternoon hours preferred for flight) from the present 1.2-1.5%
 - + A scope for an rpm increase if needed for future flights
- ✓ It hovered 15 feet sideways at that speed normally without any glitch
 - + Promotes its robustness against sand ripples
- ✓ A high-speed recording (about seven frames a second) of black-and-white navigation camera

Fourteen Ingenuity flight (If.14)	24th Oct, 2021	08:13	Sol 241
Purpose	Testing <ul style="list-style-type: none"> ✓ Faster rotor spin at 2700 rpm ✓ Vertical height to five meters ✓ Translation sideways 		
Operations			
Takeoff from	Airfield H	18.43284°N	77.43920°E
		Landing spot of 13th flight	

<table border="1"> <tr><td>! Rose vertically 16 ft</td></tr> <tr><td>! Hover</td></tr> <tr><td>! Shift eastward 6.6 ft</td></tr> <tr><td>! Hover</td></tr> <tr><td>! B/w Photos (Nav) : 182</td></tr> </table>	! Rose vertically 16 ft	! Hover	! Shift eastward 6.6 ft	! Hover	! B/w Photos (Nav) : 182	<table border="1"> <tr><td>Rotor speed</td><td>2,700 rpm</td></tr> <tr><td>Max horizontal speed</td><td>~1.1 mph</td></tr> <tr><td>Flight time</td><td>23.0 Sec</td></tr> </table>	Rotor speed	2,700 rpm	Max horizontal speed	~1.1 mph	Flight time	23.0 Sec
! Rose vertically 16 ft												
! Hover												
! Shift eastward 6.6 ft												
! Hover												
! B/w Photos (Nav) : 182												
Rotor speed	2,700 rpm											
Max horizontal speed	~1.1 mph											
Flight time	23.0 Sec											

Landed	Airfield H	18.43284°N	77.43920°E
Flight	Round trip		
Start of	Exploratory Experimental Learning (EEL)		
Ingenuity flight – 14	Success		

Ingenuity flight-Fifteen(IF.15):This flight is the first its return journey to Wright Brothers Field, at the Octavia E. Butler landing site, the start of journey on Mars for both Perseverance rover and ingenuity helicopter. The further ventures follow in time as a full-fledged scout for rover in sampling expeditions. IF.15 is second flight after the start of summer time on Mars.

Fifteen Ingenuity flight (If.15)	November 6, 2021	at 16:22	Sol 254
Purpose	First leap to return the helicopter (IF) to Wright Brothers Field (its first home on MARS—Mother-in-law abode)		
Operations			
Takeoff from	Airfield H	18.43284°N	77.43920°E
		Landing spot of 14th flight	

<table border="1"> <tr><td>! Rose vertically 39 ft</td></tr> <tr><td>! Shift eastward 1,335 ft</td></tr> <tr><td>! B/w Photos (Nav) :</td></tr> </table>	! Rose vertically 39 ft	! Shift eastward 1,335 ft	! B/w Photos (Nav) :	<table border="1"> <tr><td>Max speed</td><td>11 mph</td></tr> <tr><td>Flight time</td><td>128.8 sec</td></tr> </table>	Max speed	11 mph	Flight time	128.8 sec
! Rose vertically 39 ft								
! Shift eastward 1,335 ft								
! B/w Photos (Nav) :								
Max speed	11 mph							
Flight time	128.8 sec							

Landed	Airfield F	18.42871°N	77.44501°E
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Flight	This flight returns Ingenuity to the Raised Ridges region, imaged in Flight 10.
	Return Flight-1
Ingenuity flight – 15	Success

Ingenuity flight-Sixteen (IF.16): It is also a trip with short flight time of 108 sec raising up to a vertical height of 33ft, but glides over “Raised Ridges”.

South Séítah terrain: The raising edges of this area are challenging for Hi flights. The navigation algorithm assumes flat terrain, and thus any drastic changes to the terrain height introduces heading error. This is what happened for flight #9. Ingenuity landed 154 feet away from the center of the 164-foot radius target airfield. The mismatch was less of a concern because the terrain of South Séítah was benign i.e. it allows a large degree of uncertainty in the landing position. But, the terrain on the north side of Séítah is rockier and hence one should be more precise in the landing location on the return path.

Flight 16 will tackle the tricky terrain of the Raised Ridges by making a short flight over these ridges. That is how accumulated heading error is reduced as compared to that can build up over longer flights.

Sixteen Ingenuity flight	November 21, 2021	2:09	Sol 268							
Purpose	Second leap to return the helicopter (IF) to Wright Brothers Field (its first home on MARS – Mother-in-law abode)									
Operations										
Takeoff from	Airfield H									
<table border="1" style="width: 100%;"> <tr> <td>! Rose vertically 33 ft</td> </tr> <tr> <td>! Shift northeast 381 ft</td> </tr> <tr> <td>! to land near Airfield I</td> </tr> </table>	! Rose vertically 33 ft	! Shift northeast 381 ft	! to land near Airfield I	<table border="1" style="width: 100%;"> <tr> <td>Max speed</td> <td>3.4 mph</td> </tr> <tr> <td>Flight time</td> <td>107.9 sec</td> </tr> </table>			Max speed	3.4 mph	Flight time	107.9 sec
! Rose vertically 33 ft										
! Shift northeast 381 ft										
! to land near Airfield I										
Max speed	3.4 mph									
Flight time	107.9 sec									
Landed	Airfield I	18.43013°N	77.44645°E							
Ingenuity flight – 16	Success (Return Flight-2)									

Ingenuity flight-Seventeen (IF.17): This is another flight of series in return journey of If-Om to its start point in the harsh environment. When the helicopter descended toward the surface at the conclusion of this flight, an unexpected cutoff to the in-flight data stream occurred between Hi and the base station on the Perseverance rover. Later, of course, a handful of data radio packets were received, indicating a healthy helicopter status on the surface. On December 10th, separate data packets were downlinked to JPL's base in California, which confirmed that Ingenuity was in excellent condition and flight 17 was successful. The reason for this glitch was Hi 'flew behind a hill' or out of the rover's line of sight. It interrupted high-speed communications between the rover and Helicopter for a brief time period.

If at all radio link is lost on landing, it may take several days or weeks until the line-of-sight between Ingenuity and Perseverance improves enough to attempt a communication session. An onboard inertial measurement unit (IMU) on Ingenuity keeps track of its motion monitoring acceleration and rotation rates. Integration of this data over time extracts information on how fast it is moving and how it is oriented in space. The onboard control system responds and generates an action sequence to correct the motion of Hi by adjusting control-parameters very fast i.e., at a rate of 500 times per second. Although, post-flight data analysis is an inconvenience and associated with delay. it will become a normal routine in future Martian flights in summer on challenging terrain.

Seventeen Ingenuity flight(IF.17)	December 05, 2021	12:25	Sol 282									
Purpose	Another leap to return the helicopter (IF) to Wright Brothers Field (its first home on MARS – Mother-in-law abode)											
Operations												
Takeoff from	Airfield I											
<table border="1" style="width: 100%; border-collapse: collapse;"> <tr><td style="background-color: #e0e0e0;">! Rose vertically 33 ft</td></tr> <tr><td style="background-color: #e0e0e0;">! Shift northeast 614 ft</td></tr> <tr><td style="background-color: #e0e0e0;">! To land near Airfield K</td></tr> <tr><td style="background-color: #e0e0e0;">!</td></tr> <tr><td style="background-color: #e0e0e0;">! Reverse path of flight 9</td></tr> </table>		! Rose vertically 33 ft	! Shift northeast 614 ft	! To land near Airfield K	!	! Reverse path of flight 9	<table border="1" style="width: 100%; border-collapse: collapse;"> <tr><td>Max speed</td><td>5,6 mph</td></tr> <tr><td>Flight time</td><td>116.8sec</td></tr> </table>		Max speed	5,6 mph	Flight time	116.8sec
! Rose vertically 33 ft												
! Shift northeast 614 ft												
! To land near Airfield K												
!												
! Reverse path of flight 9												
Max speed	5,6 mph											
Flight time	116.8sec											
Landed	Airfield K	18.43306°N	77.44771°E									
Ingenuity flight – 17	Success (Return Flight)											

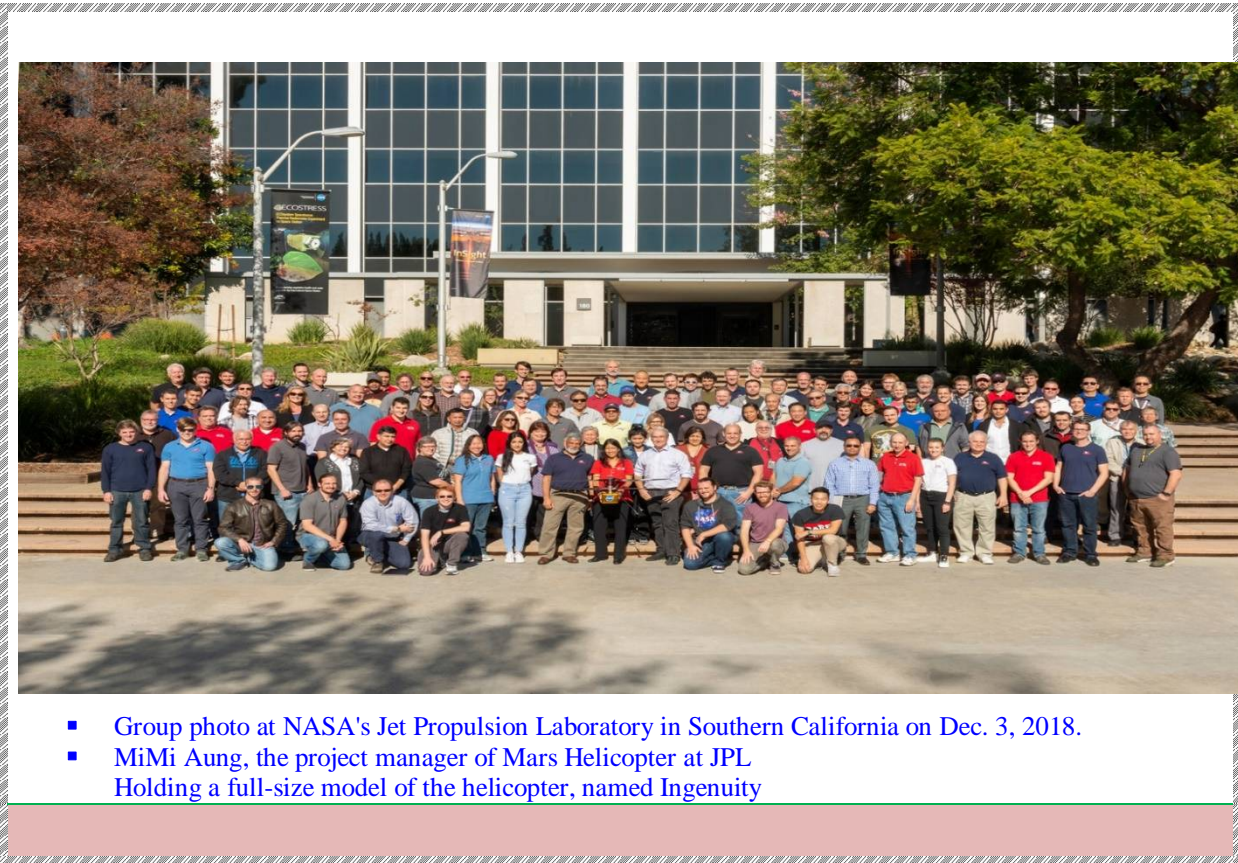
Ingenuity flight-Eighteen (IF.18):The modified flight sequence to a low-data-rate mode for communication resulted in an additional signal-strength boost to the radio link. This led with the highest chance of maintaining a link throughout landing process. Hi travelled 750 feet horizontal distance, climbed an altitude of 33feet above the surface on the inhospitable alien world. It flew at a speed of 5.6 mph. The landing site is close to the northern boundary of Séítahi.e.rotorcrafft’s 10th flight location on Mars.

Eighteen Ingenuity flight(IF.18)	December 15, 2021		Sol 292
Purpose	Another leap to return the helicopter (IF) to Wright Brothers Field (its first home on MARS – Mother-in-law abode)		

Operations

Takeoff from	Airfield K						
<ul style="list-style-type: none"> ! Rose vertically 33 ft ! Shift northeast 750 ft ! to land near Airfield I ! ! Reverse path of flight 9 	<table border="1"> <tr> <td>Max speed</td> <td>5.6 mph</td> </tr> <tr> <td>Flight time</td> <td>124.3sec</td> </tr> </table>			Max speed	5.6 mph	Flight time	124.3sec
Max speed	5.6 mph						
Flight time	124.3sec						
Landed Nearer to flight 9 takeoff spot Ingenuity flight – 18	Airfield L	18.43013°N	77.44645°E				
	Success (Return Flight)						

SI: Supplementary Information
Image-gallery
Credit : NASA.Gov
 Credit: NASA/JPL-Caltech -



Teddy Tzanetos (JPL): Taking Flight With the Mars Helicopter
Opening Doors to New Classes of Exploration

ORBITERS
Wide-Area
Lower-Res Imaging

LANDERS
Single Location
No Mobility
Local High-Res Imaging

ROVERS
Limited Mobility
Local High-Res Imaging

ROVER PAIRED WITH SCOUT
Efficient Mobility
Wide-Area High-Res Imaging

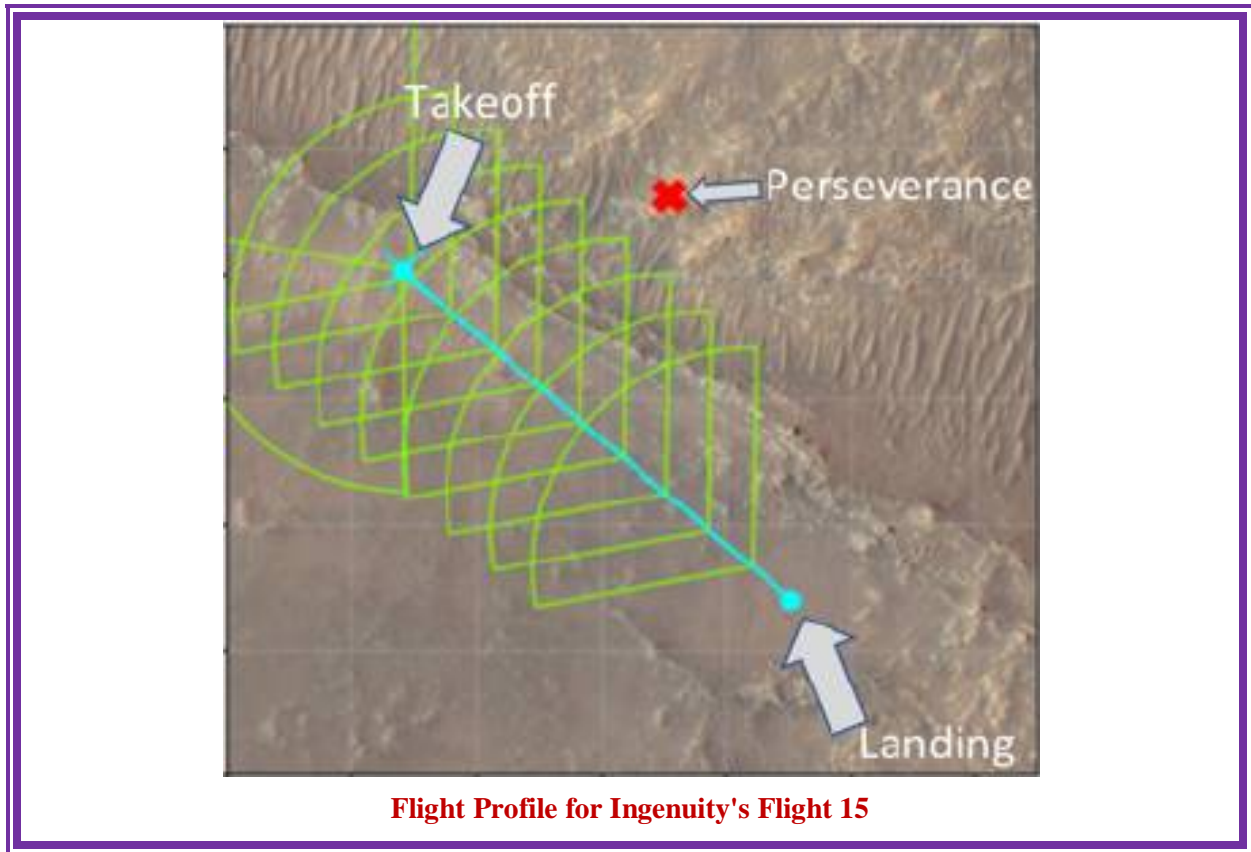
INDEPENDENT HELICOPTER SCOUT
Long-Range Mobility
Wide-Area High-Res Imaging

REGIONAL EXPLORATION USING MULTIPLE HELICOPTERS

BIOLOGICALLY SENSITIVE ZONE EXPLORATION

22:28 / 23:50





SI: Supplementary Information-2 Numerical Data

Credit : NASA.Gov
Credit: NASA/JPL-Caltech -

Timeline of Ingenuity flight Schedules (Ifs)

Exploratory Experimental Learning (Eel)			
Test@			
	204	Sep 16,2021	
14	241	October 24, 2021	08:13
15	254	November 6, 2021	16:22
16	268	November 21, 2021	2:09
17	282	December 05, 2021	12:25
18	292	December 15, 2021	
@Pre-Flight High Spin Test			



Eel (Experimental exploratory learning)			
Flight	Sol	Date	Time
10	152	24 th July, 2021	21:07
11	163	5 th August, 2021	04:53
12	174	16th August, 2021	12:57
13	193	4th Sep, 2021	12:57

Flight	Sol	Date
Demonstration. Technology (DT)		
1	58	April 19, 2021
2	61	April 22, 2021
3	64	April 25, 2021
4	69	April 30, 2021
5	76	May 07, 2021
Operations. Demonstration (OD)		
6	91	May 22, 2021
7	107	June 08, 2021
8	120	June 21, 2021
9	133	July 5, 2021

Sol: Martian Day starting with Ingenuity landing on MARS
Date: Calendar on Earth ; Time:

Flight totals¹

Flight property	(April 3, 2021/Sol 43) Since deployment	Tech demo phase	operations demo + Eel
Sols achieved	275	31	244
Number of flights	18	5	13
Distance flown (km)	3.82	0.50	3.32
Time flown (sec)	1971 (32 min 51 s)	396 (6 min 36 s)	1575 (26 min 15 s)

Ingenuity's imagery

Count of stored images from both cameras per each flight ^[144]				
Flight No.	Date (UTC) and Mars 2020 mission sol	Photographs		Comments
		b/w NAV	color RTE	
	Before April 19, 2021 (sol 58)	6	6	Preflight camera tests
1	April 19, 2021 (sol 58)	15	—	
2	April 22, 2021 (sol 61)	17	3	The first color photo session
3	April 25, 2021 (sol 64)	24	4	
4	April 30, 2021 (sol 69)	62	5	
5	May 7, 2021 (sol 76)	128	6	
6	May 23, 2021 (sol 91)	106	8	
7	June 8, 2021 (sol 107)	72	0	RTE was turned off
8	June 22, 2021 (sol 121)	186	0	
9	July 5, 2021 (sol 133)	193	10	

10	July 24, 2021 (sol 152)	190	10	Five pairs of color images of Raised Ridges taken to make anaglyphs
11	August 5, 2021 (sol 164)	194	10	
12	August 16, 2021 (Sol 174)	197	10	Five pairs of color images of Séítah taken to make anaglyphs
13	September 5, 2021 (Sol 193)	191	10	
	September 16, 2021 (Sol 204) to October 23, 2021 (Sol 240)	6	1	Preflight 14 tests
14	October 24, 2021 (Sol 241)	182	—	
15	November 6, 2021 (Sol 254)	191	10	
	November 15, 2021 (Sol 263)	—	1	Ground color photo
16	November 21, 2021 (Sol 268)	103	9	
	November 27, 2021 (Sol 274)	—	1	Ground color photo
17	December 5, 2021 (Sol 282)	5	—	
18	December 15, 2021 (Sol 292)	20	—	