Mars Helicopter Telecom

Amateur Radio Presentations, 2021-2024, as updated

Courtney Duncan, Jet Propulsion Laboratory, California Institute of Technology, Retired

Abstract

The highly successful *Ingenuity* - Mars Helicopter - technology demonstration came to an end in January 2024 after 72 flights over 1000 sols (1.5 Mars years) exploring Mars. The author led the telecommunications team for *Ingenuity* from conception through flight operations and describes it here.

Contemporaneous with this activity N5BF was also active on 23 cm EME and 3 cm tropo, and other amateur radio activities.

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- Cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.
- Images of *Perseverance* and *Ingenuity* in preparation and on Mars from https://mars.nasa.gov/
- This presentation cleared through Unlimited Release System URS301156: CL#21-2901
- Extended with material from the public domain, 2024.
  - In general, see https://science.nasa.gov/mission/mars-2020-perseverance/ingenuity-mars-helicopter/

Mars Helicopter Telecom JPL Team

- Scot Stride – Hardware, Testbed
- Nacer Chahat – Antennas
- Lauren McNally - Radio Software
- Matt Chase KF7WPG – Interface Software
- Charles Wang / Jorge Gonzalez KI6BJB - Testbed
- Carl Spurgers – Electronics Design Advisor
- Peter Ilott KN6GLO – M2020 Telecom
- Courtney Duncan N5BF – MH Telecom Lead
- Eric Archer N6CV (SK) - Founder

Field Test Team

- Dorothy Lewis
- Josh Miller KB3UUS
- Curtis Jin
- Manu Decrossas KF5QOE
- Dave Bell, ex AH6HO

What is a Helicopter?

- An Aerial Vehicle that can hover

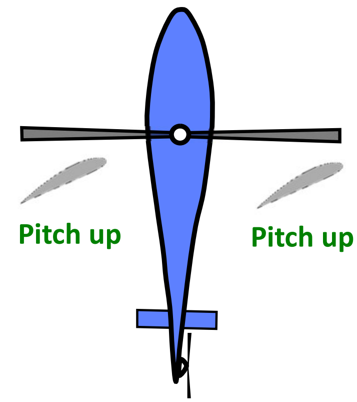
- Interesting Control Features
  - Blades operate at constant RPM throughout flight (~2585 RPM for *Ingenuity*)
  - Controlled by "Collective" and "Cyclic" pitch on blades
  - Via swashplate from servos (or "stick and rudder" for human pilots)
  - System is inherently unstable, must be actively controlled

- Mars Helicopter is a torque cancelling two-rotor counter-rotating design
  - Eliminates need for pesky tail rotor yaw control

Types of Pitch Variation

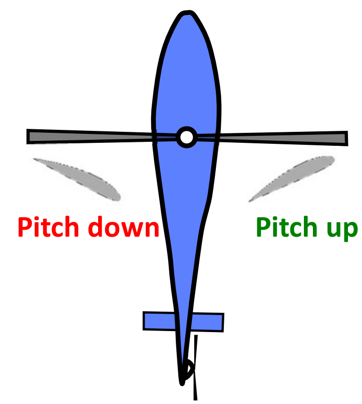
Collective control

- Changes *average* blade pitch

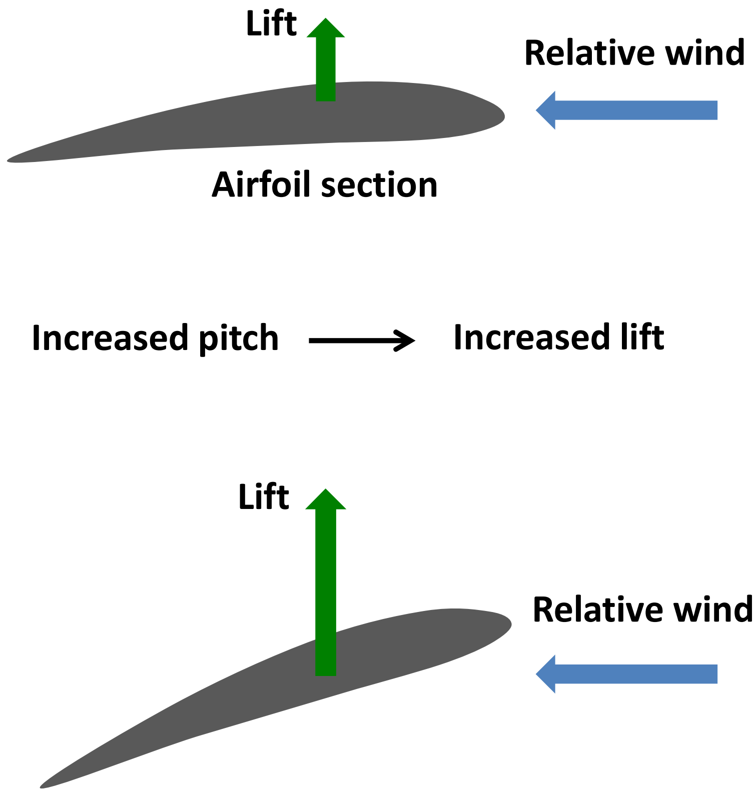


Cyclic control

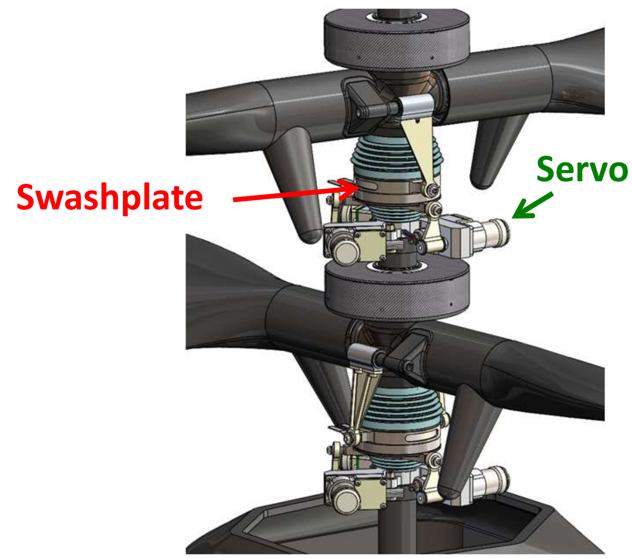
- Changes blade pitch *periodically*
- Increases lift on one side
- Decreases lift on other side



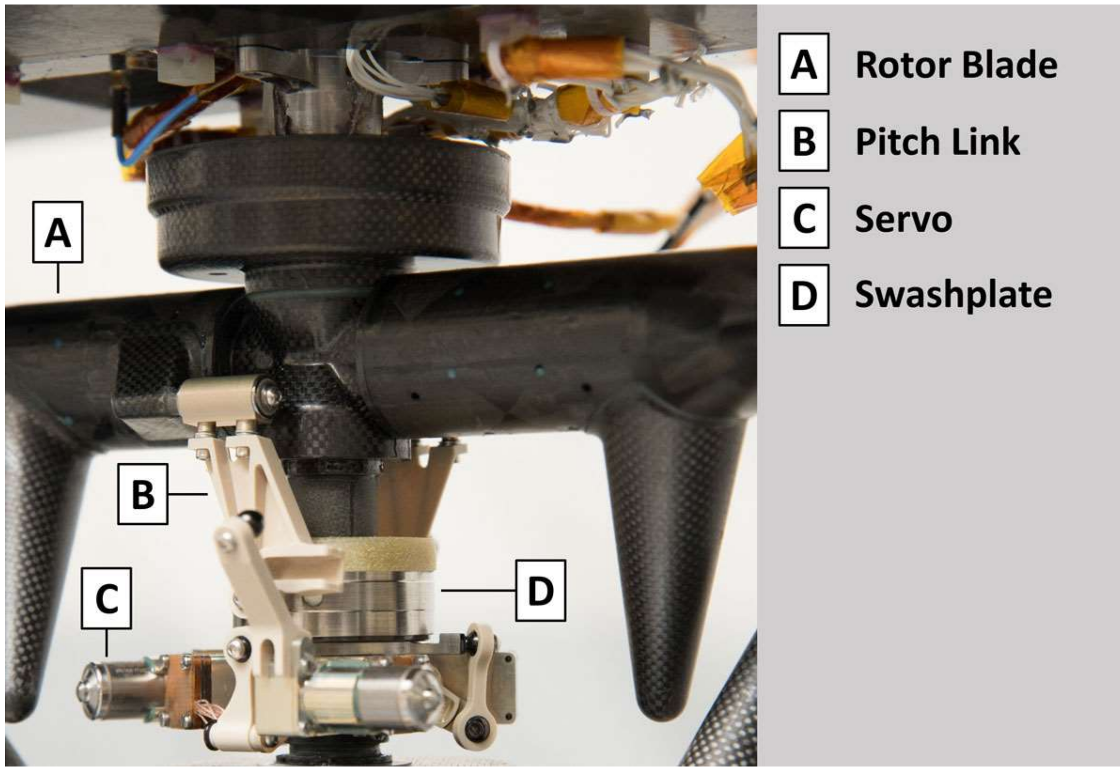
Helicopter is Controlled with Variable Pitch



Pitch controlled with servos that move *swashplates*



Actual Dual Rotor Control Assembly



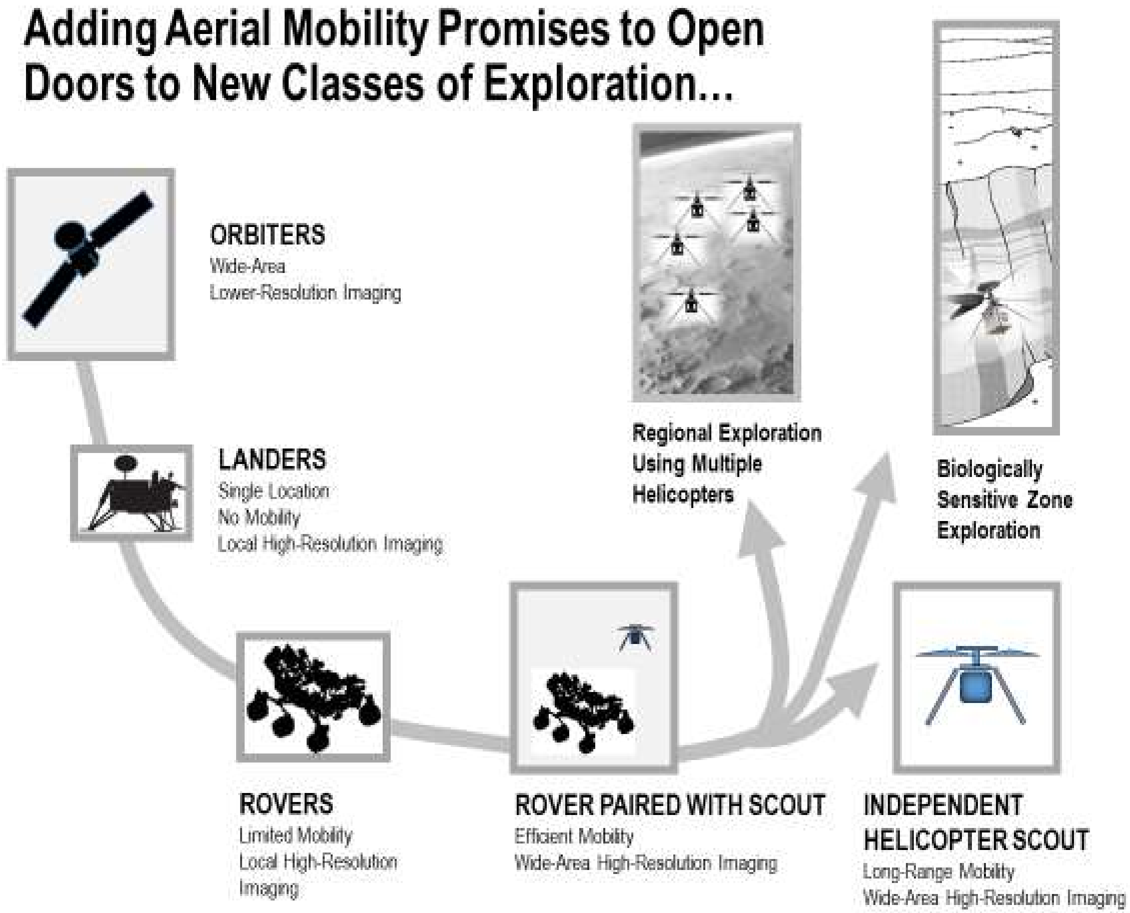
From 2021 September 28 status blog entry at https://mars.nasa.gov/technology/helicopter/status/

What is Mars Helicopter?

- First Aerial Vehicle to fly on another planet
- "Technology Demonstration"
- Deployed on Mars by *Perseverance*
  - Launched 2020 July 30 (KSC)
  - Arrived 2021 February 18 (Sol 0)
  - Deployed 2021 April 3 (Sol 43)
  - 1st Flight 2021 April 20 (Sol 59)
  - 72nd Flight 2024 January 25 (Sol 1035: 1.5 Mars years)

- Major Challenges
  - Thin air: 8 torr (30 km Earth atmosphere equivalent) CO_2
  - Must fit into some ~meter sized M2020 carrying envelope
  - So: Mass <= 1.8 kg (actual "as flown" mass 1800.0 grams)
  - Also: Environment is cold: < -40 C by day, < -100 C by night
  - Power tight: 20 W-h battery ("vaping"), solar panel, survival heaters
    - Sorties (@~300 W) one or two minutes

Why?



Adding Aerial Mobility Promises to Open Doors to New Classes of Exploration...
ORBITERS
Wide-Area
Lower-Resolution Imaging
LANDERS
Single Location
No Mobility
Local High-Resolution Imaging
ROVERS
Limited Mobility
Local High-Resolution Imaging
ROVER PAIRED WITH SCOUT
Efficient Mobility
Wide-Area High-Resolution Imaging
INDEPENDENT HELICOPTER SCOUT
Long-Range Mobility
Wide-Area High-Resolution Imaging
Regional Exploration Using Multiple Helicopters
Biologically Sensitive Zone Exploration

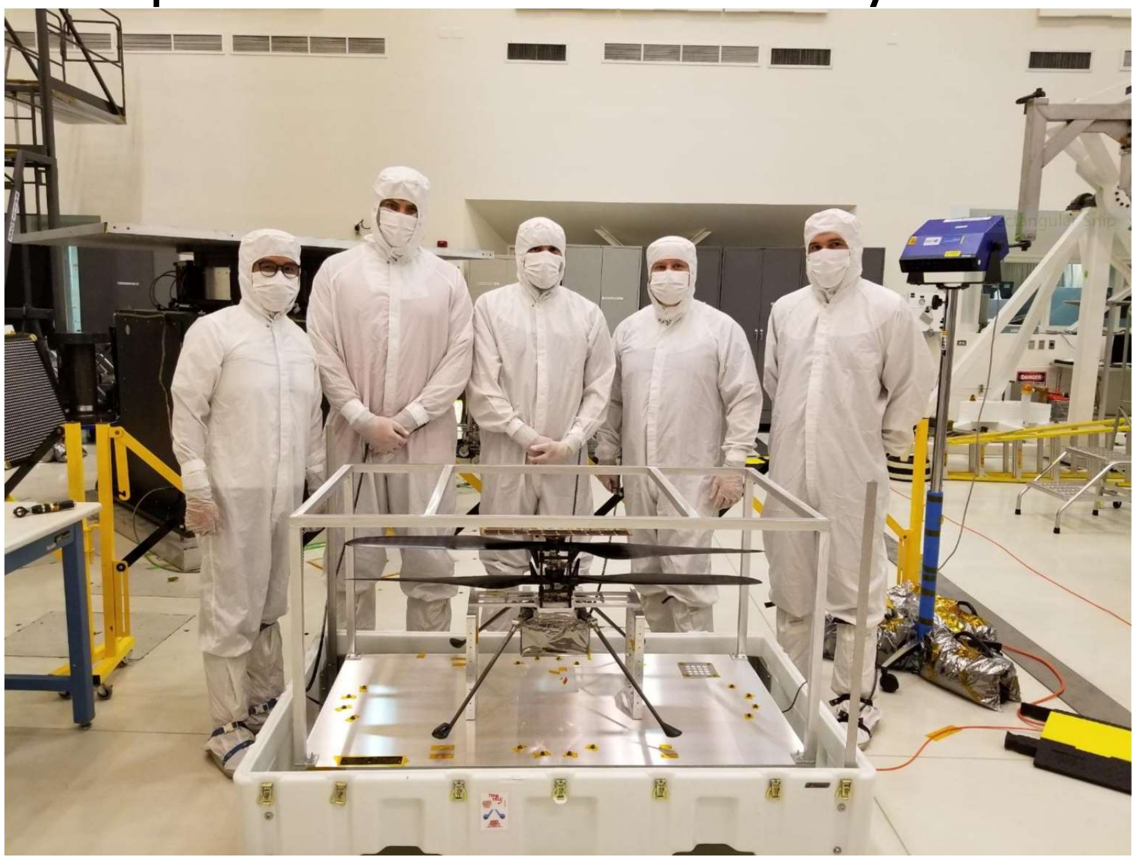
AeroVironment – Major Industrial Partner

- Founded by Paul MacReady
  - Designer of the human-powered Gossamer Condor that won the Kremer Prize
  - And the Gossamer Albatross that crossed the English Channel
    - Piloted by *Bryan Allen*, recently retired from JPL
- Simi Valley, CA
- Unmanned, electric aerial vehicles, drones and such
- Experience with unusual designs and environments
- Military systems, precision agriculture, etc.

- Mars Helicopter rotors, motors, servos, mast & wiring, landing gear
  - JPL does the rest – electronics, IP, I&T, ATLO, mission design
  - Ames Research Center does aerodynamic analysis

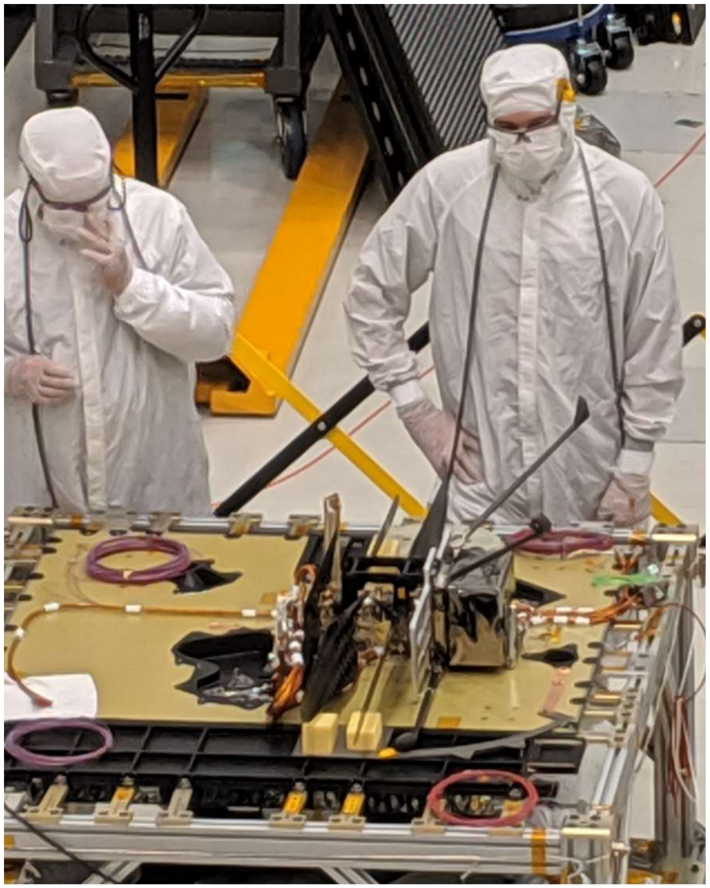
to Mars on Perseverance

Mars Helicopter Flight Model in Spacecraft Assembly Facility



Ingenuity delivered for integration on *Perseverance* 7/9/19

Installation on Deployment Mechanism

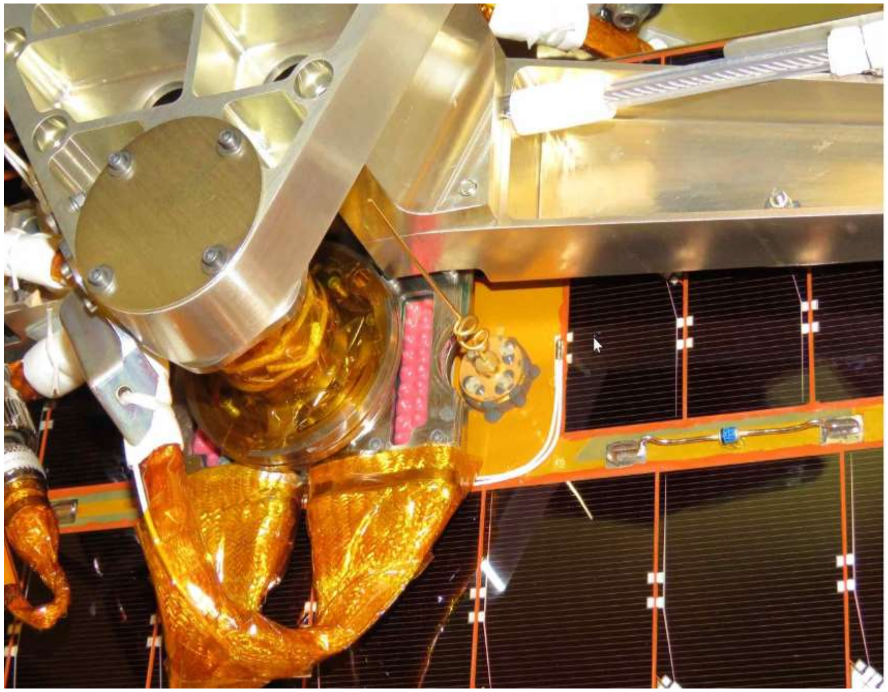


Landing Gear
being folded

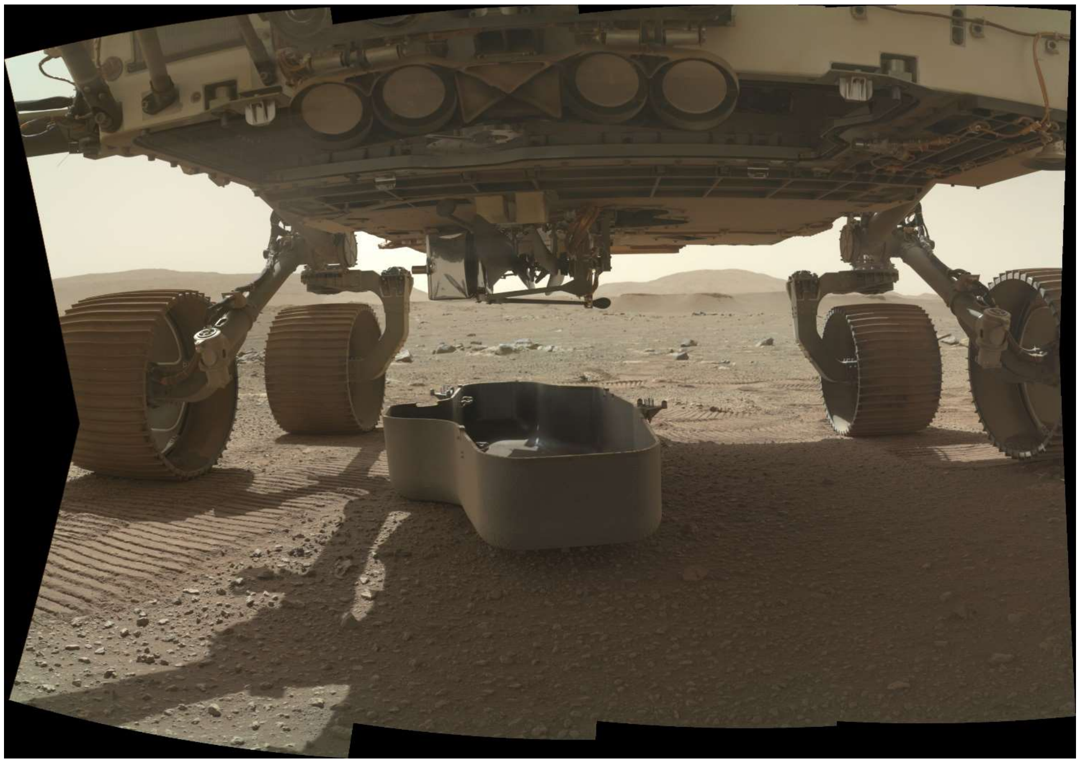
Pebble Shield

Ingenuity underneath *Perseverance*

914 MHz Antenna on Solar Panel next to “Mouse Trap” attachment



On Mars Ready to Deploy

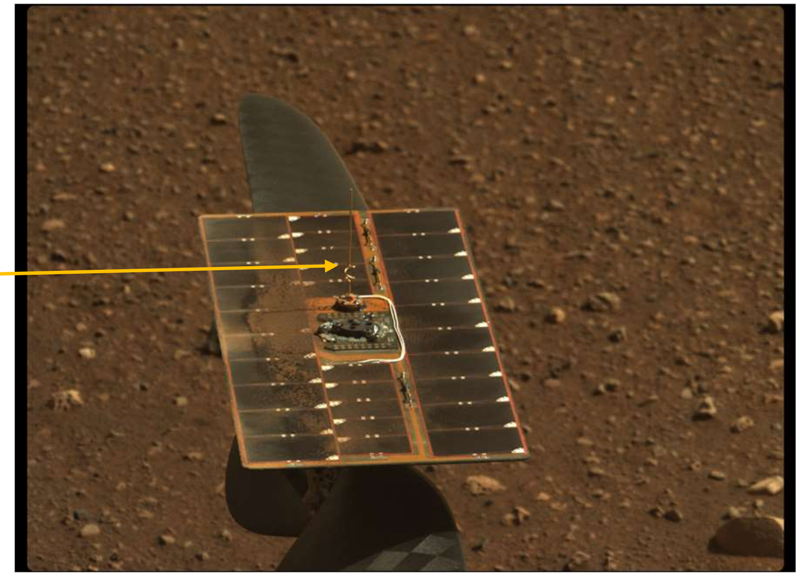


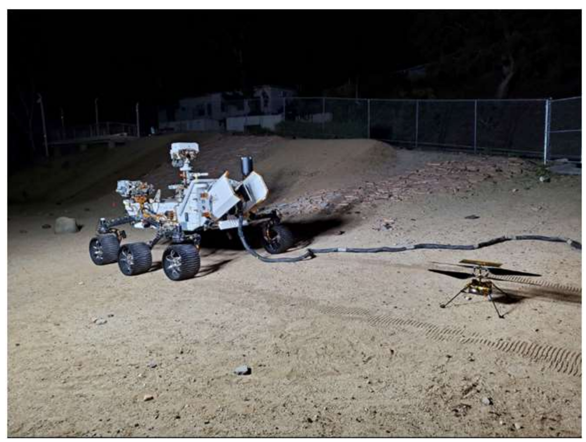
Debris Shield on Mars (with a little dirt in it)

Swing Down

Drive Off
Ingenuity is on its own.

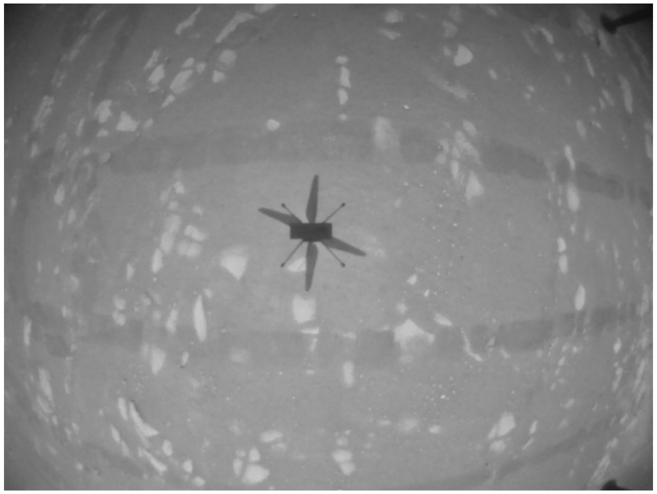
Ingenuity solar panel closeup feature 914 MHz whip antenna and EDL Mars dirt.





“Practice” drive off in the JPL Mars Yard

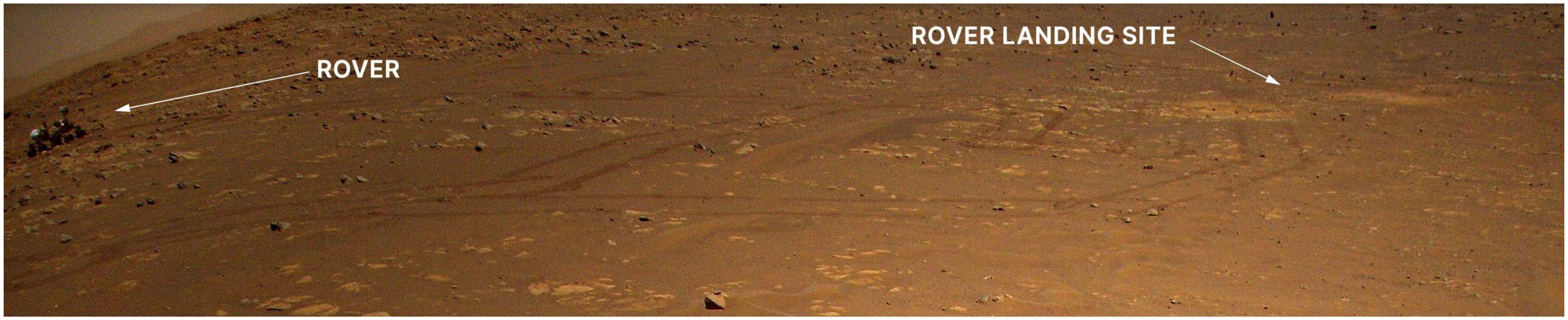
Flights on Mars!



Flight #1 around local noon on Sol 59
Helicopter shadow "straight down" from 3 meters in navigation camera image. (Notice rover tracks.)

Flight #2 viewed from *Perseverance* at Van Zyl Overlook. Altitude 5 meters.

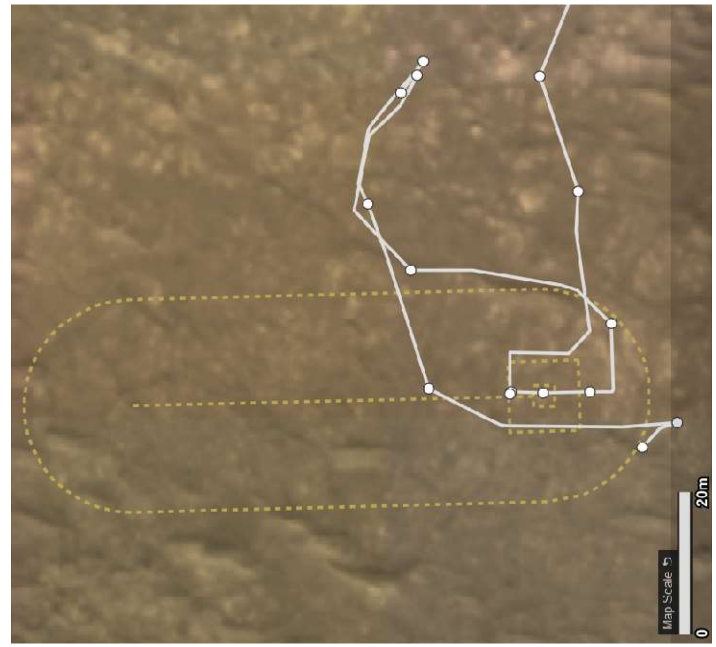
Glimpse of *Perseverance* by "Return To Earth" (RTE) camera during Flight #3



View from Return to Earth Camera on Flight #3

Helicopter Shadow

Helicopter Landing Gear

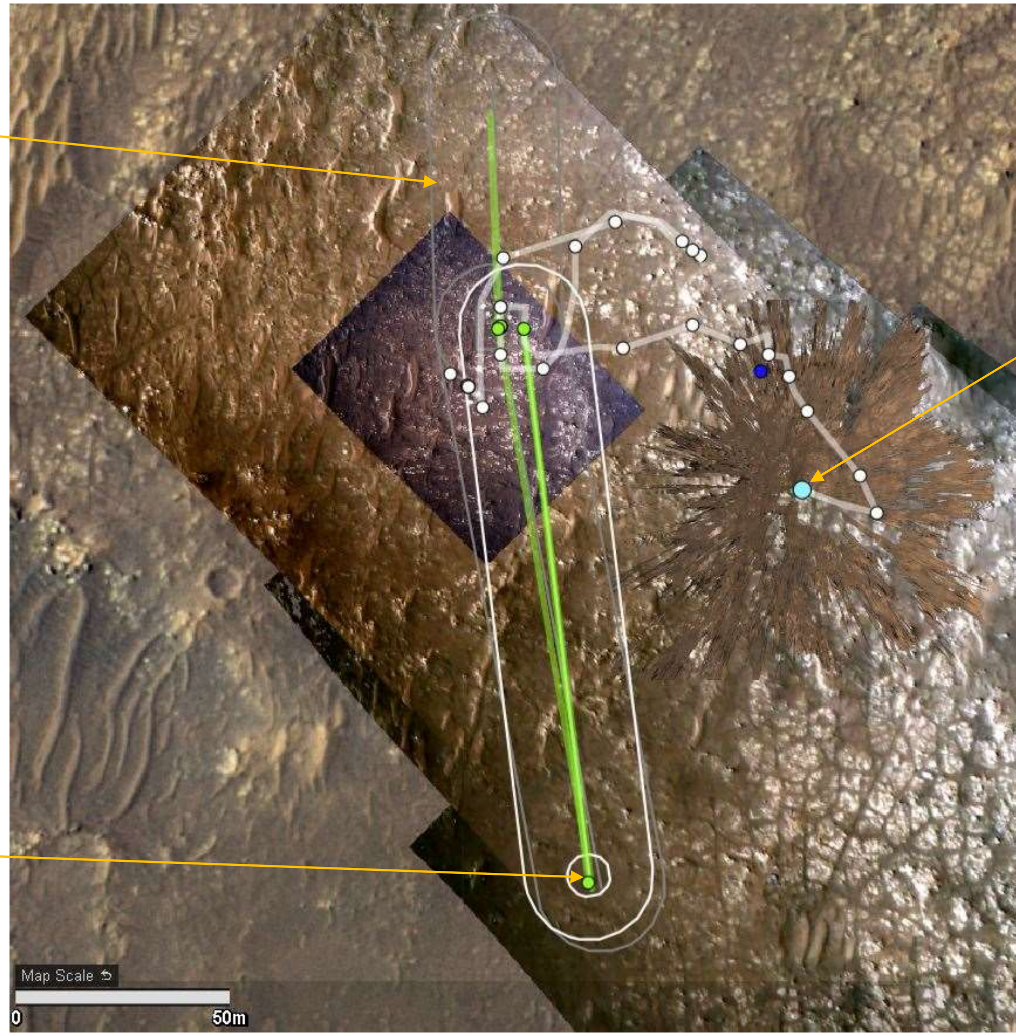


Compare with
https://mars.nasa.gov/mars2020/mission/where-is-the-rover/
(Yes, flying with camera pointed to the side.)

Original Wright Field

Flights 4 and 5 planning based on HiRISE (high resolution imaging experiment) data from Mars Reconnaissance Orbiter

Flight 4 inspection and return
Flight 5 landing spot



Perseverance location at Van Zyl Overlook

Flight #5 Telecom Performance

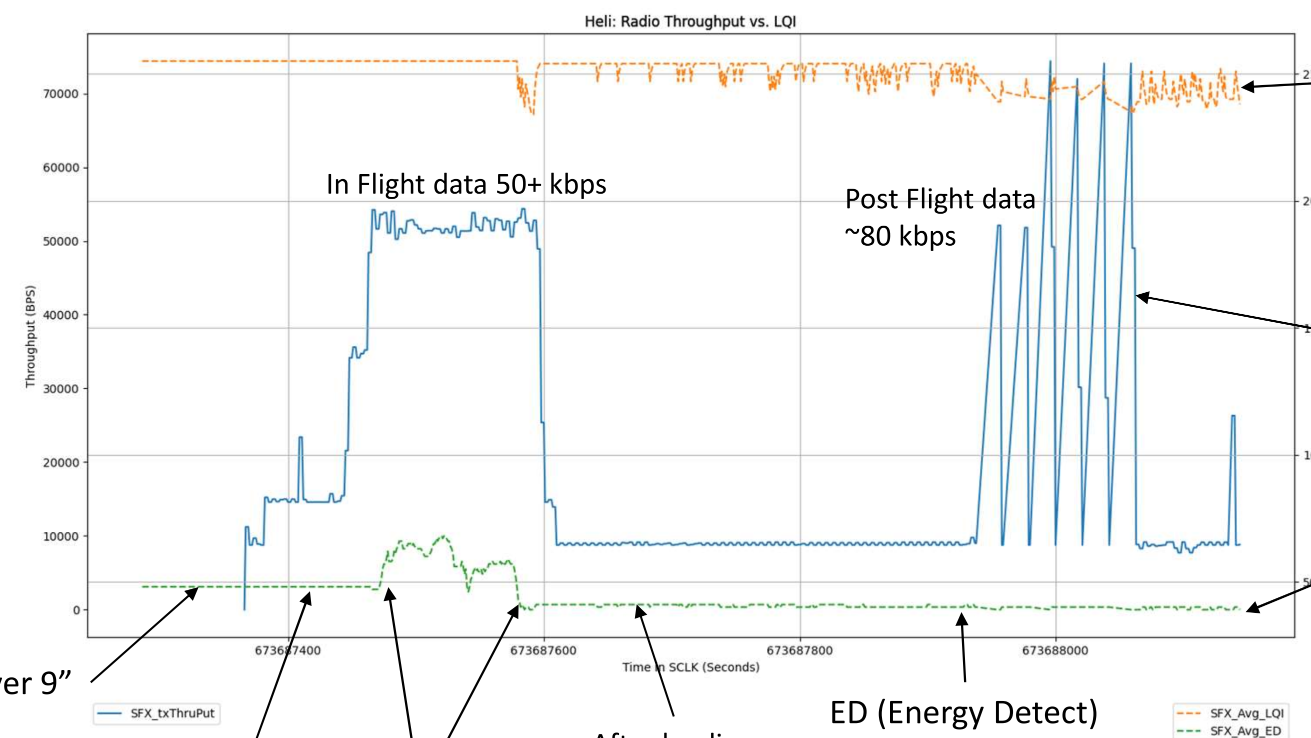
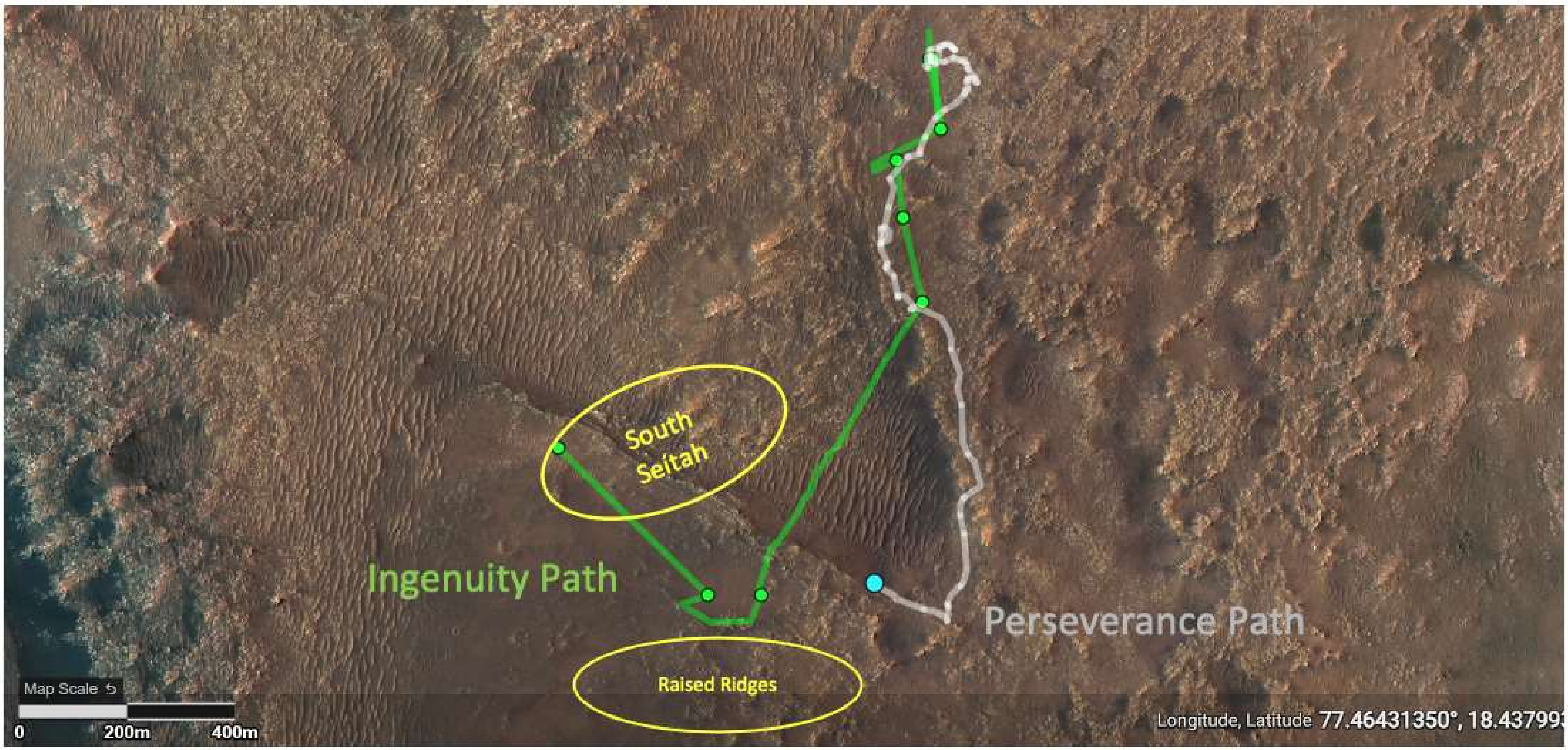


Table of Flights (through 07/08/21)

Flight #	Sol	Earth Date	Remark
Drop	43	04/03/21	Underneath comm max'd @ -21 dBm
50 Hz Spin	48	04/08/21	-37 dBm @ 45 m.
High Speed Spin	56	04/17/21	1st attempt Sol 49 failed "twiddle bug"
#1 (tech demo)	58	04/19/21	3 meter hover @ 63 m. -37 dBm up, -50 dBm down
#2 (tech demo)	61	04/22/21	5 m. up 2 m. east and back and down
#3 (tech demo)	64	04/25/21	5 m. up, 50 m. north and back and down, -51 to -39 dBm
#4 (tech demo)	69	04/30/21	5 m. up, 143 m. south and back, 118 seconds aloft (twiddle Sol 69)
#5 (op demo)	76	05/07/21	10 m. up 143 m. south, land there, -57, -37, -65 dBm
#6 (op demo)	91	05/22/21	10 m. up 100 m. WSW, survey, land, -60 to -70 dBm
#7 (op demo)	107	06/08/21	10 m. up 105 m. south, -42, -38, -70 dBm (SW upload, fixed twiddle)
#8 (op demo)	120	06/21/21	10 m. up 170 m. south, -70 dBm
#9 (op demo)	133	07/05/21	630 m. over hazardous, undulating terrain @ 210 true, -85 dBm

Ingenuity and *Perseverance*



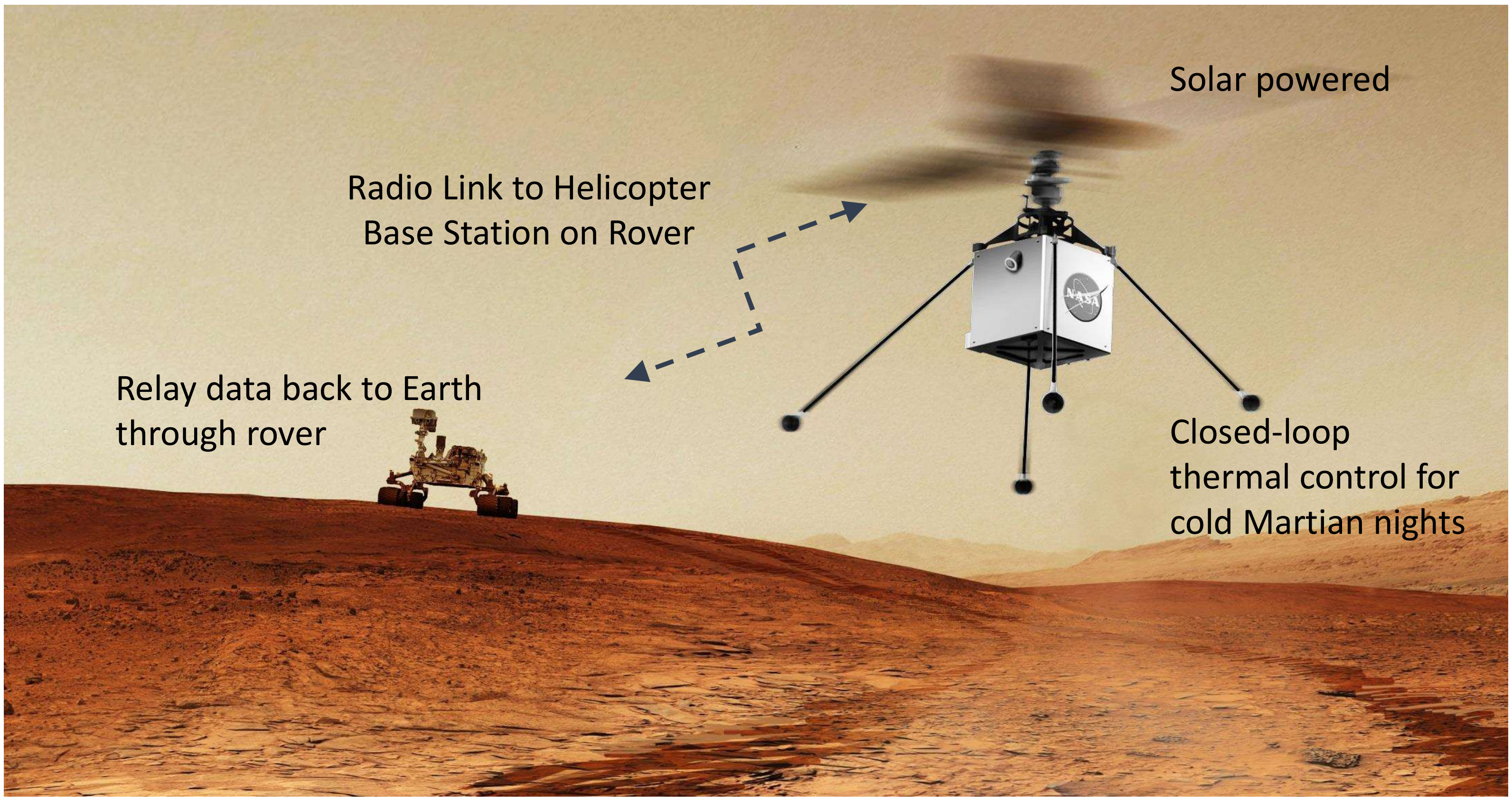
See https://mars.nasa.gov/mars2020/mission/where-is-the-rover/

Mars Helicopter Telecom Development Overview

Mars Helicopter Technology Demonstration on Mars 2020

- Capable of flight in thin Mars atmosphere (~1% of Earth)
- “Co-axial” Helicopter
- Blades 1.2-meter tip-to-tip
- Mass ~1.8 Kg
- Solar powered – up to 90-second flight per sol
- Flight distances up to 300 m
- Heights up to 10 m
- Autonomous flight & landing
- Up to 5 flights
- Telecommunication to Base Station on Rover
- Self-sufficient thermal control

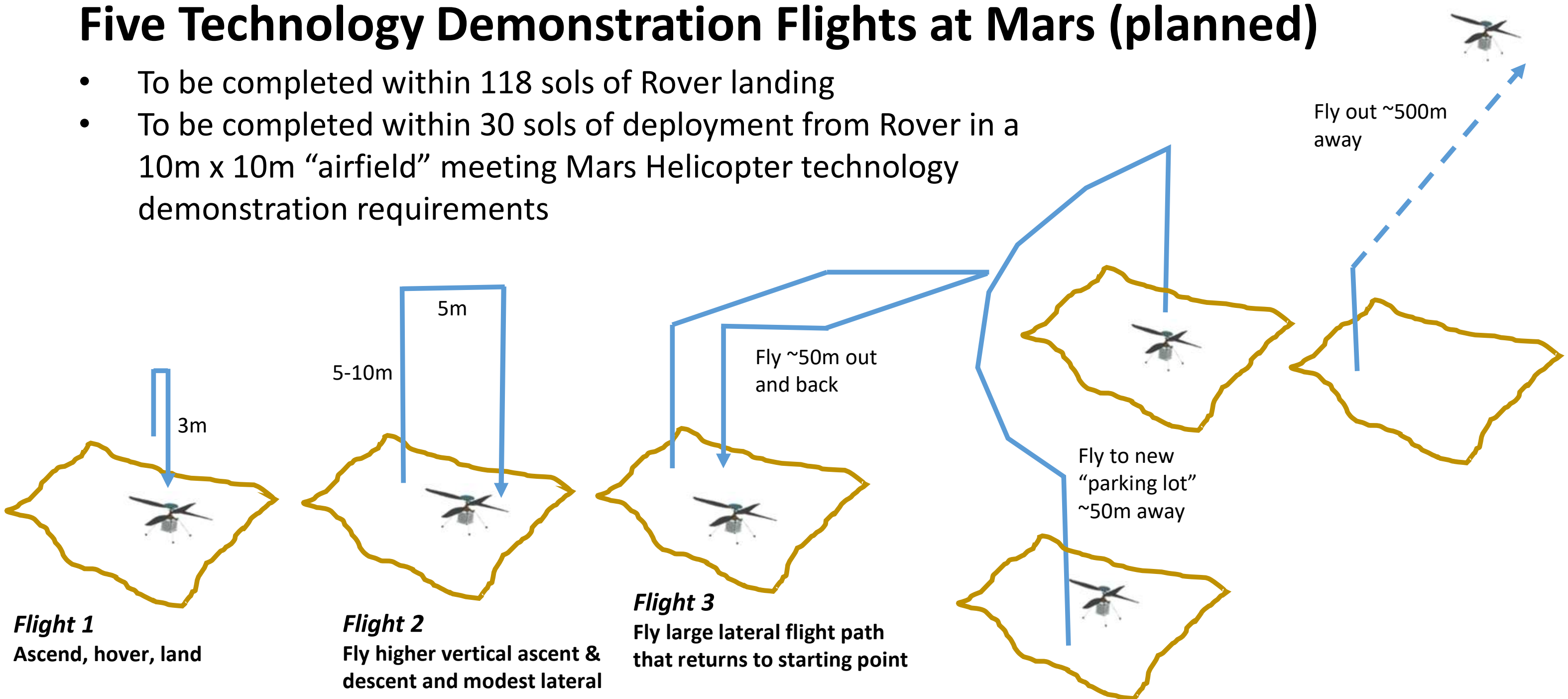
After Deployment from Rover *(cutting of the UART)*, Mars Helicopter Operates in Stand-Alone Fashion, with Radio Link to Base Station on Rover



2016 marketing material
Back when it was known
Internally as *Leonardo*

Five Technology Demonstration Flights at Mars (planned)

- To be completed within 118 sols of Rover landing
- To be completed within 30 sols of deployment from Rover in a 10m x 10m “airfield” meeting Mars Helicopter technology demonstration requirements



Flight 1
Ascend, hover, land

Take picture of Rover

Rover takes picture of Helicopter in flight

Minimum Mission Success

Flight 2
Fly higher vertical ascent & descent and modest lateral motion

Flight 3
Fly large lateral flight path that returns to starting point

Perform scout function to image terrain far ahead of “parking lot”

Certify new “parking lot” (on Earth)

Flight 4-5
Contingency for Flights 1-3

If contingency flights are not needed, then consider the following options:

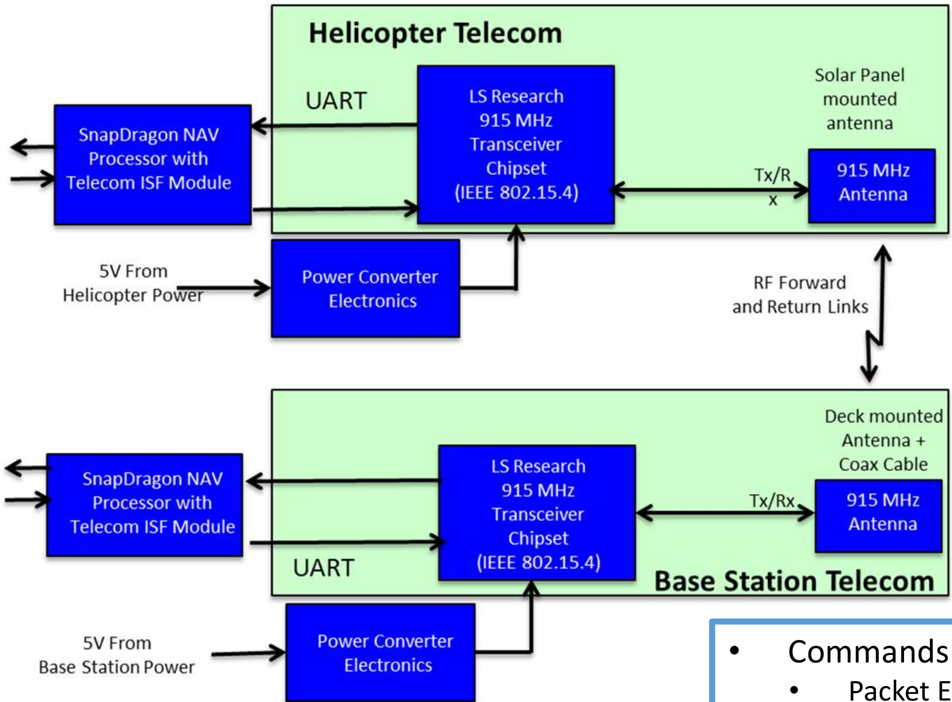
Fly to new “parking lot”

Fly away to maximum distance that the vehicle can fly (~500m). Note: destination landing site will not have been surveyed.

Telecom “Objectives”

- 10 gram mass
  - Includes antennas and cables
  - 13.3 grams achieved (helicopter side)
- Rover side uses the same electronics boards
- Telecom up to 1000 m., two-way
  - No Fly Zone ended up being 45 meters radius from *Perseverance*
  - No radio navigation
  - OTA rates 20 kbps, 250 kbps, actual throughput 9 kbps, 80 kbps (200 kbps “vomit”)
- DC power: TX < 3 W, RX < 0.2 W
- Temperature -40 to +85 C, -50 C non-op
- Protocol modified heavily from ZigBee (IEEE 802.15.4)

Telecom Design Overview



- Operation while landed or in flight
  - Range: 2 m. to 1000 m.
  - 900 MHz – low path loss

- Mass, Power, Environment
  - 13.3 g on helicopter
  - 3 W DC transmit peak
  - < 0.5 W receive
  - -40C to +60C

- 900 MHz activity added to ERD and license
- Part modified for full power output, touched up

- Commands and Telemetry - 802.15.4 (ZigBee)
  - Packet Error Rate (PER) <1%
  - Packet or ack loss triggers retries, failure indication
  - Protocol adapted to two-point, high-throughput need
- Flight Software Driver – ISF
  - Heli and HBS drivers identical

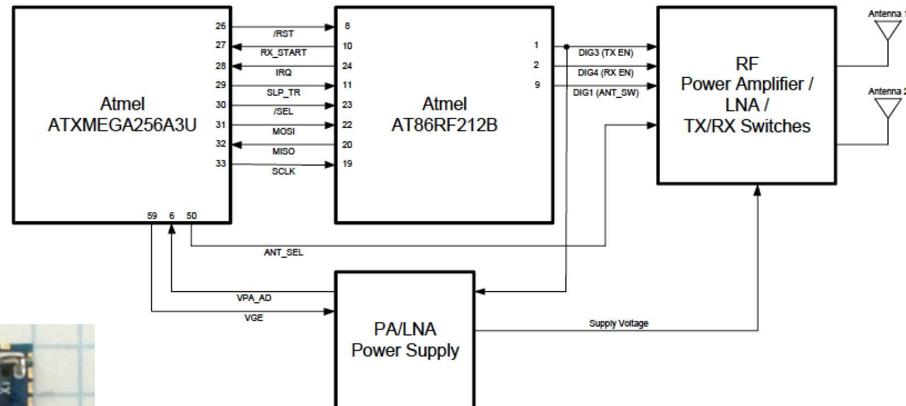
COTS Part Selection Criteria

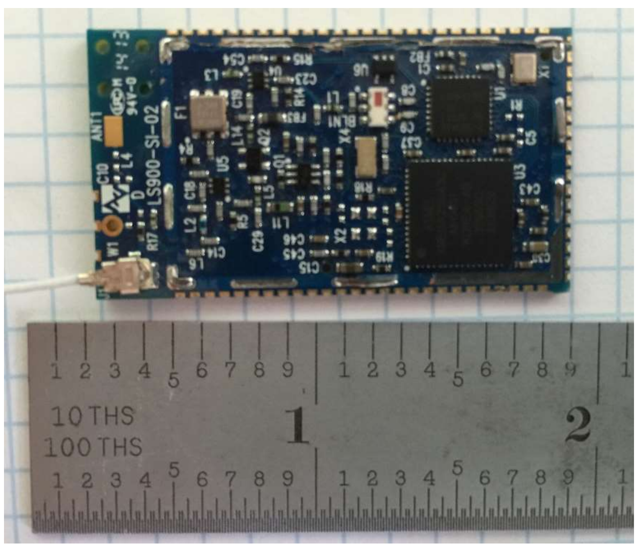
1) Very Low Mass suggests COTS ISM
2) Low frequency for lowest omni to omni path loss
   - 900 MHz is lowest ISM band
3) "High Power"
   - Most ISM parts (and 802.11…) run a few 10s of mW
   - Want closer to a watt
4) Diversity – possibility of > 1 antenna

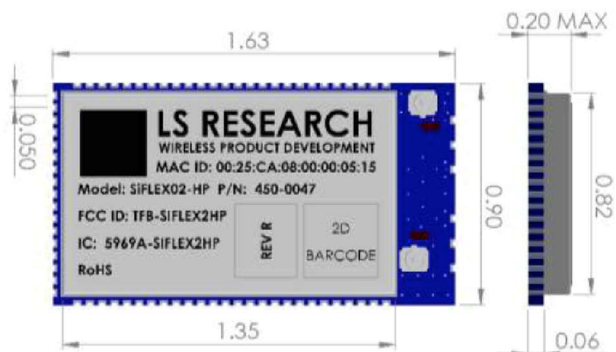
Radio that was Picked: RF Modem: LS Research SiFlex02-R2-HP

Minimum Order Qty: 50 units
Cost: $60 per unit
Mass prepped: ~3.5g
Power Out: 28 dBm
Band: 906-924 MHz (10 ch.)
Antennas: 1 or 2
UART: 460.8 kbps

… but, shortly after purchase
SiFlex sold to Laird late 2016
SiFlex support discontinued

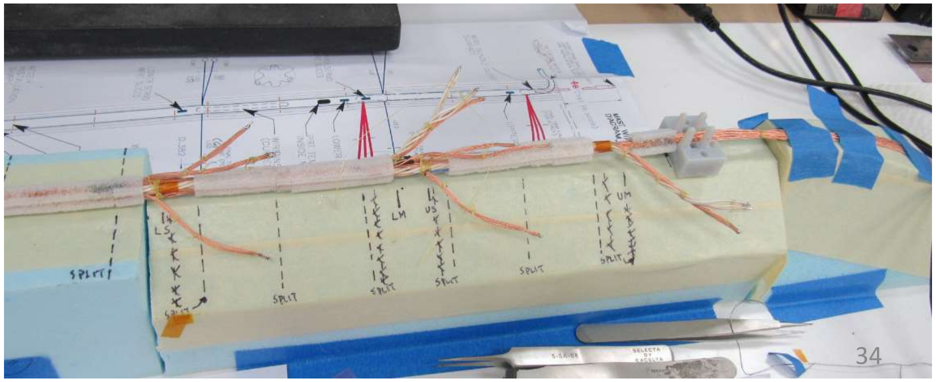






Antenna Location, Mast Bundle

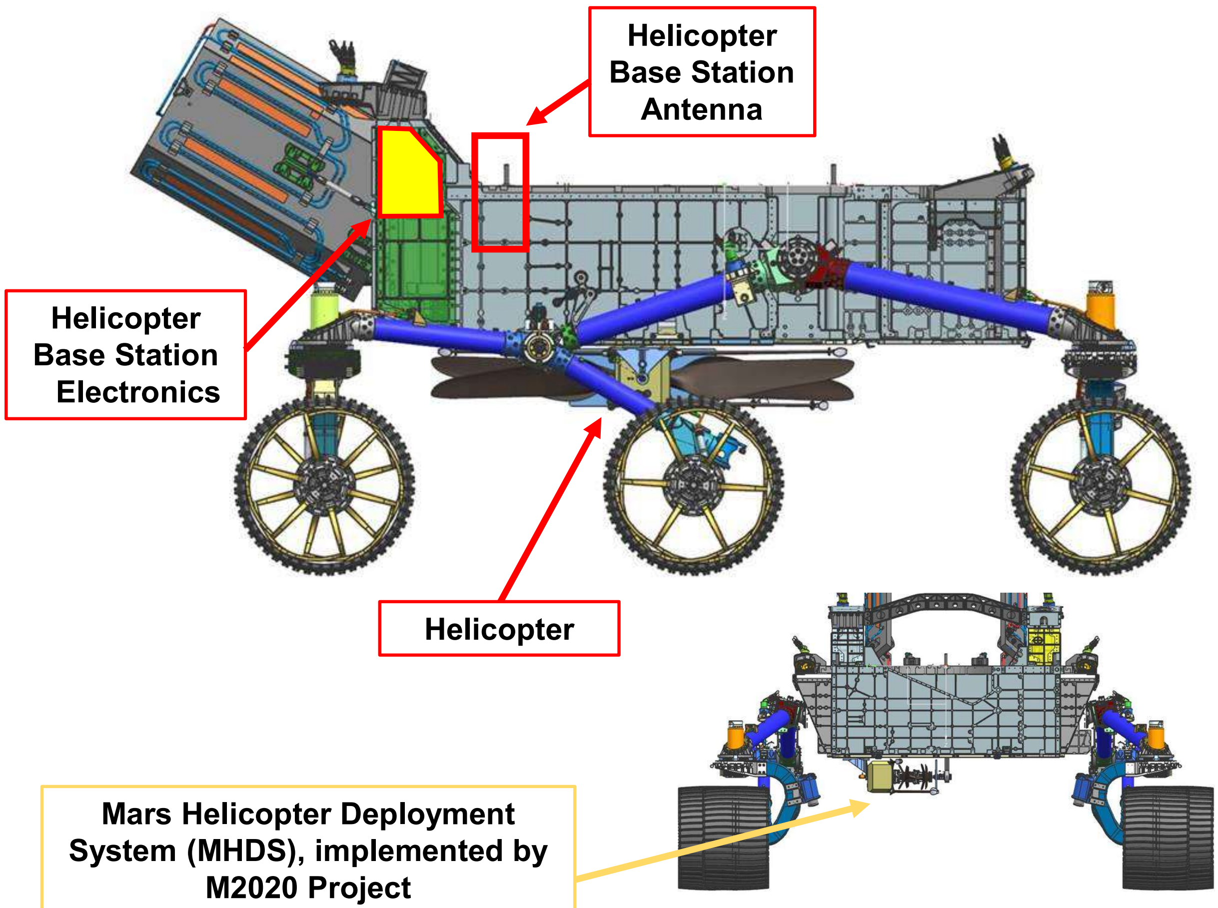
- On top because most comm is from the ground not from flight
  - And 10 m. altitude / 50 m. range is 20 milliradians elevation
  - And telecom from flight is easier
- Heli antenna on top of solar panel (ground plane)
  - Cable routed through mast during mast assembly
  - GPPIO on antenna side
  - Soldered to SiFlex in final assembly on radio side
- Helicopter Base Antenna (HBA)
  - Delivered directly to M2020
  - Flight cables



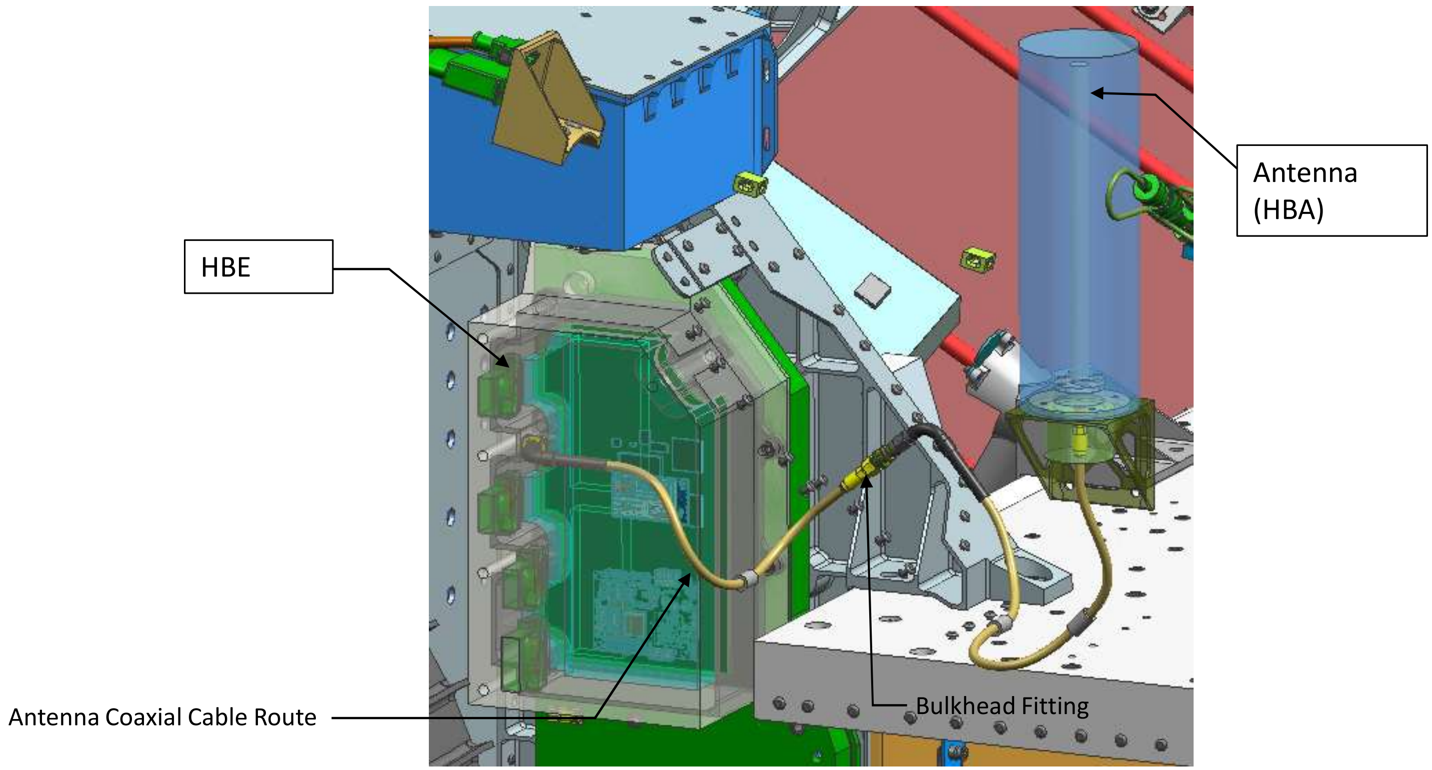
FM Baseline Design

1.2 m blade span
Counter-rotating
1.8 kg max mass
Solar power
Autonomous
Radio "leash" to M2020 Rover

Mars Helicopter Accommodation on Mars 2020 Rover

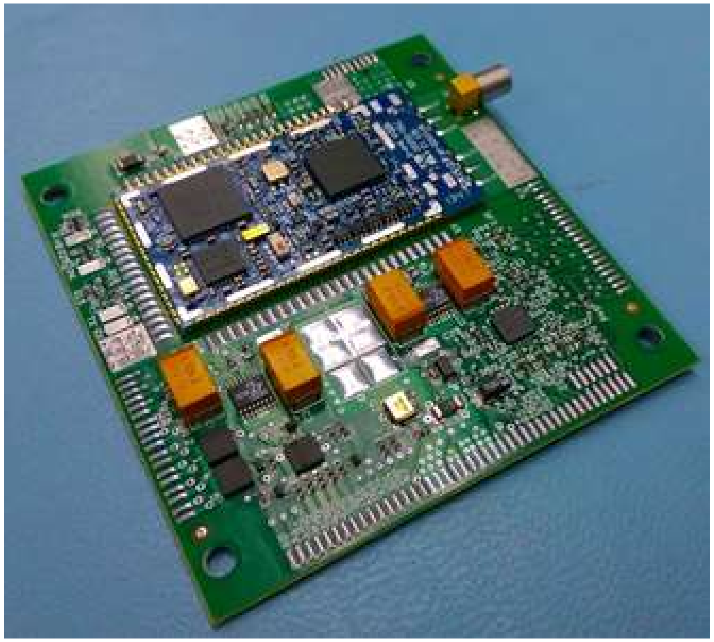


Helicopter Base Station (HBS), Antenna (HBA) and Coax detail



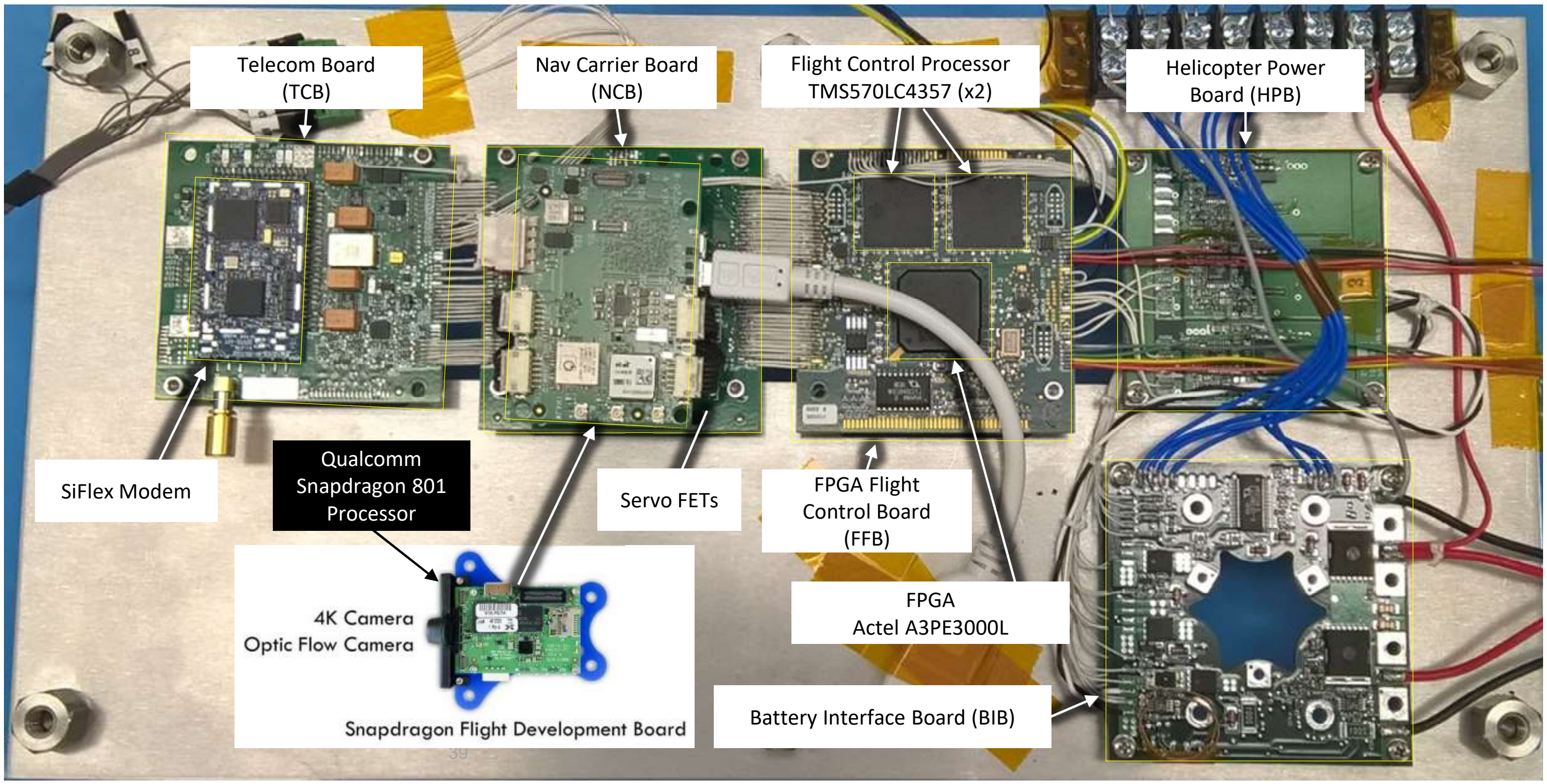
MH Telecom Board (TCB)

- Telecom Board
  - Hosts COTS SiFlex radio module
    - LSR SiFLEX02 high performance 900MHz IEEE 802.15.4 radio
    - Main radio link between helicopter and base station.
    - Identical modems on each end of the link
  - Provides 1 ADC, temperature MUX and heater control
- Both Helicopter and Base
  - Helicopter stack form factor is “cube”
  - Base stack form factor is “wallet”
- Modified SiFlex
  - Delidded – inspected – parts changes



Helicopter FlatSat

Electronics Core Module (ECM)



MHS Flatsat 001 (HBS configuration very similar)

T. Canham says the Snapdragon is more powerful than all deep space computers flown on NASA missions to date. (Rad 750…)

ConOps and SiFlex / Protocol Mods

- This is not a multimode mesh network
  - That ZigBee is meant for
  - Early design had three nodes
- This is a two-node network where radio silence needs to be enforceable from HBS, so
  - The helicopter speaks when spoken to via
- "Beacon Mode"
  - HBS beacons and helicopter replies in its slots, when powered
  - HBS silent, helicopter silent, regardless
  - Beacons assign slots to both sides for transmission

MHT Operating Modes

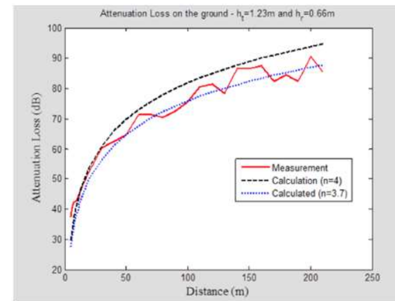
Name	OTA* Rate	Throughput	Modul ation	Bandw idth	Direct ion	Default H/B	Bit Size	Packet Size	Note	
Silent	NA	0	NA	NA	NA	NA			No TX	
Default	20 kbps	9 kbps	BPSK	600 KHz**	Both	50/50	50 usec	50 msec	Boot Up	Down to -105 dBm
Data	250 kbps	80 kbps	OQPSK	2 MHz ***	Both	90/10	4 usec	4 msec	With OTA acks	Down to -95 dBm
TCOW ****	250 kbps	204 kbps	OQPSK	2 MHz	Heli- >HBS	100/0	4 usec	4 msec	Without OTA acks	Down to -95 dBm

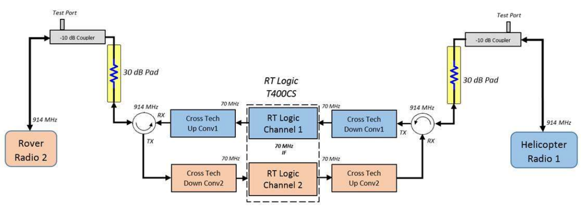
* OTA: Over the Air
** Due to 15 chip spreading code
*** Due to Mcps signaling scheme
**** TCOW (Time Critical One Way); VOMIT (Vulnerable, One-way, MHS Information Transfer)

Telecom Performance Tests

- Testbed verification of
  - ✓ Power output
  - ✓ Receive sensitivity
  - ✓ Over temperature
- 206 kbps throughput demonstrated in lab, over the air

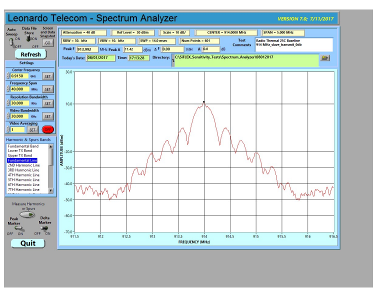
Field Test verified surface link properties



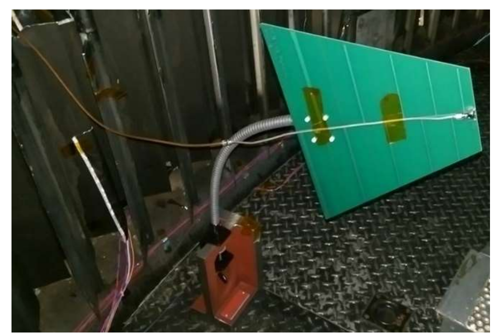


TCB and antenna on EDM-2 passed command and telemetry check

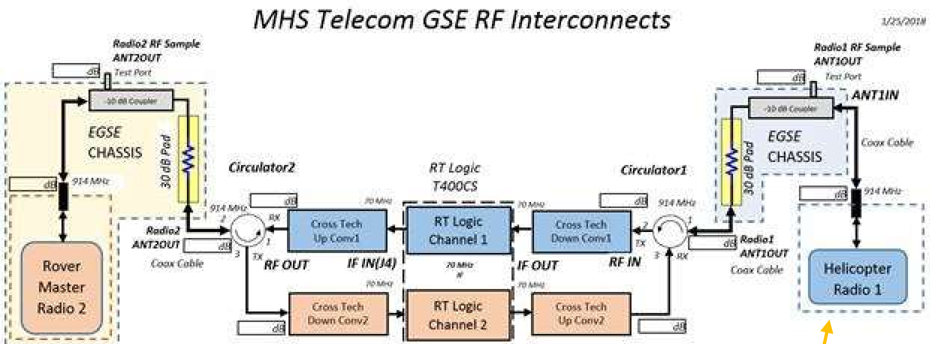
Threshold, interference, sortie, parameter measurements, flight assembly prep are ongoing



"Sniffer" antenna in chamber flight and ETL tests sees Helicopter EMI environment to support enhanced, more realistic performance testing

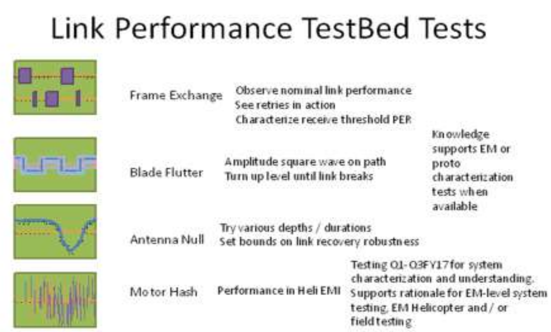


Link Performance Testbed



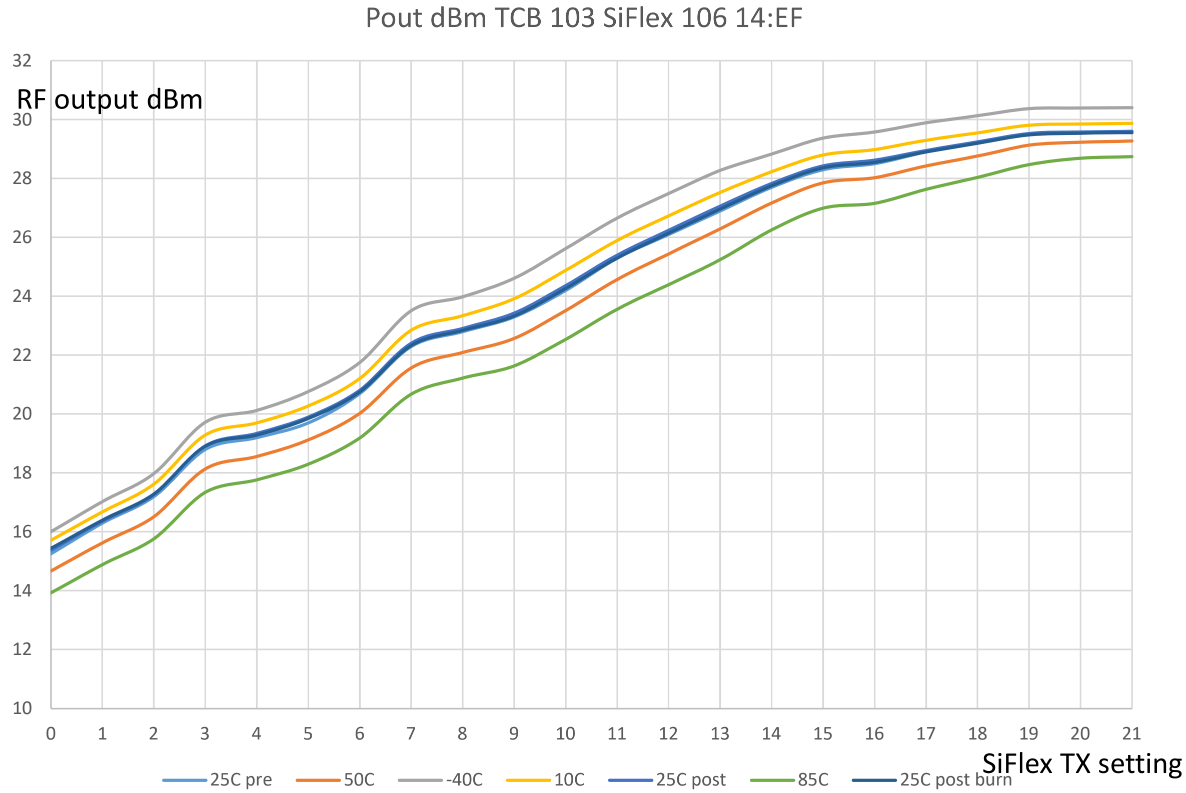
Unit Under Test is always
Helicopter Radio 1 in Test Fixture

Original Test Plans - 2016



TCB 103 SiFlex 14:EF FM HBS

Transmitter Performance Over Temperature

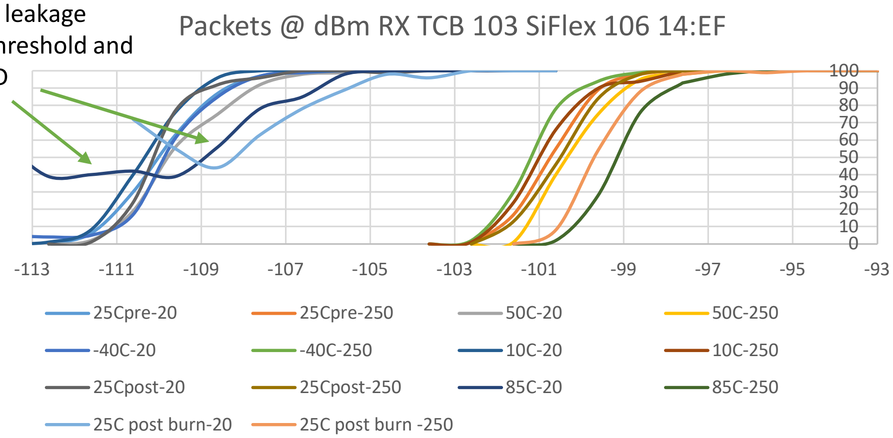


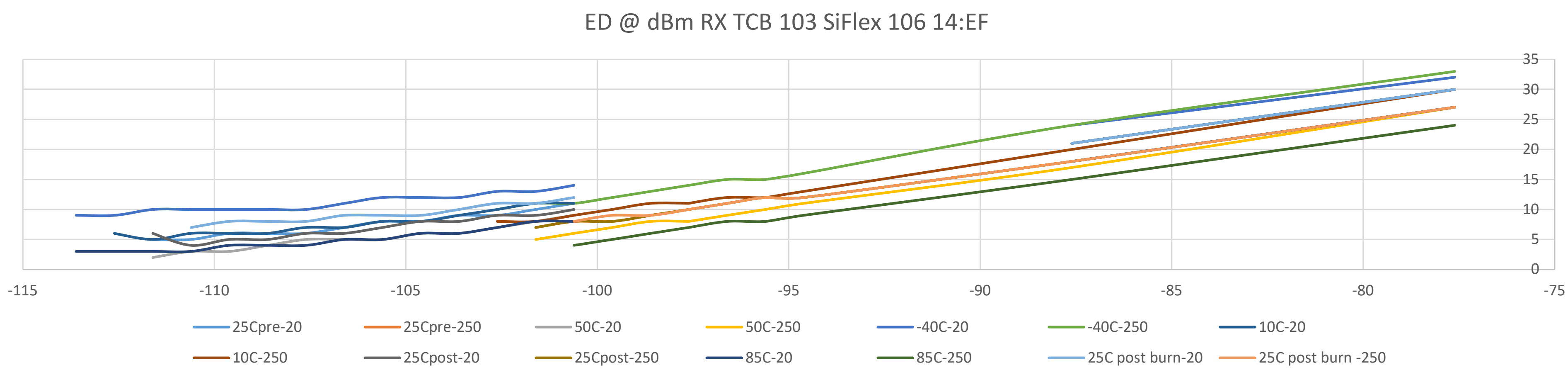
FM TCB 103 tested before, during, and after thermal cycles and burn-in

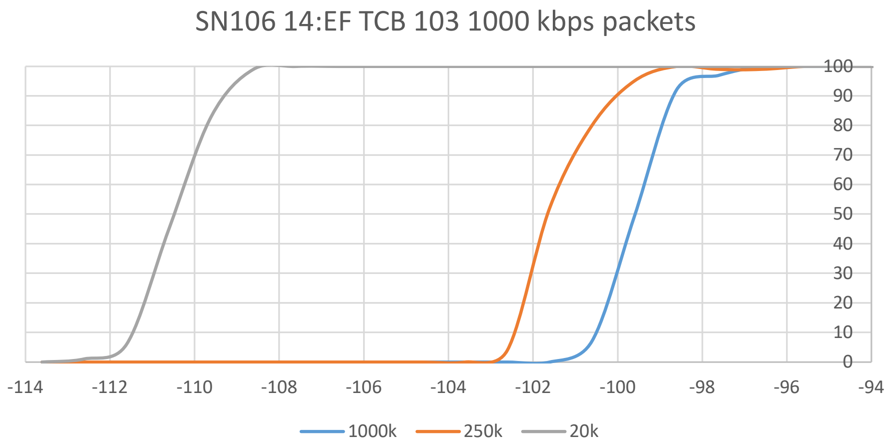
FM TCB 103 P1dB setting 15.5 = 30.0 dBm

TCB 103 SiFlex 14:EF FM HBS Receiver Packet Recovery vs. ED

Testbed RF leakage obscures threshold and true LQI/ED

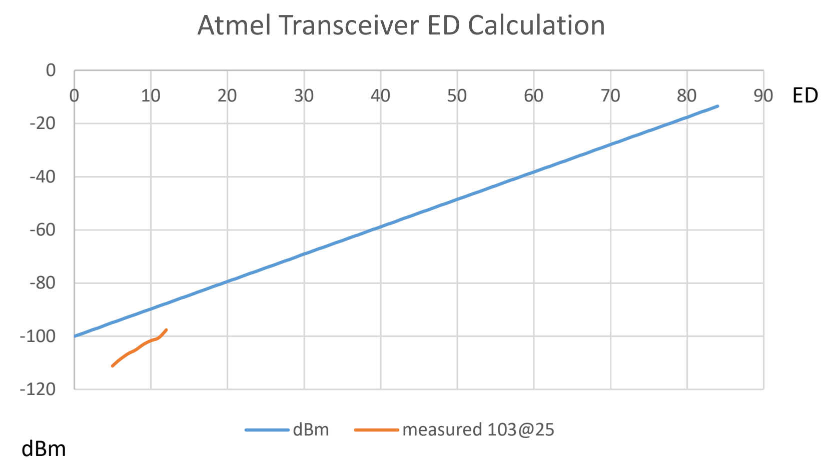




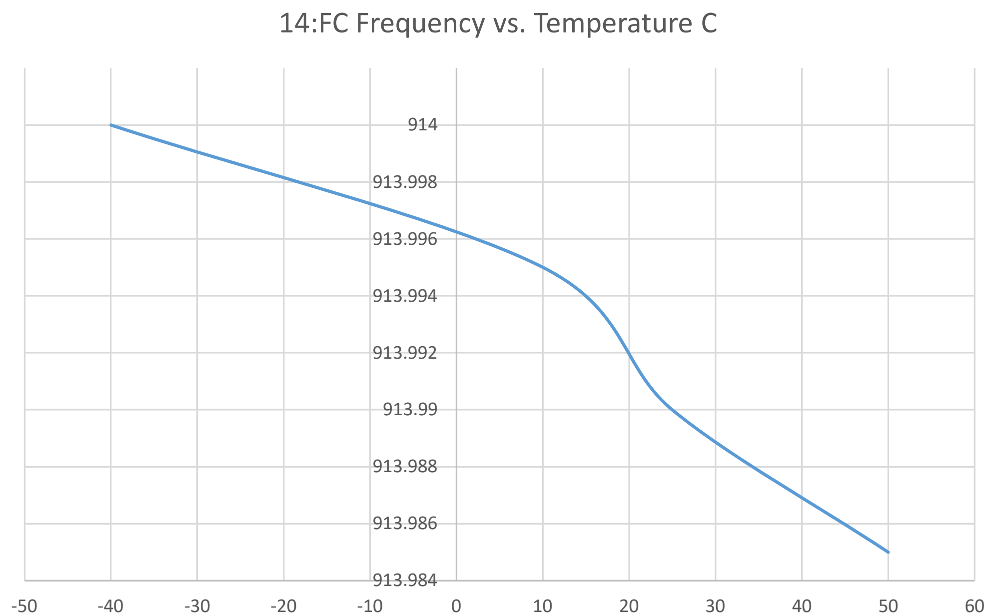


Test of 1000 kbps mode – packet recovery 1000 kbps threshold poorer than 250 kbps threshold as expected

Atmel transceiver spec. sheet ED calculation compared to TCB 103 receiver measurements showing performance improvement due to low noise amplifier (LNA) on SiFlex System On Module (SOM).



Frequency vs. Temperature

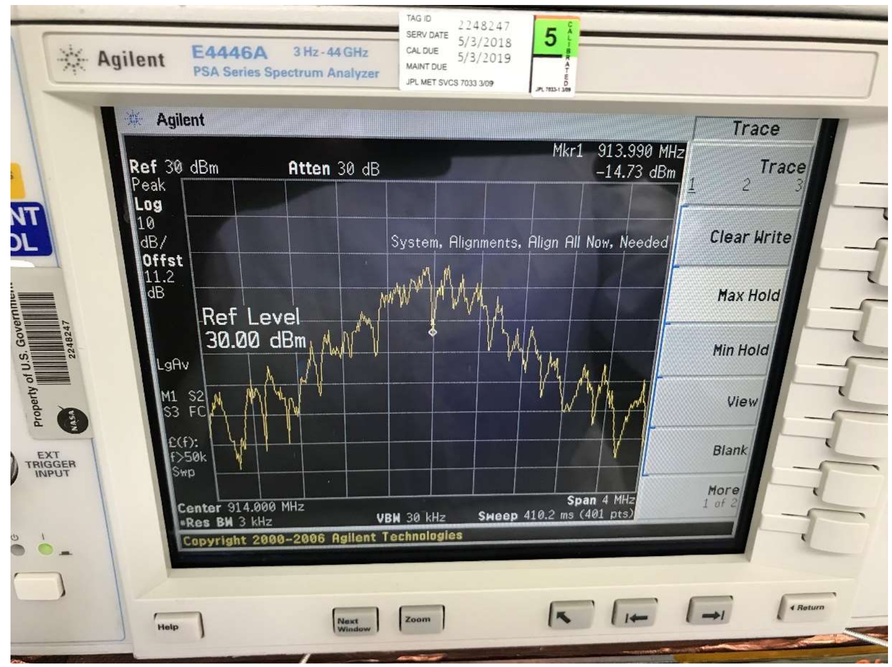


All SiFlex were tested over temperature against lab GSE SiFlex master 15:08 operating @ 22-25C similar to the flight situation where HBS will be controlled ~20C while helicopter radio is varying -20 to +20C.

No performance effects attributed to differential temperature performance.

Bandwidth is 300 KHz or 1000 KHz
Range shown here is 16 KHz, ~5% of low rate (20 kbps) bandwidth.

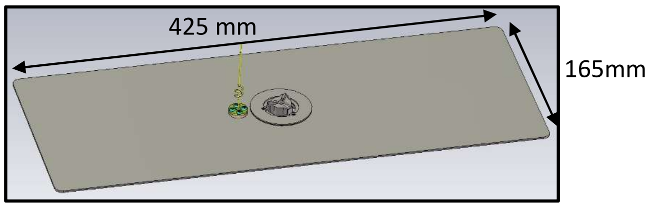
Spectra of 20 kbps transmission



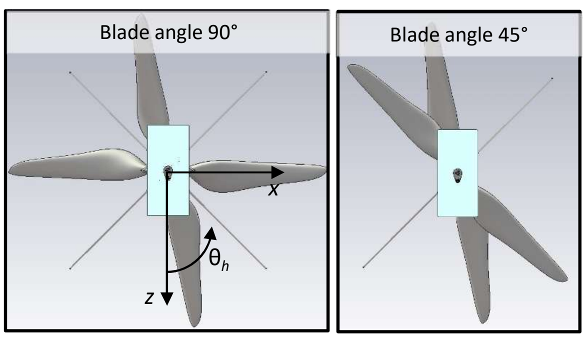
Spectra of 250 kbps transmission

Helicopter antenna (rectangular solar panel)

$H_{antenna}$ = 63mm

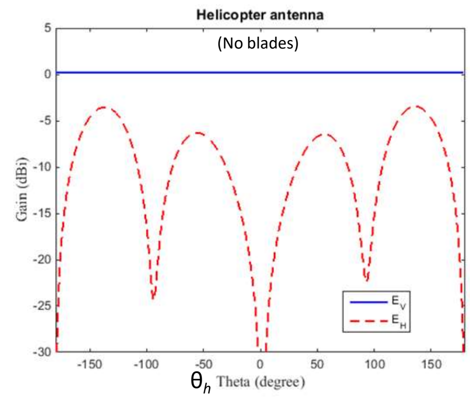


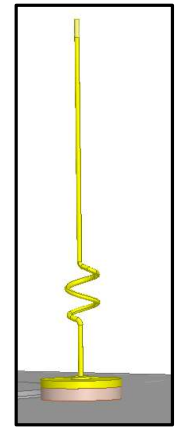
Helicopter antenna on its solar panel



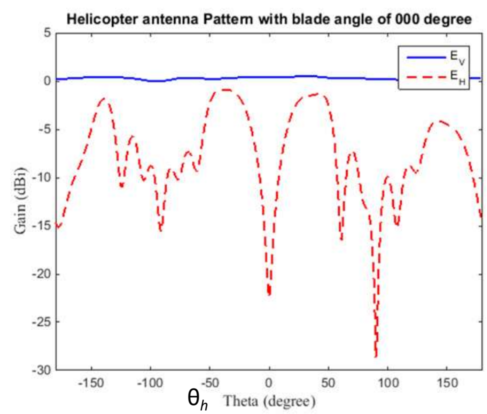
Helicopter antenna on its solar panel (includes blades)

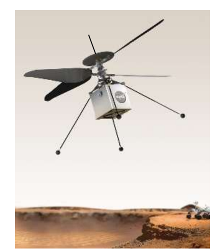
HBA radiation pattern



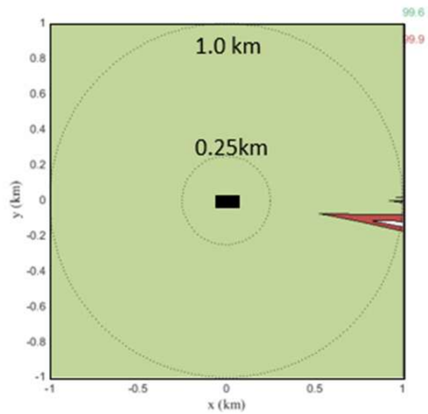


Antenna design



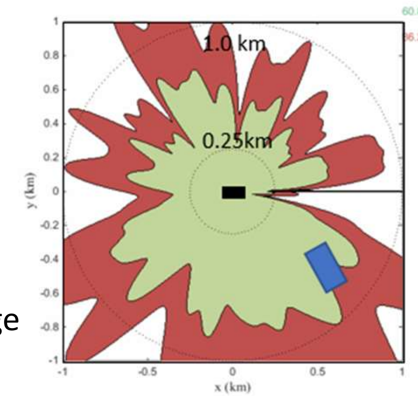


Initial Telecom Analysis – Nacer Chahat

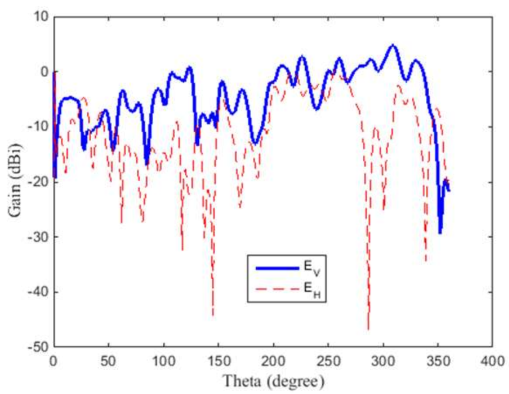


Predicted in-flight coverage

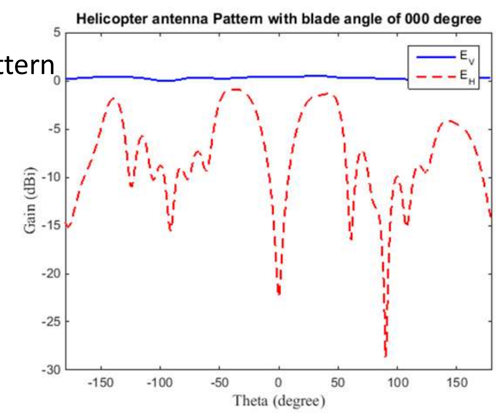
Green – high rate
Red – low rate
White – no coverage



Predicted landed coverage

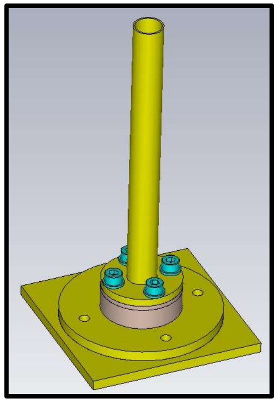


Rover Antenna Pattern

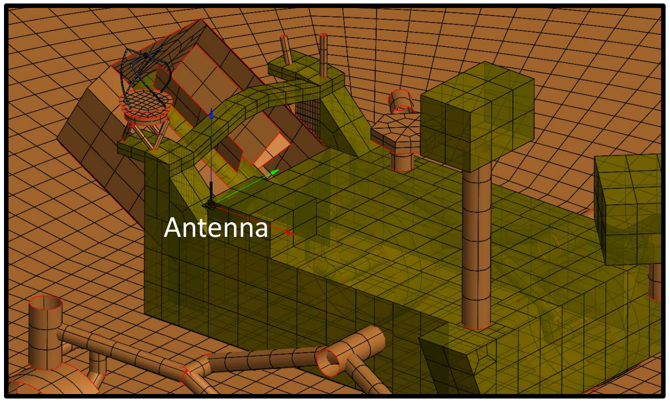


Helicopter Antenna Pattern

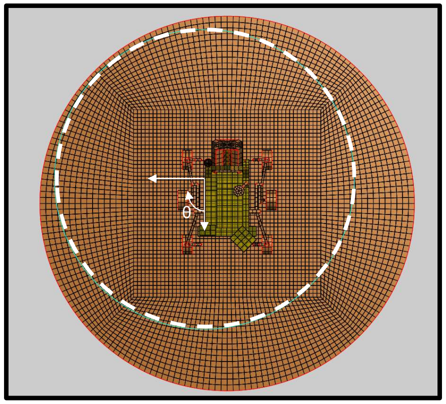
HBS Antenna performance on Mars2020 rover



Antenna design

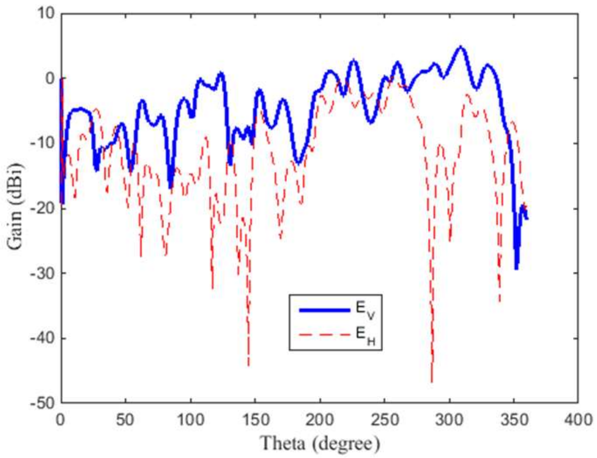


Antenna on M2020 Rover



Coordinate system

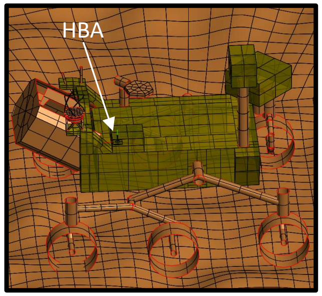
Helicopter Base Station Antenna (HBA) radiation pattern



<u>Interpretation of results:</u>

- Shadowing effects
- Multipath (reflections)
- Suffers from a very small ground plane
- Larger ground plane and/or location would improve the result

Base Station Antenna

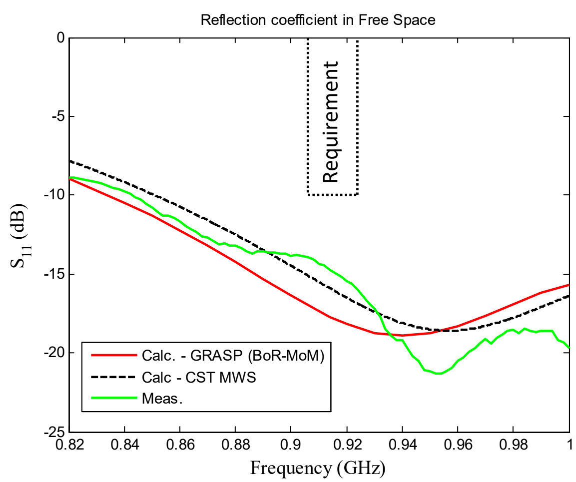


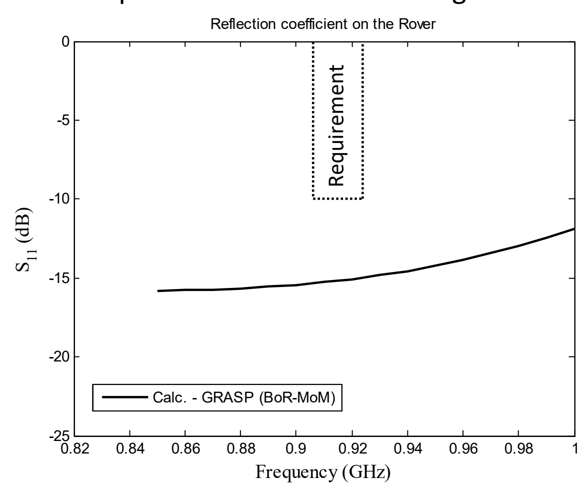
HBA: Helicopter Base Station Antenna

Helicopter Basestation Antenna (HBA) radiation pattern

The HBA was designed and optimized on the Rover as the ground plane of the antenna is so small, it will impact the antenna performance. The reflection coefficient of the antenna should be lower than -10dB to minimize the amount of power reflected back to the radio (i.e. power loss and risk of damaging the radio).

The reflection coefficient of the HBA was fabricated and tested in free space. **Excellent agreement was obtained.** The antenna was simulated with two different tools. GRASP allows to simulate large structure such as the M2020 Rover with the Mars soil. This is not possible or too time consuming with other software such as HFSS and CST MWS. However, until now, complex antenna such as the HBA could not be simulated in GRASP. I managed to simulated it using BoR-MoM in GRASP allowing us to run quick simulation of the entire Rover with the antenna. The reflection coefficient was optimized on the Rover using GRASP.



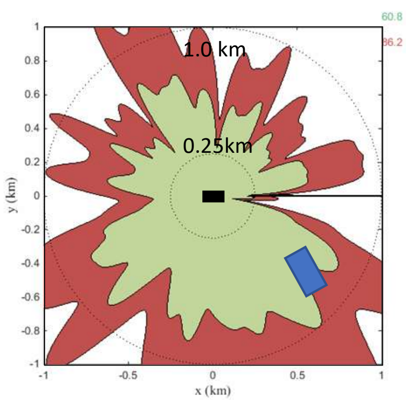


Map Coverage Around M2020 Rover on the ground: antenna 1

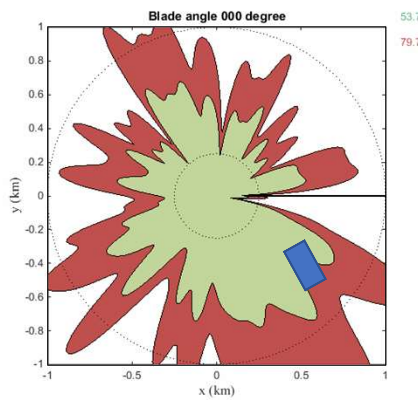
Map coverage assuming min, mean, max polarization loss with blade rotating.
The math is done for all azimuth angles around the helicopter.
These results were obtained using **Bullington** with ***h*$_t$=0.48m** and h_r=1.23m.

Green	Received power of >-94dBm ⇔ 250kbps
Red	Received power of [-102, -94] dBm ⇔ 40kbps
White	No link

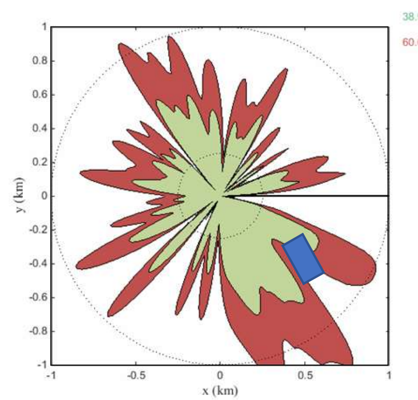
5%



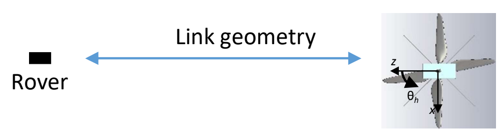
Min polarization loss



Mean polarization loss



Max polarization loss



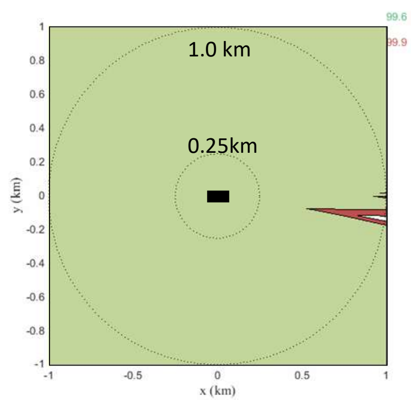
Azimuth angle θ_h = [0°-359°]

Map Coverage Around M2020 Rover with antenna 1 only: Flying

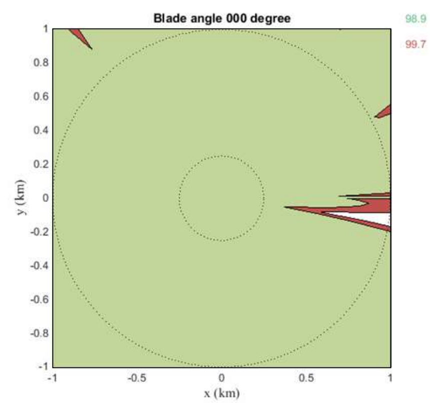
Map coverage assuming min, mean, max polarization loss with blade rotating.
The math is done for all azimuth angles around the helicopter.
These results were obtained using **Bullington** with $\boldsymbol{h_t}$**=10m**, h_r=1.23m, and Req = [0.25 - 1] km.

- Received power of >-94dBm ⇔ 250kbps
- Received power of [-102, -94] dBm ⇔ 40kbps
- No link

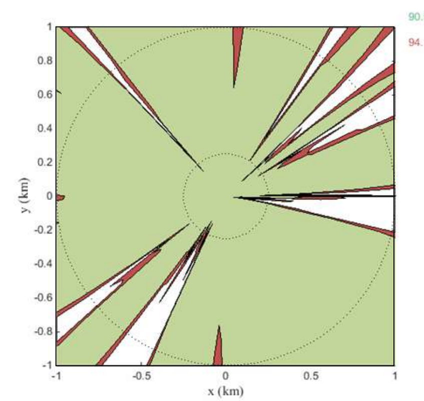
5%



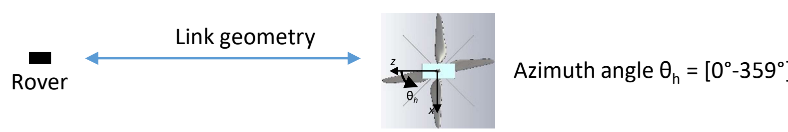
Min polarization loss



Mean polarization loss



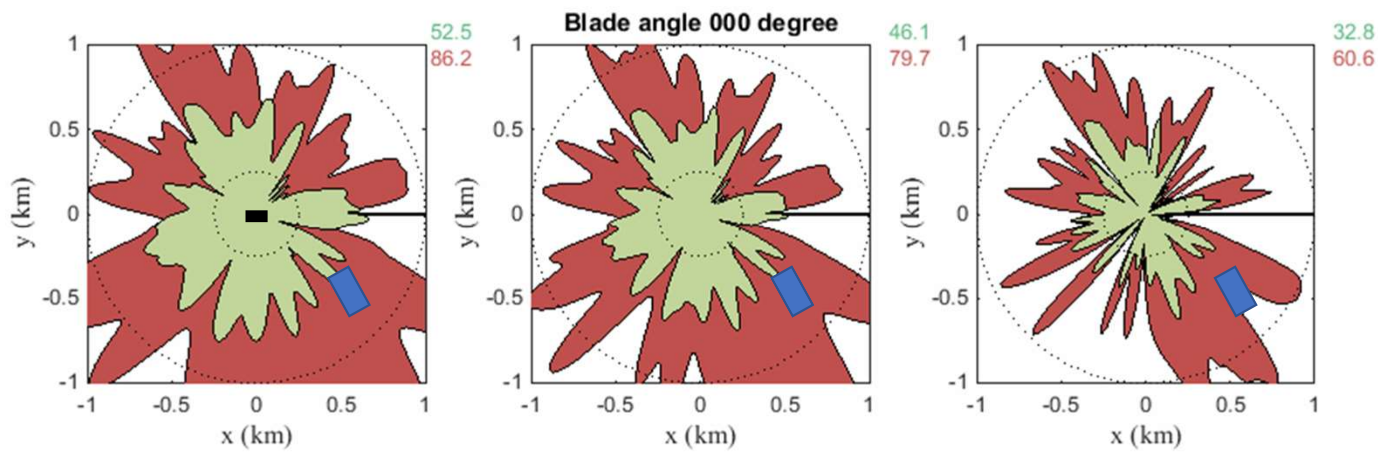
Max polarization loss



Map Coverage Around M2020 Rover on the ground: antenna 1

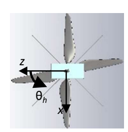
Map coverage assuming min, mean, max polarization loss with blade rotating.
The math is done for azimuth angle around the helicopter.
These results were obtained using **Bullington** with $\boldsymbol{h_t}$**=0.48m** and h_r=1.23m.

Received power of >-94dBm ⇔ 250kbps (no margin) – 40kbps (8dB margin)
Received power of [-102, -94] dBm ⇔ 40kbps (no margin)



Min polarization loss   Mean polarization loss   Max polarization loss

Rover   Link geometry

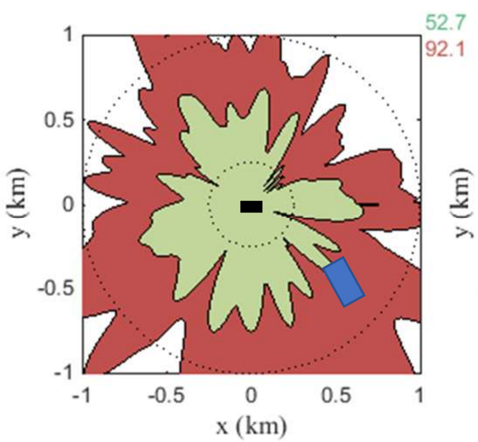


Azimuth angle θ_h = [0°-359°]

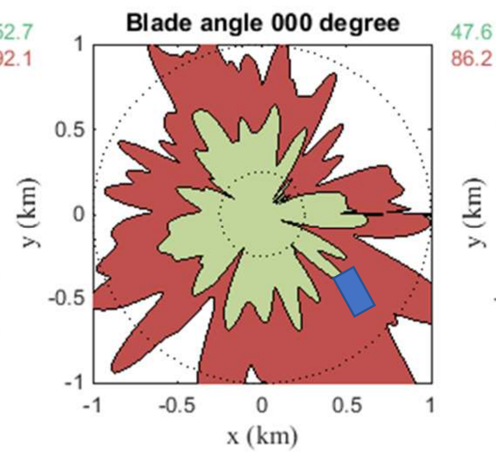
Map Coverage Around M2020 Rover on the ground: antenna 1 and 2

Map coverage assuming min, mean, max polarization loss with blade rotating.
The math is done for azimuth angle around the helicopter.
These results were obtained using **Bullington** with $\boldsymbol{h_t}$**=0.48m** and h_r=1.23m.

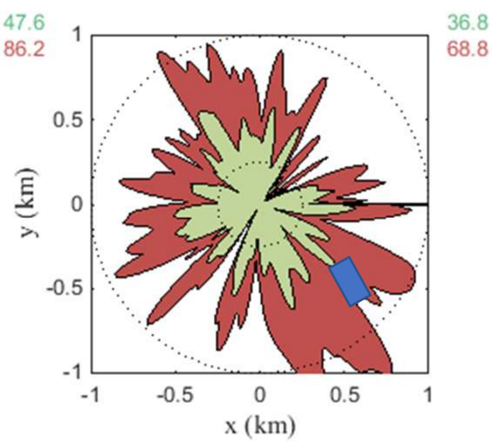
Received power of >-94dBm ⇔ 250kbps (no margin) – 40kbps (8dB margin)
Received power of [-102, -94] dBm ⇔ 40kbps (no margin)



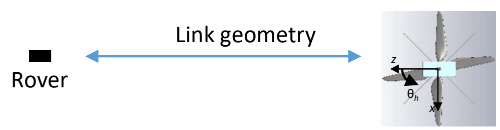
Min polarization loss



Mean polarization loss



Max polarization loss

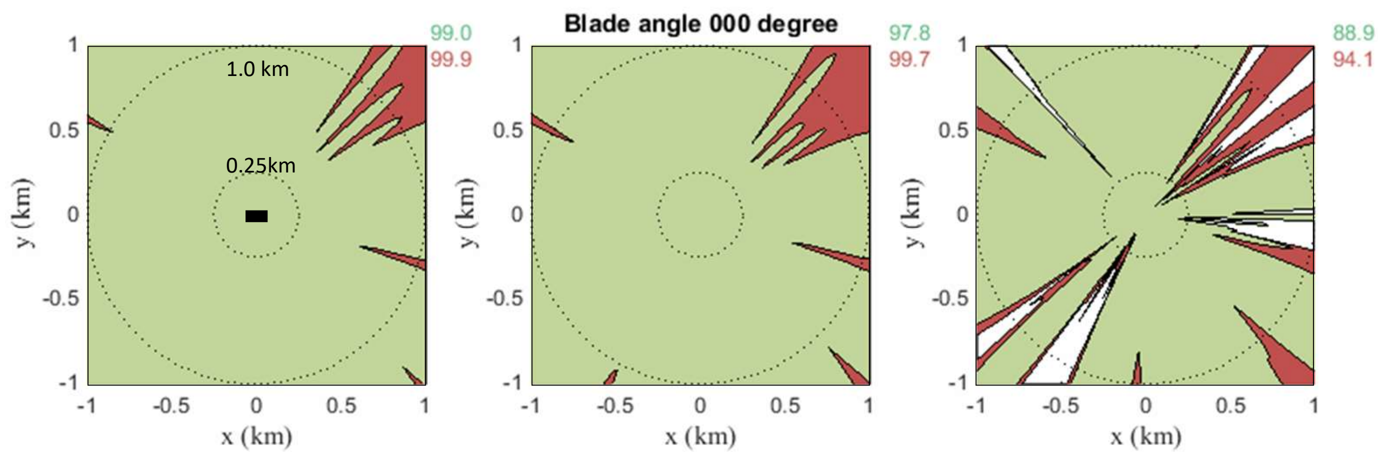


Azimuth angle θ_h = [0°-359°]

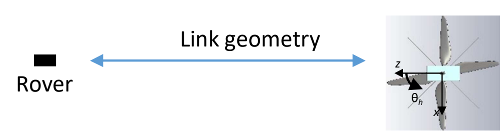
Map Coverage Around M2020 Rover with antenna 1 only: Flying

Map coverage assuming min, mean, max polarization loss with blade rotating.
The math is done for azimuth angle around the helicopter.
These results were obtained using **Bullington** with ***h_t*=10m**, h_r=1.23m, and Req = [0.25 - 1] km.

- Received power of >-94dBm ⇔ 250kbps (no margin) – 40kbps (8dB margin)
- Received power of [-102, -94] dBm ⇔ 40kbps (no margin)



Min polarization loss | Mean polarization loss | Max polarization loss

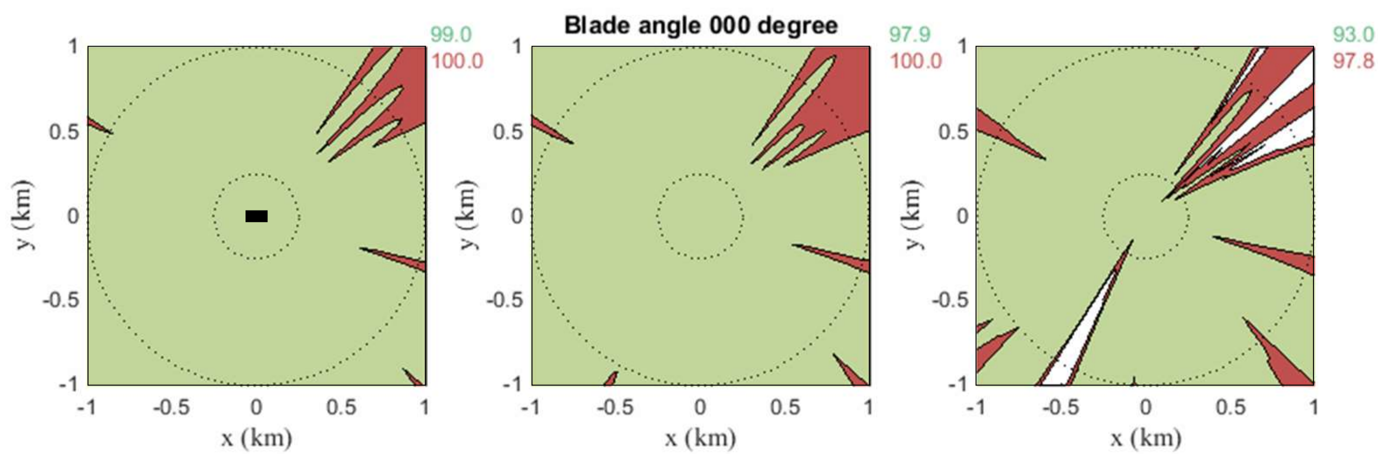


Azimuth angle θ_h = [0°-359°]

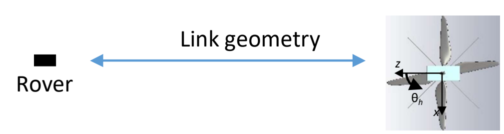
Map Coverage Around M2020 Rover with antenna 1 and 2: Flying

Map coverage assuming min, mean, max polarization loss with blade rotating.
The math is done for azimuth angle around the helicopter.
These results were obtained using **Bullington** with ***h_t*=10m**, *h_r*=1.23m, and Req = 0.25m.

- Received power of >-94dBm ⇔ 250kbps (no margin) – 40kbps (8dB margin)
- Received power of [-102, -94] dBm ⇔ 40kbps (no margin)



Min polarization loss | Mean polarization loss | Max polarization loss



Azimuth angle θ_h = [0°-359°]

Arroyo Field Test

Obscured view of model rover from model helicopter.

Obscured view of model helicopter from model rover.

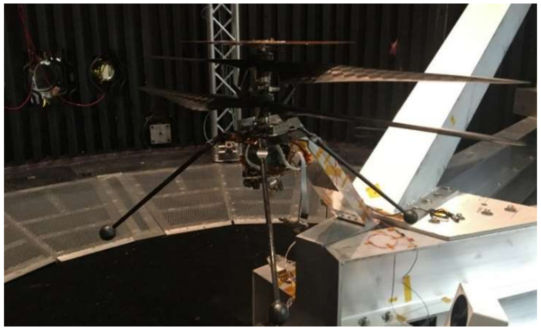
Model helicopter under model helicopter.

Engineering Design Model Vehicles Met the Stringent Constraints for Mars

- **Mass** Met requirement for Mars flight
  - As-built: 1.78 Kg
- **Volume** compatible with Rover accommodation
- **Helicopter aerodynamic/power/energy** performance met
- **Original Mars Helicopter architecture held – no changes needed for FM**
  - Rotor System – Integrated Avionics – Power - Telecom - Thermal – Motor Control - Flight Control
- **Thrust and stable flight control**
  - Validated simulation for hover flight
  - Simulations extended successfully to forward flight with winds

    up to 9 m/s

  - Flight tests to-date match modeling & simulation

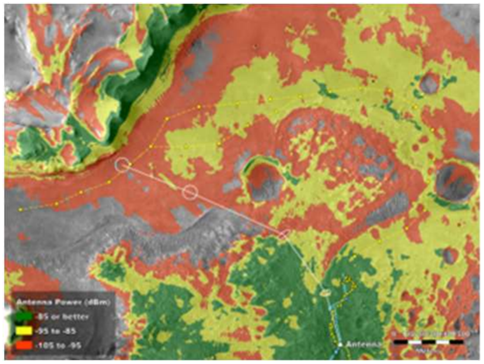


EDM-1 Helicopter

EDM-2 Helicopter

Link Analysis Improvements

- As the *Ingenuity* team got braver, they flew further and further away
  - Without regard to terrain or rover orientation
  - I told them not to go behind terrain or behind the rover if they wanted to talk
  - Landed on the other side of a hill – lost for several sols
  - Team (Chahat) developed a propagation analysis tool based on Parabolic Equation using Altair Winprop, generating “heat maps” like
- After that radio performance largely as predicted
  - And still couldn’t land behind hills and still talk



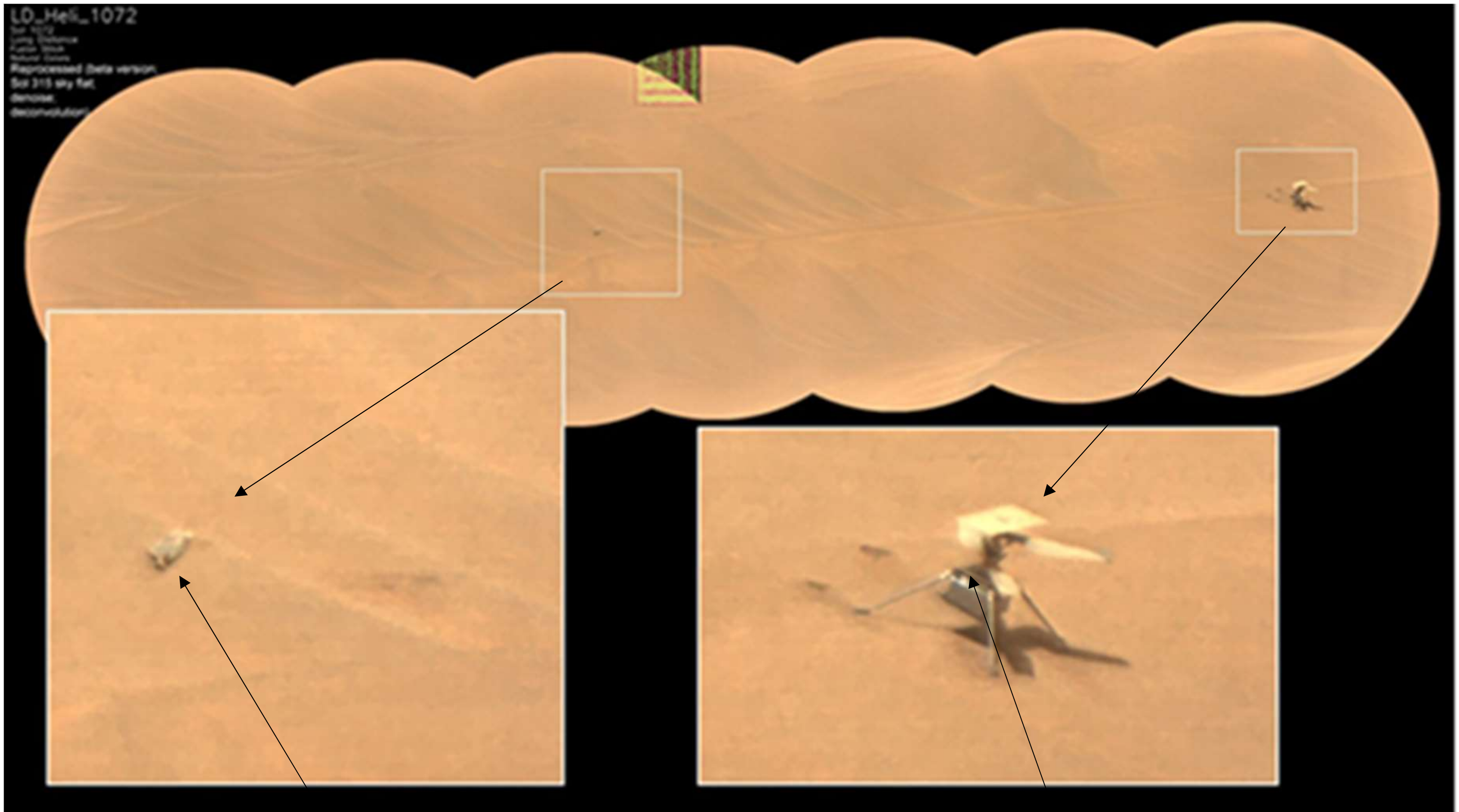
Many flight anomalies

- Due to low operational priority of the *Ingenuity* ride-along many problems were encountered and handled in due course
- After a few sols team would announce “comms recovered” and then proceed
    - Your Welcome

End of Mission

- Flight 72 was a “pop up” localization flight
- Anomaly on landing – brown out – touchdown data lost
- “Featureless” terrain confused navigation
  - That’s why there was a “land now” emergency in first place on Flight 71
- Best theory: nav algorithm saw helicopter shadow, thought it was a fixed feature, tipped over to “chase” it, blade struck sand dune
  - Blade striking sand dune would guarantee a brownout and reboot
  - And breakage….
- Communication was recovered
  - Your welcome
- Final software load configured to take status data indefinitely and report when and if ever queried
  - Range is still on the order of 1000 m. so rover must be nearby for these attempts

No Longer Flightworthy



Missing blade ~15 meters away

Ingenuity with missing blade(s)

Detection from Earth (your EME station)

Case	MRO to Earth	*Ingenuity/Perseverance* to Earth	Notes
TX Power dBm	47	29	MRO* residual carrier (pi/3 mod index)
Antenna Gain dBi	46.7	5	Heli vertical polarization on Mars surface
EiRP dBm	93.7	34	
Frequency GHz	8.439	0.914	
Distance Gm	79	79	Millions of km @ opposition, .53 A.U.
Path Loss dB	269	250	1 A.U. at EDL is 5.5 dB worse, conjunction is 9.2 dB worse plus sun noise
Antenna, m.	2	10	Amateur Radio Astronomers see MRO, assuming W5LUA, KL6M, et al for 914 MHz
Antenna Gain dBi	42	37	55% eff. Assumed
Signal at Front End, dBm	-133	-179	In situ radios decode down to -108 dBm
System Temperature, K	100	100	-145 dBm in 2500 Hz
SNR in 2500 Hz BW dB	12	-34	34 m. @ 30 Kelvin (DSS-13) gets -18

*MRO telecom info: https://descanso.jpl.nasa.gov/monograph/series13/DeepCommo_Chapter6--141029.pdf

Notes on planetary radio link analysis

- You'd have a slightly better chance with the rover – better antenna
- And near the edge of the planet, earthrise or earthset
- *But, Ingenuity* radios do not transmit carrier in Mars configuration
  - Low ("Default") rate: BPSK suppressed carrier, 300 KHz bandwidth ~ 10 packets per second
  - High ("Data") rate: QPSK suppressed carrier, 2 MHz bandwidth ~ 100 packets per second
  - See slide 47
- But, there is good news for the future:
  - Path losses end up being similar to EME path losses (R^2 versus R^4 with poor reflector)
  - Meaning that if we could put amateur stations at or near the planets, EME stations on earth could be working them
  - With some struggle. ☺

Collier Trophy for *Ingenuity*

Ted Tzanetos, Operations Lead
Bob Balaram, Chief Engineer
Mimi Aung, Project Manager

Bobby Braun, NASA HQ
Larry James, JPL Deputy Dir.
Håvard Grip, Chief Pilot

2022 June 9

Favorite Quote

- “Hardware Eventually Fails…”

Favorite Quote

- “Hardware Eventually Fails;
- “Software Eventually Works.”

    - *David Zhu, Mars Helicopter Electronics, 8/14/17*

Questions?

N5BF 23 cm EME 8/16/2016 – 7/15/2023

N5BF 3 cm rover, 2013-present

Author Bio

Courtney Duncan N5BF has been a licensed radio amateur since 1972 and has been involved in most aspects of the hobby from that time. He retired from NASA's Jet Propulsion Laboratory - California Institute of Technology in July 2021 shortly following the initial demonstration flights of the Mars Helicopter *Ingenuity.*

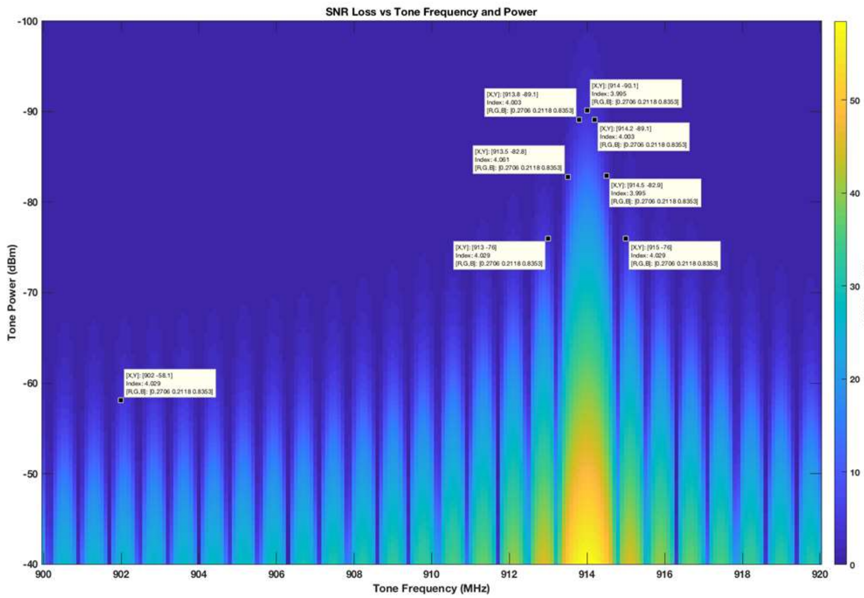
His 35-year career included support for space shuttle missions and experiments, GPS radio occultation technology from space, stellar interferometry, deep space navigation software, gravity mapping, Deep Space Network transponders for deep space CubeSats, and finally, *Ingenuity* telecom.

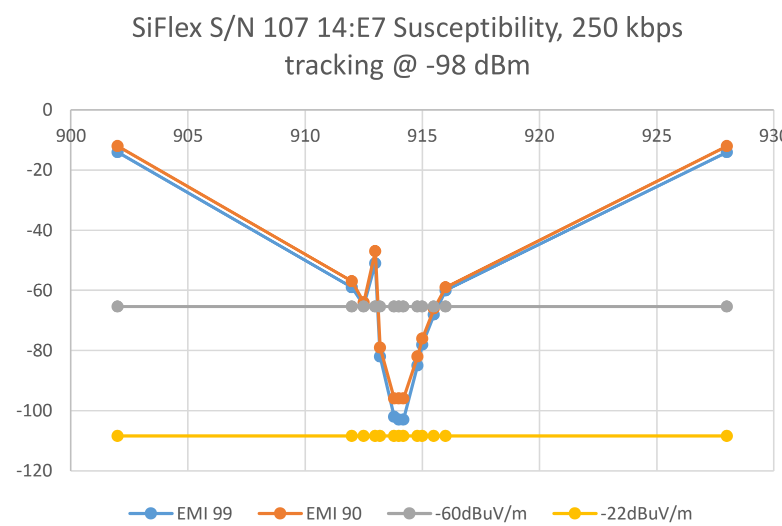
He is a past president of the San Bernardino Microwave Society, a past official of AMSAT-NA and of the JPL Amateur Radio Club, and frequently gives talks on both the Mars Helicopter and on the profound value to society of avocations such as amateur radio.

Courtney was married to Viann WD5EHM (SK) for 45 years and has three children, Viannah KG6GXW, Katherine KG6HUI, John KG6HCO, and two grandchildren. He is also a classically trained pianist and is routinely involved in a variety of musical performances.

Other Material

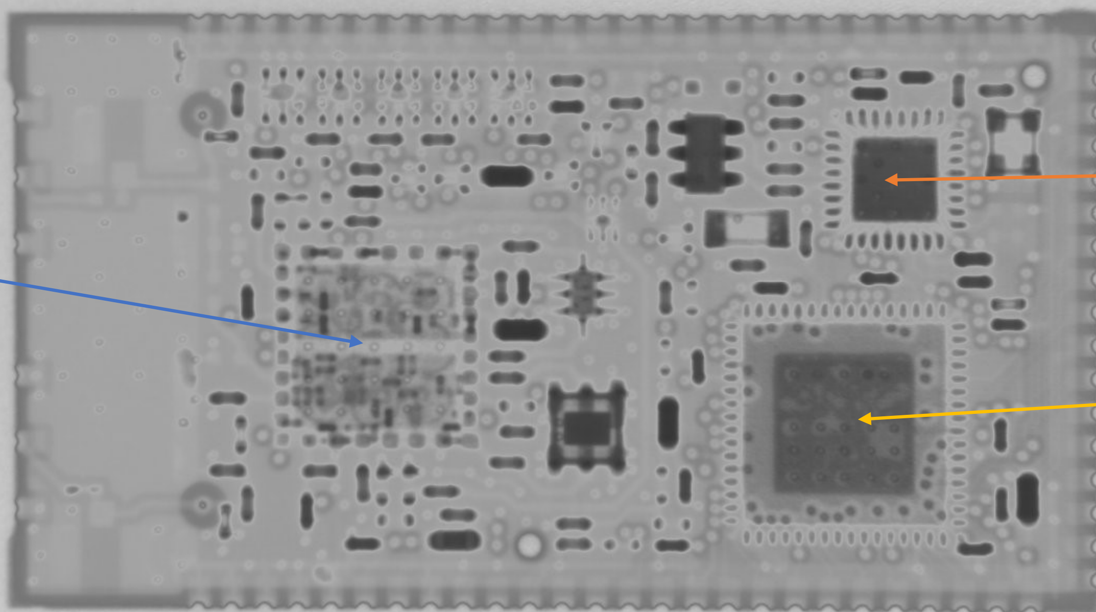
Theoretical Performance of interference on 250kbps OQPSK signal



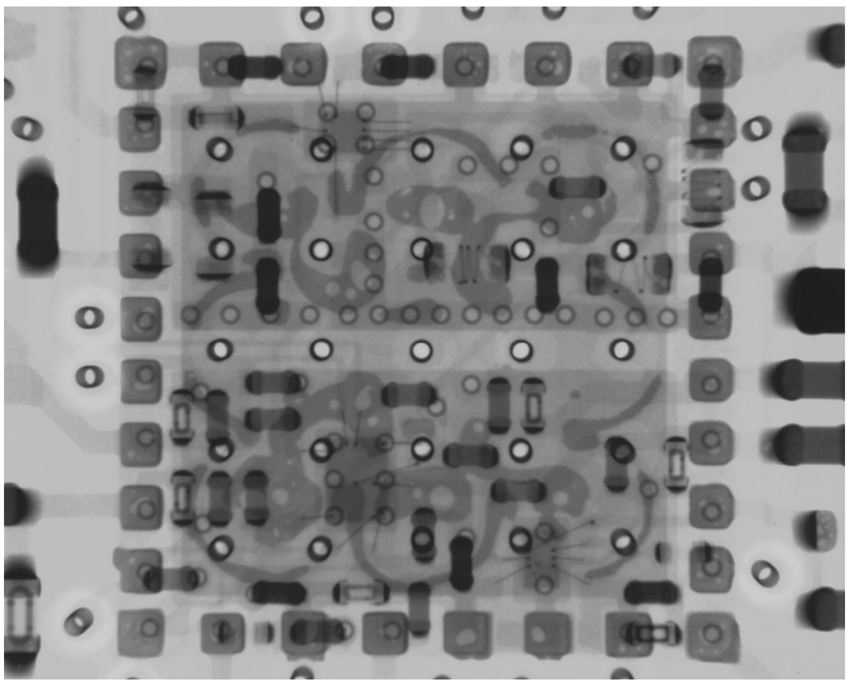


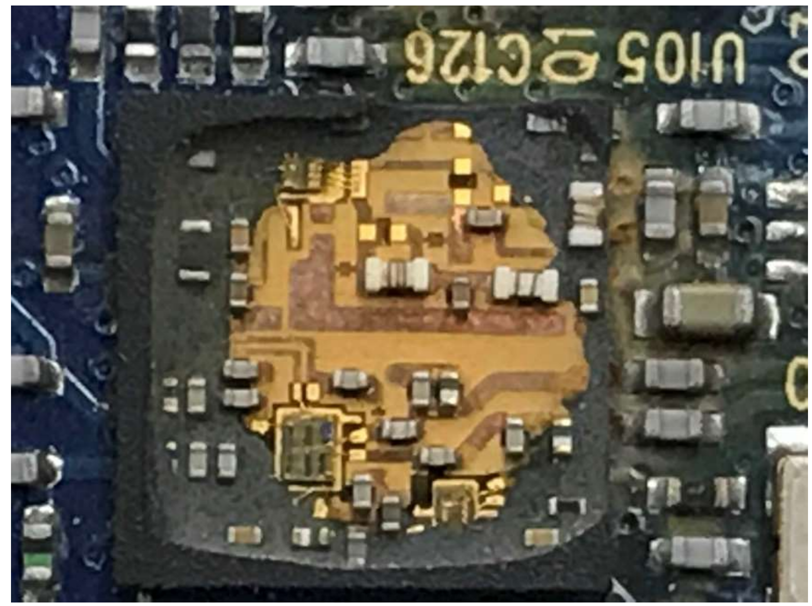
- BPSK model used to mimic the OQPSK modulation.
- Ignoring synchronization effects, performance will still be greatly degraded if a tone with > -90dBm power appear in the main-lobe.

SIFLEX02-R2-HP SOM
Modified for MH FM
SN103 14:EE



X-Ray of the RFMD RF3858 part compared to an optical photo of a part etched for radiation testing
Notice that RFMD is itself a SOM





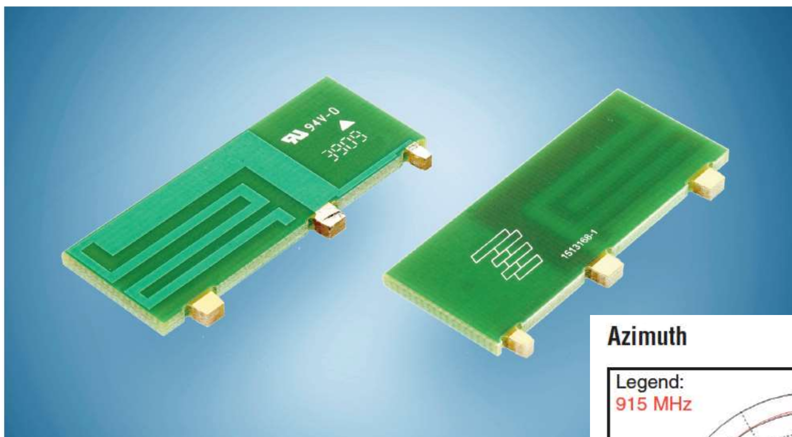
REWORK

The module can be unsoldered from the host board if the Moisture Sensitivity Level (MSL) requirements are met as described in this datasheet.

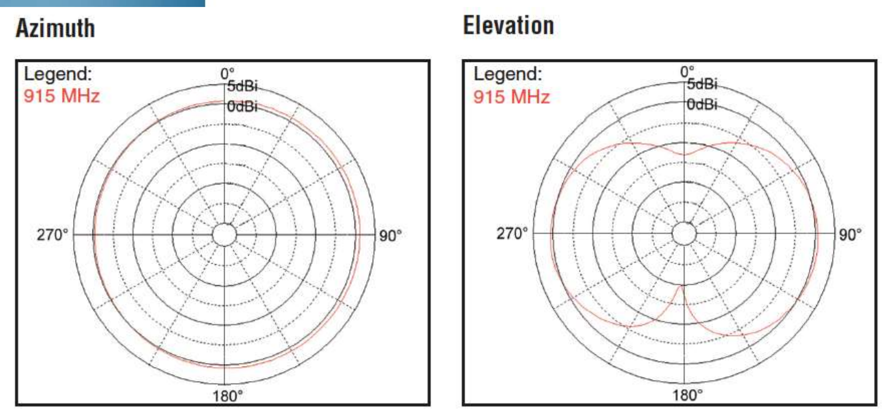
Never attempt a rework on the module itself, e.g. replacing individual components. Such actions will terminate warranty coverage.

Original
Helicopter Side Antenna
Tyco Electronics

902 – 928 MHz – Single Band Antenna (includes frequencies of 915 ISM and ZigBee US)

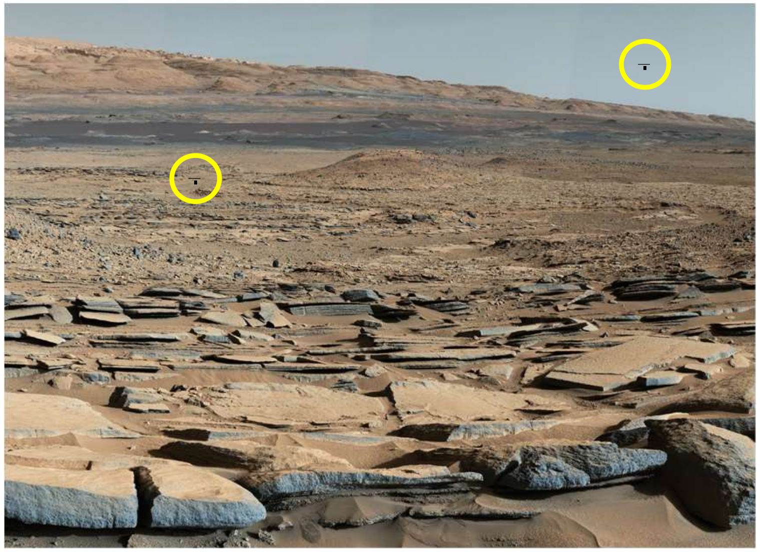


Length: 38 mm
Height: 15 mm
Mass: 1.8 grams (Measured)
Gain: ~0 dBi
Polarization: Vertical
PCB Solder attachment



Free Space Radiation Patterns

Potential Images From Rover

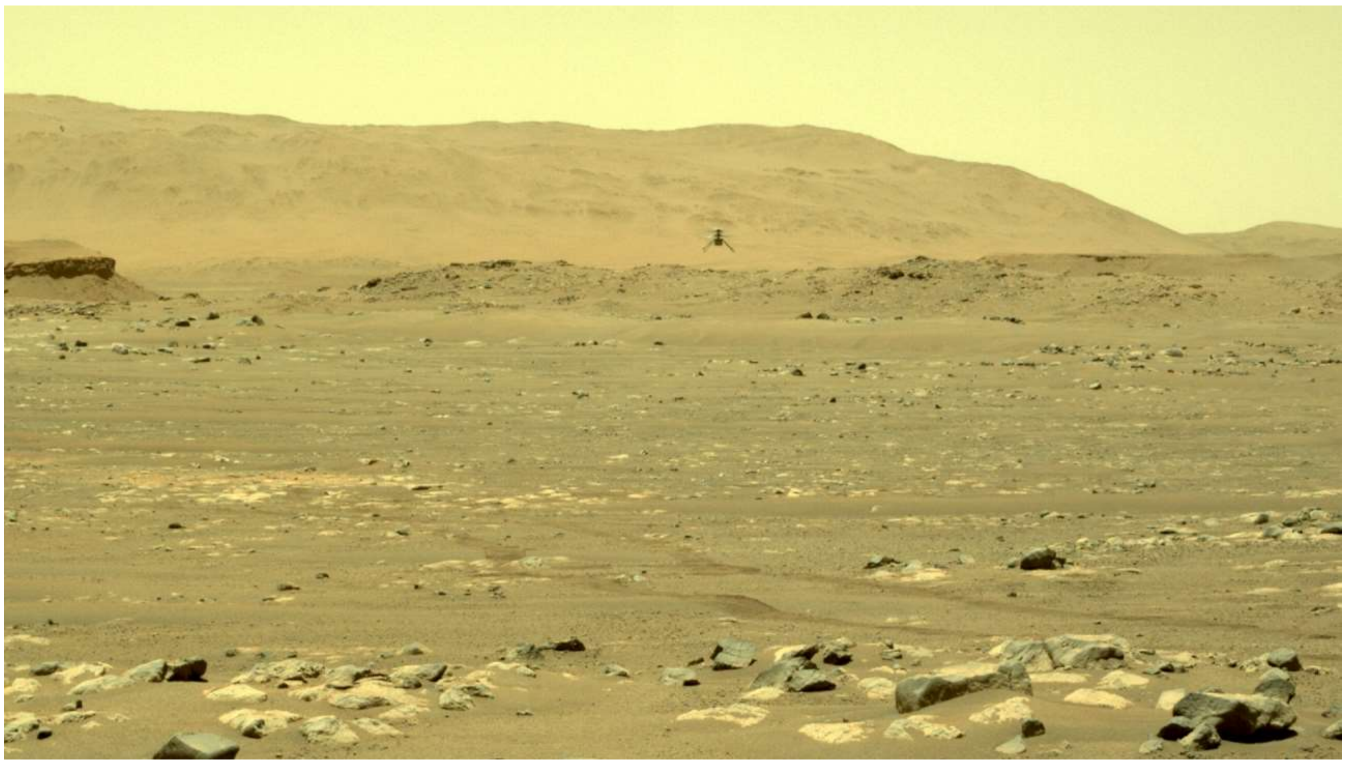


- NavCams at 100m:< 3.5 cm/pixel
- At highest resolution:
  - Blade length = 36/5120 pixels
  - Body cube = 3.6/5120 pixels
- NavCam Imaging Plan Proposal:
  - 2x2 & 2x2 tile exposed and read out every ~ 6 seconds
  - 7 cm/pixel

Mastcam-Z
(Full Res) w/ some noise)

Blades are ~ 145 pixels at full zoom
Body Cube ~ 19 pixels at full zoom

Flight 2 in the air at 5 meters altitude

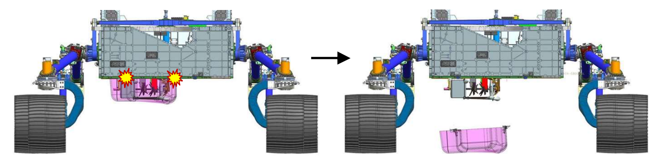


as viewed from Van Zyl Overlook.

Helicopter Deployment Overview

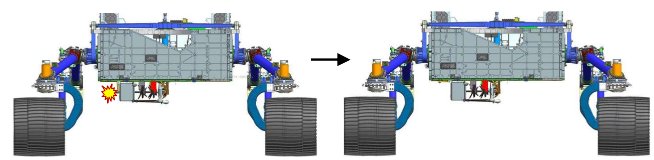
A: Jettison Debris Shield

¼” Cable Cutter Pyros fired severing restraint cables that allows the Debris Shield to drop from the Rover. After drop Rover executes forward drive to prepare for rest of deployment activities



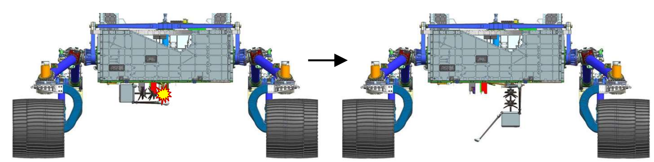
B: Heli Launch Lock Release

Frangibolt energized releasing lower Heli Launch Lock Restraint. Egress Arm / Heli Assy held in place by Egress Arm Restraint



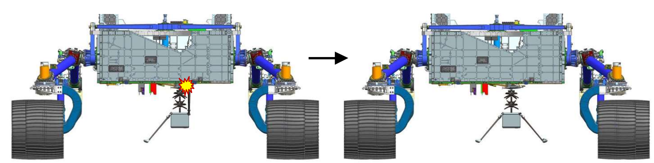
C: Egress Arm Restraint Release and Egress Arm Deploy

Cable Cutter Pyro fired releasing MHDS Egress Arm. Egress Arm Release initiates rotation of Egress Arm & Heli with actuator in dynamic braking mode. Near the end of the deploy motion the actuator completes the arm deploy motion by driving to the hardstop and latching.



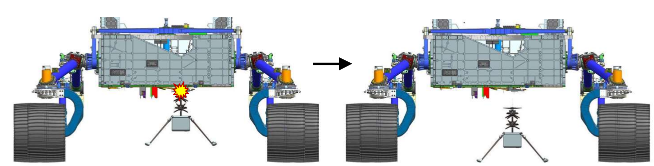
D: Leg Restraint Release

Cable Cutter Pyro fired releasing Helicopter Leading Legs allowing them to spring into their fully deployed state. Helicopter is fully configured for drop after this event.



E: Primary Heli Restraint Release & Heli Drop

Frangibolt energized releasing Helicopter from Rover & Egress Assy. Helicopter drops to Martian Surface below Rover. After nominal drop is confirmed via telemetry and imagery review Rover executes forward drive to allow Heli Solar Arrays to resume charging



Jet Propulsion Laboratory
California Institute of Technology

Presentation History

- 2018 Flight Radios Section Seminar – Pickering @ JPL
- 2018 IEEE Thousand Oaks Chapter - Live
- 2019 JPL ARC - live
- 2021 CV ARC - Zoom
- 2021 September 2 San Bernardino Microwave Society W6IFE - live
- 2021 October 26 Pasadena ARC W6KA – Zoom
- 2024 August 9 20th International EME Conference, Trenton, NJ