# NASA’s Deep Space Network and the Challenges of Deep Space Communications

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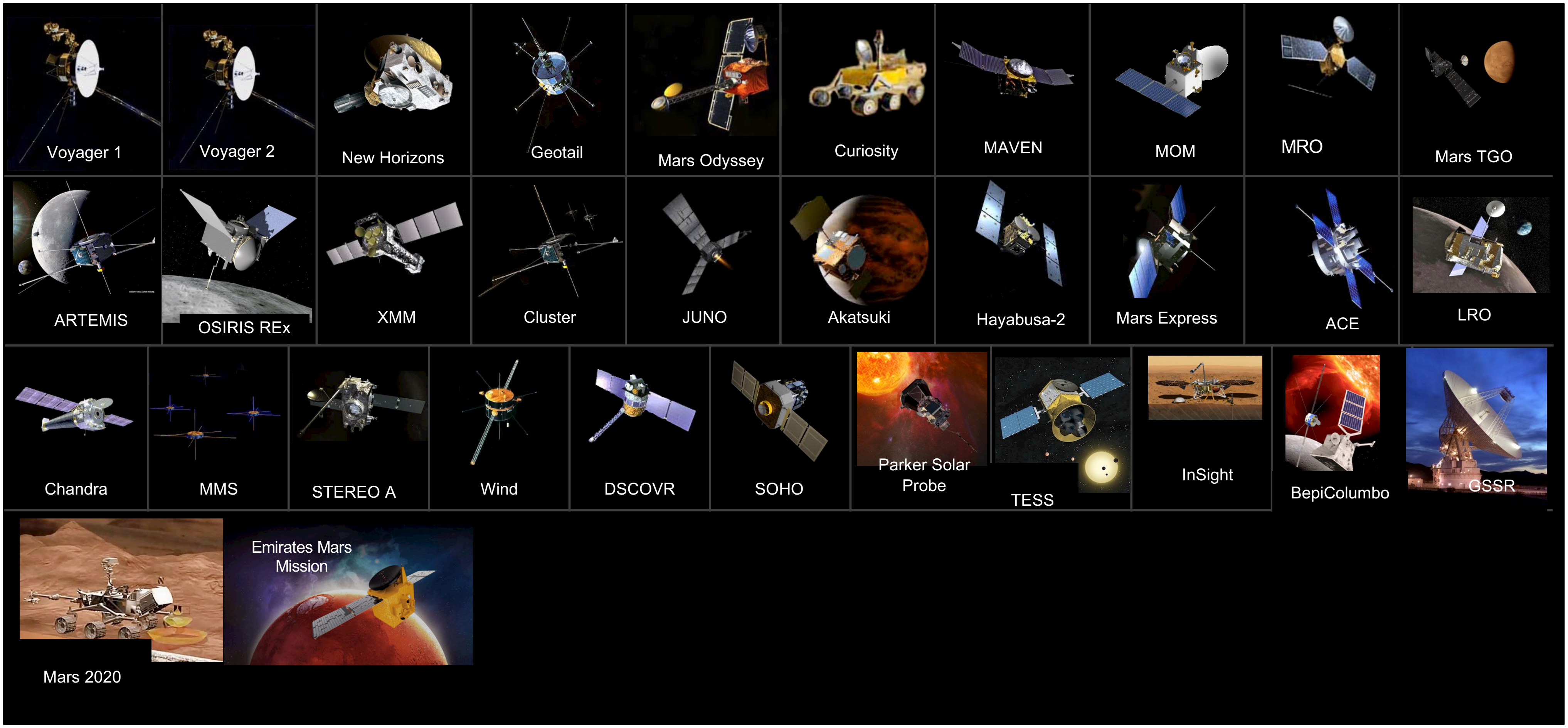
*2021 JPL Webinar - Optical Society of America*

# NASA Deep Space Network (DSN)

# Some of the Missions Supported by the DSN



# Deep Space Network (DSN)

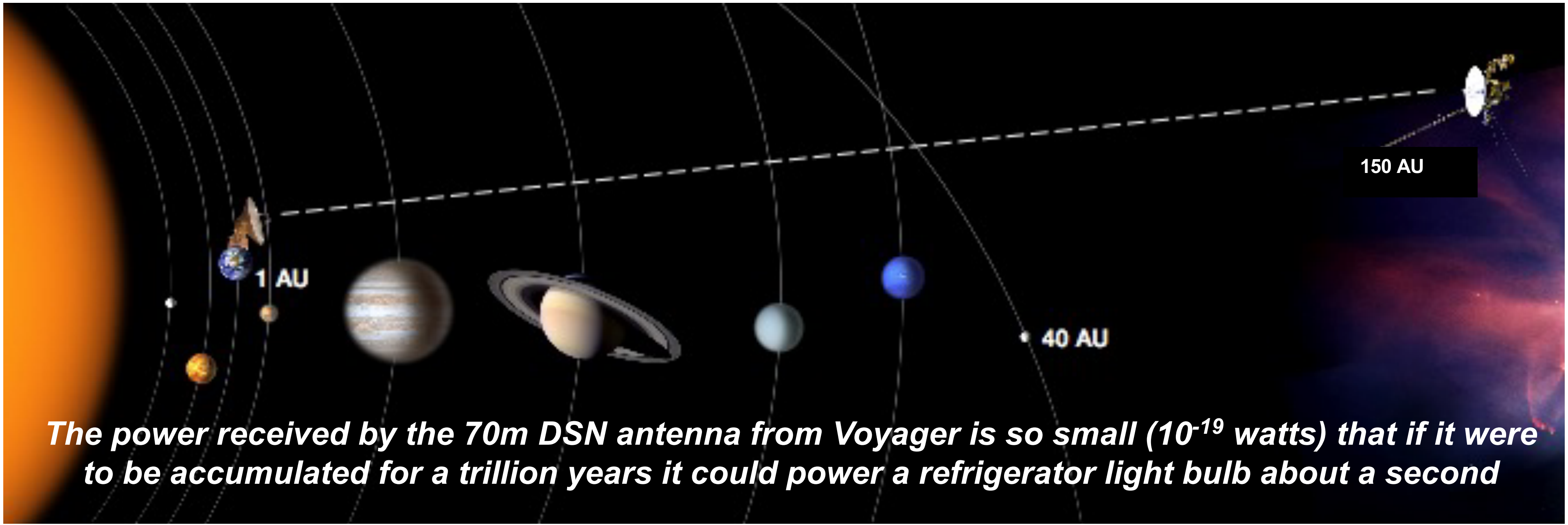
- The DSN has currently 13 operational deep space antennas in three Deep Space Communication Complexes (DSCC)
- These antennas are among the largest (34m and 70m) and most precise, equipped with the lowest noise, most sensitive radio receivers in the world
  - RF DSN equipment covers L-, S-, X-, K-, and Ka-bands (1 to 35 GHz)
  - The DSN can support deep space, near-Earth, radio astronomy and radar science bands
- The DSN supports 35+ missions

This is what a DSN 70m antenna would look like inside the Rose Bowl

# Why Deep Space Communications Is So Difficult

- Vast distances
- No second chances for critical events
- Limited power, aperture, mass
- Harsh environment, long timespans

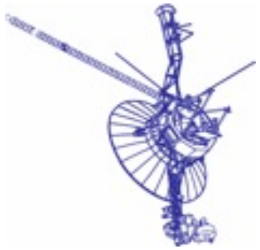
| Location | Distance | Loss/Geo | R/T Time |
|---|---|---|---|
| Cell Phone | 2.5 km | -100 dB | - |
| Geo | $4 \times 10^4$ km | 0 dB | 0.3 sec |
| Moon | $4 \times 10^5$ km | 20 dB | 3 sec |
| Mars | $3 \times 10^8$ km | 80 dB | 30 min |
| Saturn | $10^9$ km | 90 dB | 2 hours |
| Voyager 1 | $2 \times 10^{10}$ km | 114 dB | 42 hours |

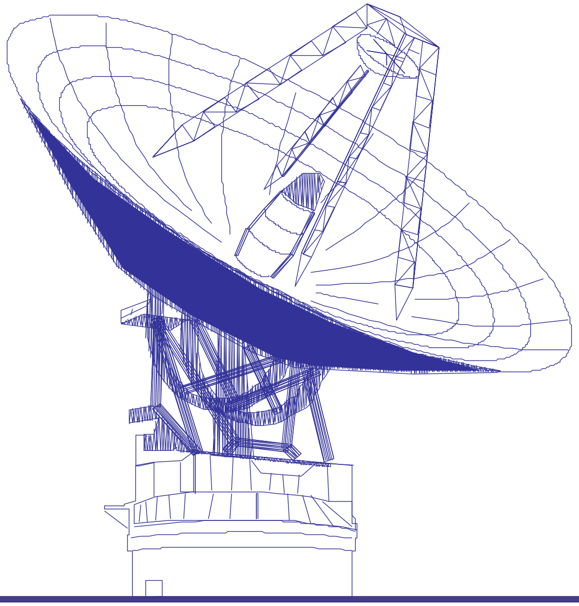


***The power received by the 70m DSN antenna from Voyager is so small ($10^{-19}$ watts) that if it were to be accumulated for a trillion years it could power a refrigerator light bulb about a second***

# Why Deep Space Communications Is So Difficult

- *f* = FREQUENCY
- $P_T$ = TRANSMITTER POWER (RF)
- $L_{TP}$ & $L_{RP}$ = POINTING LOSSES
- $L_A$ = LOSS THROUGH ATMOSPHERE(S)
- $A_T$ & $A_R$ = EFFECTIVE ANTENNA APERTURES
- R = RANGE BETWEEN S/C & DSS
- $T_S$ = SYSTEM NOISE TEMPERATURE



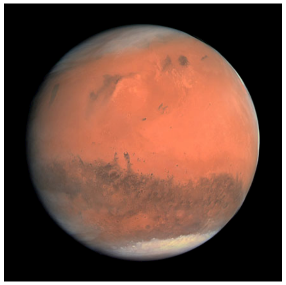


$$\textbf{Data Rate} \propto \frac{P_T A_T A_R f^2}{T_S L_{TP} L_A L_{RP} R^2}$$

- There are always severe constraints on spacecraft power (tens of watts) and antennas (a few meters)
- What we do on the ground: cryogenically cooled low noise amplifiers (6-12 K) and receivers; large apertures; ultra-precise antenna surfaces and pointing; high power transmitters (100 kW); higher frequencies

# Interplanetary Missions Are Risky and Difficult

- Light travel time to Mars: between 3 (closest) and 22 minutes (farthest)
- Light travel time to Saturn: about 90 minutes
- Light travel time to Pluto: about 5.5 hours
- => dynamic critical events, such as planetary encounters, orbit insertions, and surface landings, have to be sequenced and conducted autonomously



- Number of missions (and spacecraft) to Mars: 49 (65 spacecraft)
- Failure rate: > 55% (36/65) of the spacecraft were lost or failed
- Multiple factors make Mars high risk
  - Mission complexity
  - Larger launch vehicles and rockets; long cruise (6 months) with multiple maneuvers
  - Stringent navigation for Mars orbit insertion (orbiters) and atmospheric entry (landers)
  - Mars gravity, while weaker than Earth’s, causes rapid spacecraft acceleration; Mars atmosphere is thinner but more variable than Earth’s, posing a significant descent hazard
  - Harsh Martian environment and distance from the Sun make capture of solar energy and power management more challenging

# M2020 Perseverance Mission Overview

## LAUNCH

Jul/Aug 2020

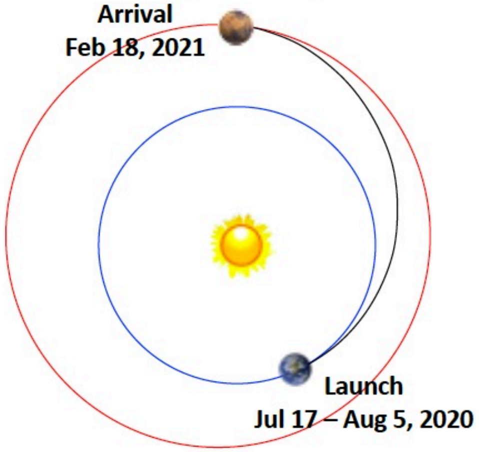
M2020
stowed
in 5-m
payload
fairing

Cape Canaveral Air Force
Station - SLC-41
(Eastern Test Range)

Atlas V 541

## INTERPLANETARY CRUISE

197 days to 216 days



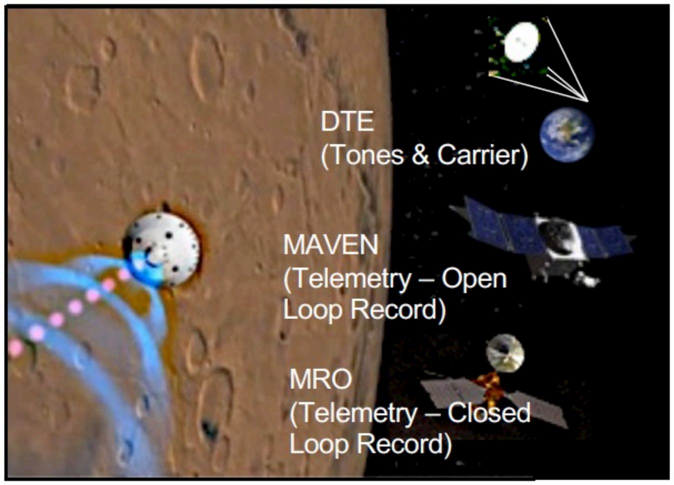
## APPROACH & EDL

Guided Entry with Range Trigger (7 x 7.5 km landing ellipse) and Terrain-Relative Navigation (TRN)

Max. Entry Speed = ~ 5.4 km/s (relative)
Ls = 5.6 deg
Landing elevation ~ -2.5 km
Landing LMST ~ 3:42 – 3:53 PM

## EDL COMMUNICATIONS

Ultra-High-Frequency and X-band Links

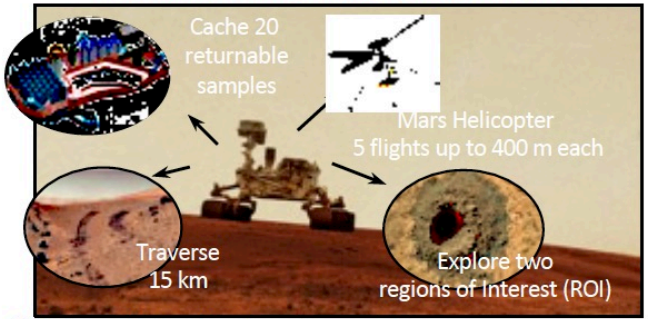


## INITIAL LANDED OPERATIONS

- Operations on CEDL software for first ~7 sols
- Surface FSW transition on Sols 7-11
- Critical rover deployments: HGA, RSM, release of arm launch locks, belly pan deployment
- Rover and early instrument health checks
- Establishment of Earth communications
- Imaging of landing site

## SURFACE OPERATIONS

1.5 Martian Years on a 5-hr tactical timeline

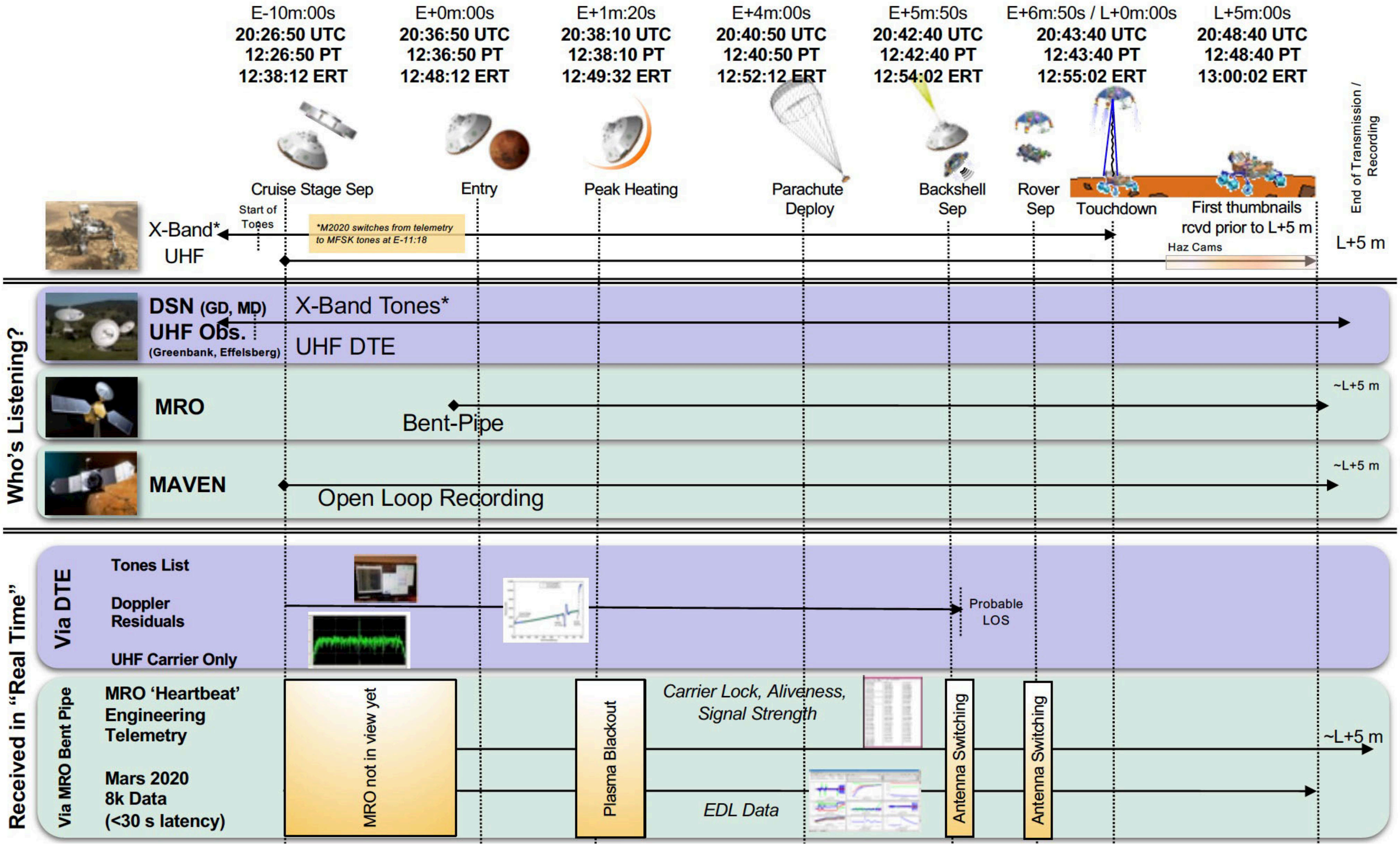


Sol Types (6 day/week surface ops):

1. Survey Remote Sensing
2. Workspace Proximity Science (Natural and Abraded)
3. Traverse and Approach
4. MOXIE (ISRU)
5. MEDA-dedicated
6. Sample acquisition and borehole science

# M2020 Perseverance Entry, Descent, Landing Communications Overview

## EDL Comm Information Received in "Real Time"



| Cruise Stage Sep | Entry | Peak Heating | Parachute Deploy | Backshell Sep | Rover Sep | Touchdown | First thumbnails rcvd prior to L+5 m |
|---|---|---|---|---|---|---|---|
| E-10m:00s<br>20:26:50 UTC<br>12:26:50 PT<br>12:38:12 ERT | E+0m:00s<br>20:36:50 UTC<br>12:36:50 PT<br>12:48:12 ERT | E+1m:20s<br>20:38:10 UTC<br>12:38:10 PT<br>12:49:32 ERT | E+4m:00s<br>20:40:50 UTC<br>12:40:50 PT<br>12:52:12 ERT | E+5m:50s<br>20:42:40 UTC<br>12:42:40 PT<br>12:54:02 ERT | | E+6m:50s / L+0m:00s<br>20:43:40 UTC<br>12:43:40 PT<br>12:55:02 ERT | L+5m:00s<br>20:48:40 UTC<br>12:48:40 PT<br>13:00:02 ERT |

End of Transmission / Recording

X-Band*
UHF

Start of Tones

*M2020 switches from telemetry to MFSK tones at E-11:18

Haz Cams

L+5 m

**Who's Listening?**

**DSN** (GD, MD)
**UHF Obs.**
(Greenbank, Effelsberg)

X-Band Tones*

UHF DTE

**MRO**

Bent-Pipe

~L+5 m

**MAVEN**

Open Loop Recording

~L+5 m

**Received in "Real Time"**

**Via DTE**

**Tones List**

**Doppler Residuals**

**UHF Carrier Only**

Probable LOS

**Via MRO Bent Pipe**

**MRO 'Heartbeat' Engineering Telemetry**

**Mars 2020 8k Data (<30 s latency)**

MRO not in view yet

Plasma Blackout

*Carrier Lock, Aliveness, Signal Strength*

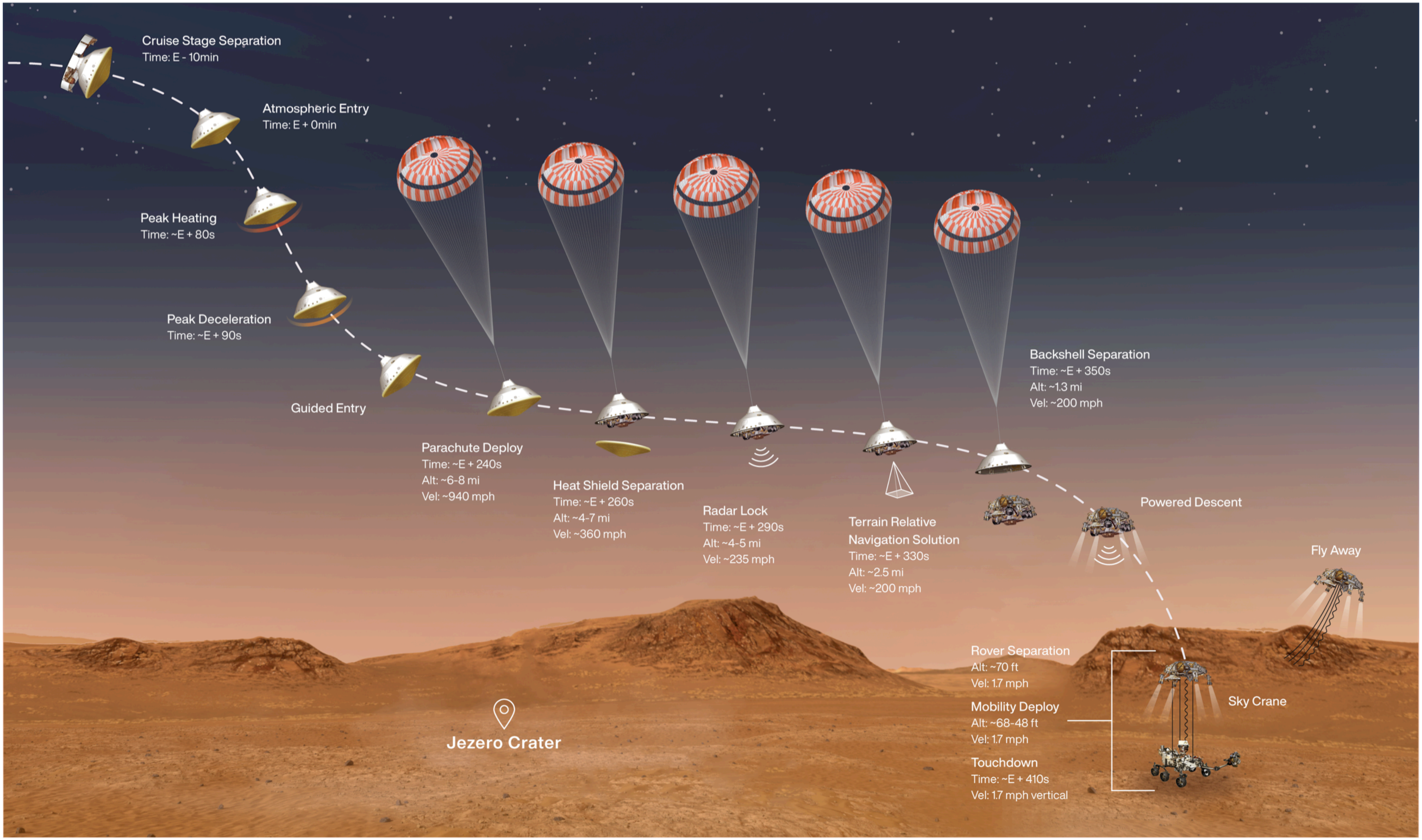
*EDL Data*

Antenna Switching

Antenna Switching

~L+5 m

# M2020 Perseverance Entry, Descent, Landing Overview



**Cruise Stage Separation**
Time: E - 10min

**Atmospheric Entry**
Time: E + 0min

**Peak Heating**
Time: ~E + 80s

**Peak Deceleration**
Time: ~E + 90s

**Guided Entry**

**Parachute Deploy**
Time: ~E + 240s
Alt: ~6-8 mi
Vel: ~940 mph

**Heat Shield Separation**
Time: ~E + 260s
Alt: ~4-7 mi
Vel: ~360 mph

**Radar Lock**
Time: ~E + 290s
Alt: ~4-5 mi
Vel: ~235 mph

**Terrain Relative Navigation Solution**
Time: ~E + 330s
Alt: ~2.5 mi
Vel: ~200 mph

**Backshell Separation**
Time: ~E + 350s
Alt: ~1.3 mi
Vel: ~200 mph

**Powered Descent**

**Rover Separation**
Alt: ~70 ft
Vel: 1.7 mph

**Mobility Deploy**
Alt: ~68-48 ft
Vel: 1.7 mph

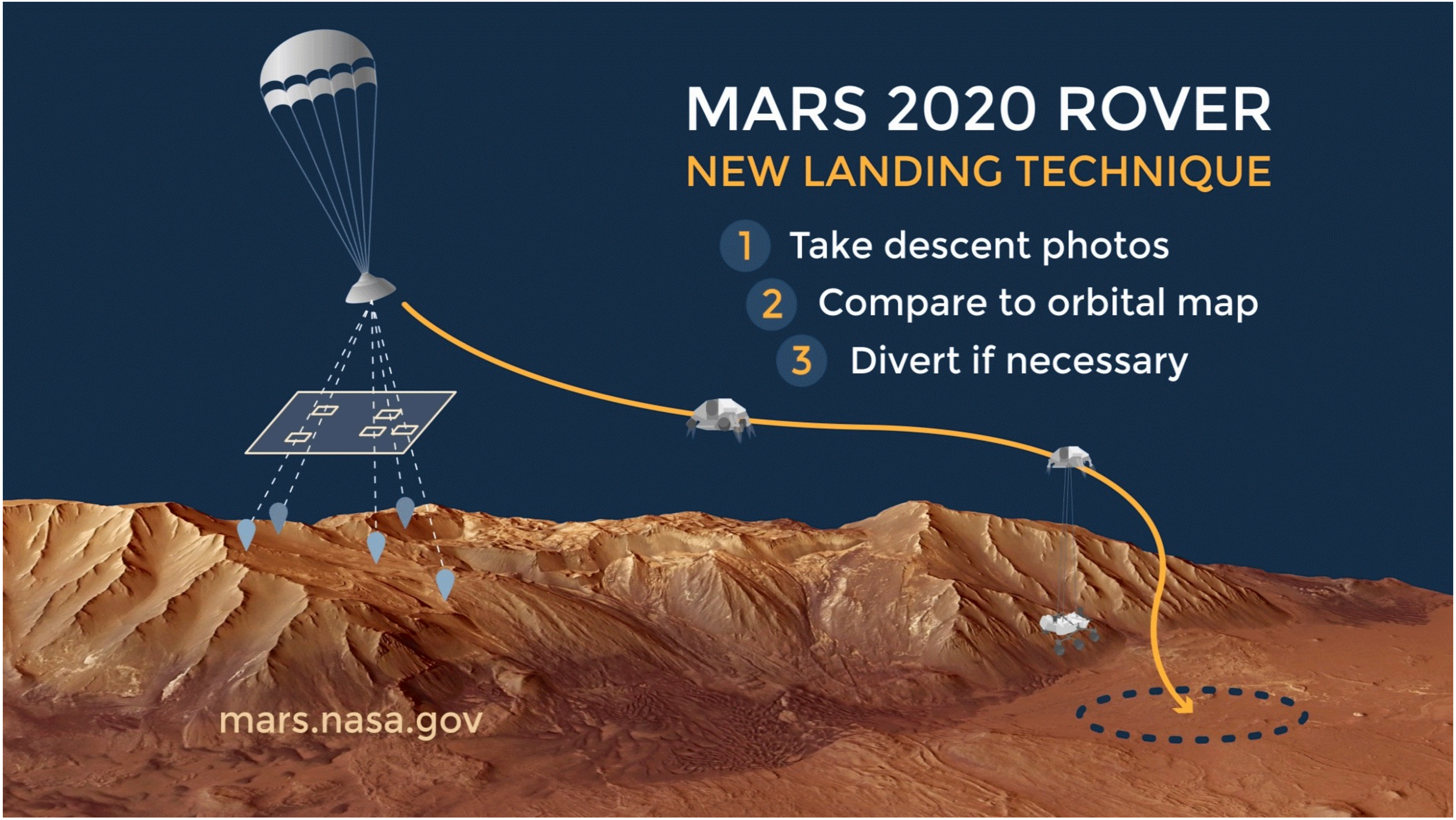
**Touchdown**
Time: ~E + 410s
Vel: 1.7 mph vertical

**Sky Crane**

**Fly Away**

**Jezero Crater**

# M2020 Perseverance’s New Terrain Relative Navigation Technique



MARS 2020 ROVER

NEW LANDING TECHNIQUE

1 Take descent photos

2 Compare to orbital map

3 Divert if necessary

mars.nasa.gov

M2020 Also carried new cameras and a microphone to better record Entry, Descent, and Landing

# NASA MARS2020 PERSEVERANCE ENTRY, DESCENT, AND LANDING MOVIE

https://www.youtube.com/watch?v=4czjS9h4Fpg

*NOTE: the Flight Director at JPL announced progress of the vehicle in real time through the atmosphere through landing on the surface based on minimal telemetry that ranged from just a few bits/sec to 8k kbps, received either direct-to-Earth to the DSN or relayed through the Mars Reconnaissance Orbiter back to the DSN in real time. The DSN had multiple antennas at two complexes, Goldstone/USA and Madrid/Spain, all tracking and receiving the signals. The video was assembled from camera data recorded on the M2020 rover and later relayed back to Earth through the DSN via the Mars Relay Network of orbiting spacecraft. The video was paired with the real-time narration that the Flight Director had made during the landing event.*

# Mission Requirements Continue to Increase

- Requirements for data return volume

| | |
|---|---|
| (Mars) MER-B (Opportunity rover): | 50 Mb/sol |
| (Mars) MSL (Curiosity rover): | 250 Mb/sol |
| (Mars) M2020 (2020 rover): | 1140 Mb/sol |
| (L2 orbit) JWST: | 2700 Mb/day |

***x500 since 2004***

- Downlink data rates in DSN (X-band and Ka-band frequencies)

| | |
|---|---|
| Mars Odyssey: | 0.256 Mb/s |
| Mars Reconnaissance Orbiter: | 6 Mb/s |
| – Could be 25 Mb/s without transponder constraint | |
| Kepler (1 AU): | 4 Mb/s |
| TESS (eccentric Earth orbit 2:1 lunar resonance): | 125 Mb/s |

***x500 since 2001***

- Anticipated crewed mission requirements from Moon and Mars:
  150 Mb/s – 220 Mb/s (and higher)

***x3000 since Apollo (50 Kb/s)***

- ***Future astrophysics missions are looking for > 1 Gb/s***
- ***SpaceOps 2016 Deutsch et al: "we expect deep space data rates to increase 10-fold each decade for 50 years"***

# RF Telecommunications

- What is the radio signal we use?
  - A phase modulated carrier (or sub-carrier)
  - Note: Phase modulation and freq modulation are very closely related, and some textbooks even treat only one or the other, knowing that the properties can be derived one from the other.
  - Opposite shows time domain examples of various modulation forms.
  - The generic equation for a Phase mod signal is given by

$$y(t) = A_C \sin(\omega_C t + m(t) + \phi_C)$$

  - where $A_c$ is the carrier amplitude, $\omega_c$ is the carrier frequency, and $\phi_c$ is a phase offset (a constant)
- *M(t)* is the modulation, the data as a function of time, in our case a digital bit stream

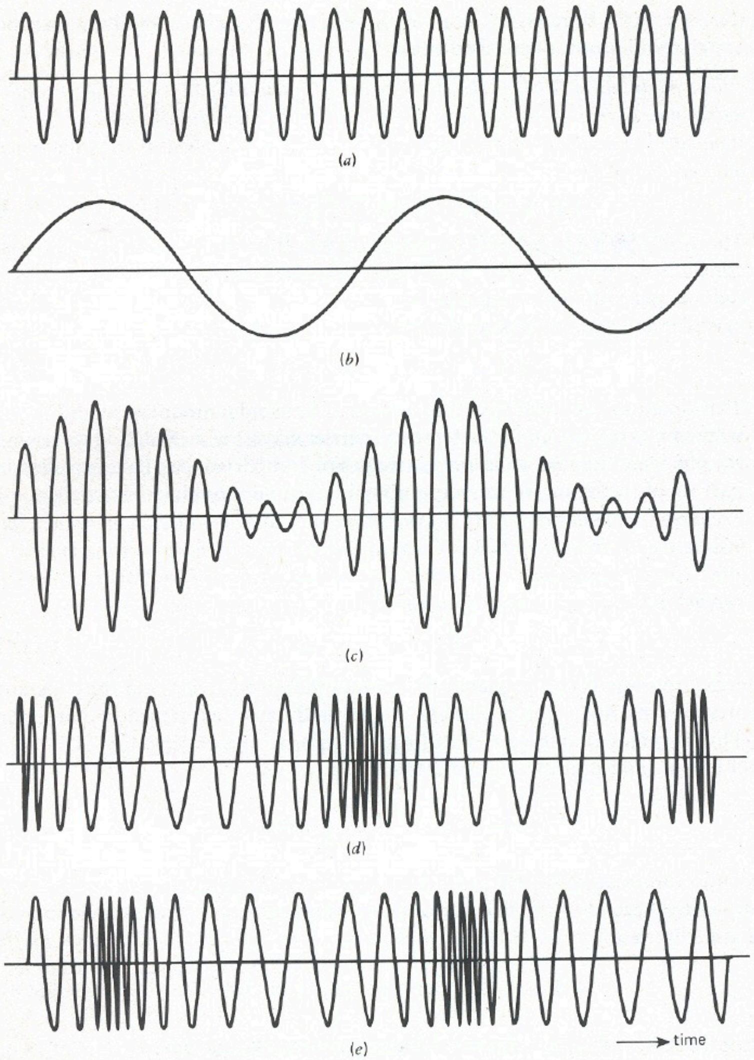


**Figure 4.1** Illustrating AM, PM, and FM waves produced by a single tone. (a) Carrier wave. (b) Sinusoidal modulating wave. (c) Amplitude-modulated wave. (d) Phase-modulated wave. (e) Frequency-modulated wave.

# RF Telecommunications

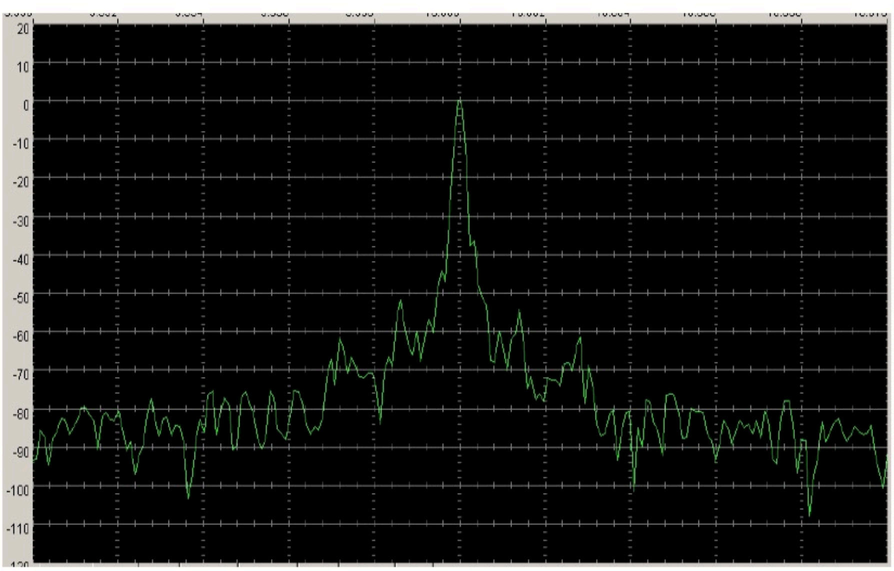
- If M(t) is a stream of zeros and ones (digital), represented by

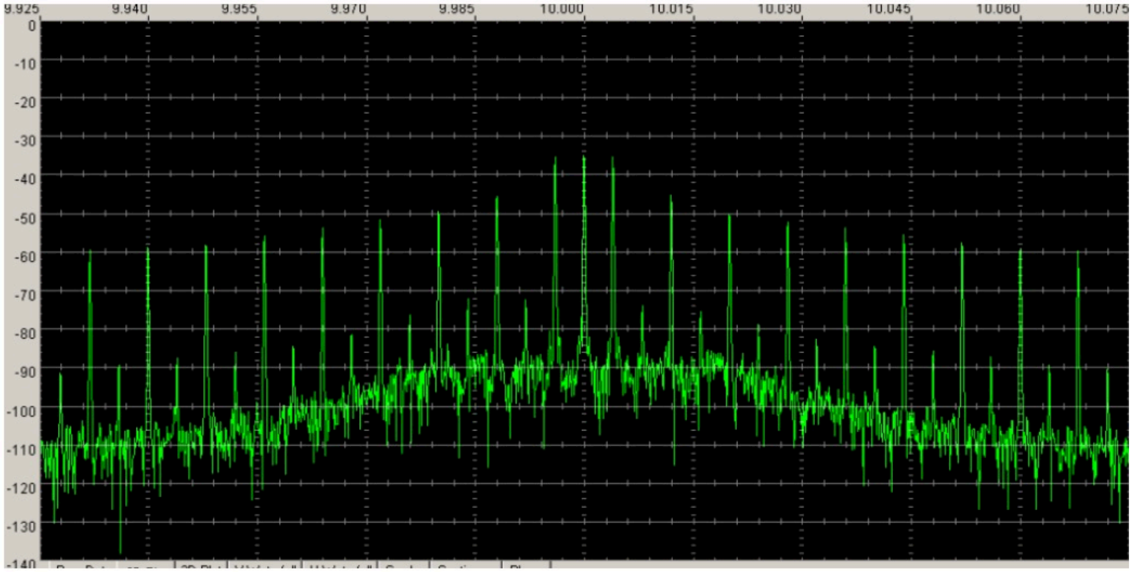
$$m(t) = \Delta q(t)$$

  - where $\Delta$ is the amount of phase shift being imposed (amplitude of the phase), also known as the modulation index, and q(t) is just ±1
  - The result is given by

$$y(t) = [A_C \cos(\Delta)]\cos(\omega_C t) - [A_C \sin(\Delta)]q(t)\sin(\omega_C t + \phi_C)$$

  - The first term is just the carrier reduced or "suppressed" by the cos($\Delta$) factor
  - (Note: as $\Delta$ appraoches 90degs, the carrier vanishes, hence the term "Suppressed Carrier")
  - The second term is the information part of the spectrum
  - The bottom left shows a measured carrier only signal (with noise), the right modulated with a stream of one's and zero's





# Deep Space Optical Telecommunications

- ❑ Unlike conventional RF communications that uses phase modulation of the carrier, Pulse Position Modulation uses direct photon detection with a time interval that is divided into a number of possible pulse locations, but only a single pulse is placed in one of the possible positions. The position of that pulse is determined by the information (word) that is to be transmitted.

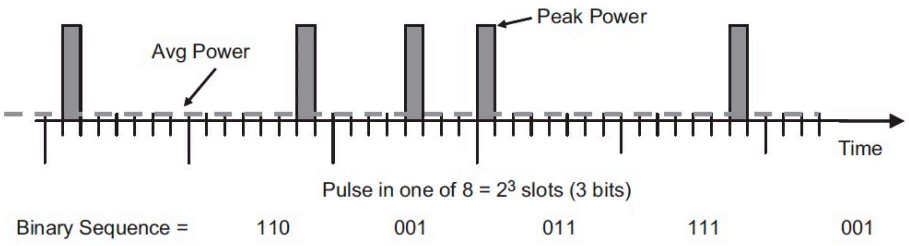
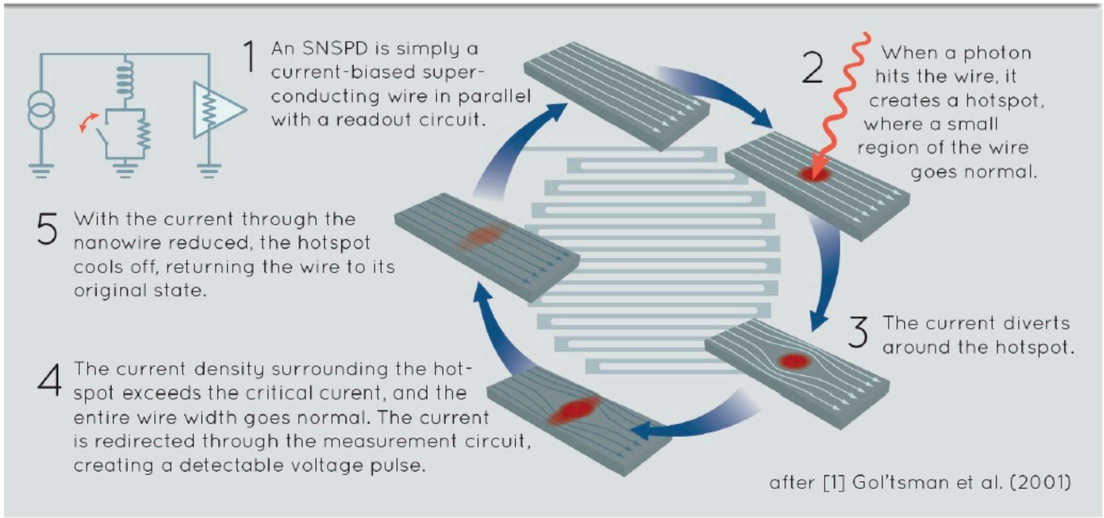


**Fig. 2-7. Example of a M-ary PPM modulation with *M* = 8 and straight binary mapping.**



1 An SNSPD is simply a current-biased superconducting wire in parallel with a readout circuit.

2 When a photon hits the wire, it creates a hotspot, where a small region of the wire goes normal.

3 The current diverts around the hotspot.

4 The current density surrounding the hotspot exceeds the critical current, and the entire wire width goes normal. The current is redirected through the measurement circuit, creating a detectable voltage pulse.

5 With the current through the nanowire reduced, the hotspot cools off, returning the wire to its original state.

after [1] Gol'tsman et al. (2001)

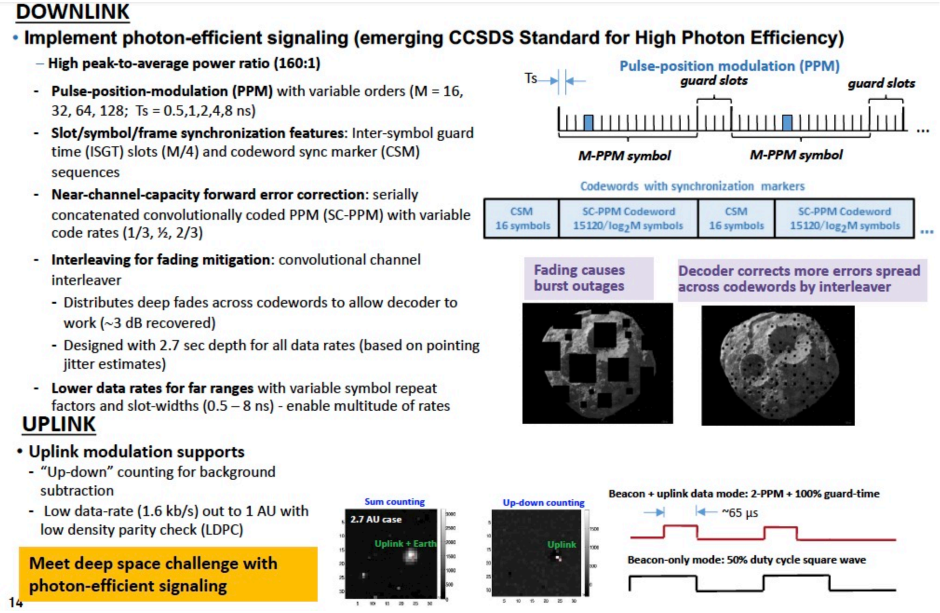
- Highest performing detector available for time-correlated single photon counting, UV to mid-IR
- Requires 1 – 4 Kelvin cryogenic cooling
- Commercial single-pixel SNSPDs have been widely adopted by the quantum optics community

Deep space optical communications is typically in a photon starved regime requiring Superconducting Nanowire Single Photon Detectors (SNSPD) to maximize photon information efficiency. SNSPD are also important in quantum physics and astrophysics.

***Shaw et al., IceQubes 2019: International Workshop on Cryogenic Electronics for Quantum Systems, Batavia, Illinois, June 17-20, 2019***

# Deep Space Optical Telecommunications

- ❑ Deep Space Optical Communications (DSOC) is a new flight optical terminal that will fly on a NASA Discovery mission Psyche in 2022. The Palomar telescope will be used for downlink reception in this technology demo. An early, small prototype optical collector is planned for deployment at the Goldstone DSN site as well.



**DOWNLINK**

- **Implement photon-efficient signaling (emerging CCSDS Standard for High Photon Efficiency)**
  - **High peak-to-average power ratio (160:1)**
  - **Pulse-position-modulation (PPM)** with variable orders (M = 16, 32, 64, 128; Ts = 0.5,1,2,4,8 ns)
  - **Slot/symbol/frame synchronization features**: Inter-symbol guard time (ISGT) slots (M/4) and codeword sync marker (CSM) sequences
  - **Near-channel-capacity forward error correction**: serially concatenated convolutionally coded PPM (SC-PPM) with variable code rates (1/3, ½, 2/3)
  - **Interleaving for fading mitigation**: convolutional channel interleaver
    - Distributes deep fades across codewords to allow decoder to work (~3 dB recovered)
    - Designed with 2.7 sec depth for all data rates (based on pointing jitter estimates)
  - **Lower data rates for far ranges** with variable symbol repeat factors and slot-widths (0.5 – 8 ns) - enable multitude of rates

**UPLINK**

- **Uplink modulation supports**
  - "Up-down" counting for background subtraction
  - Low data-rate (1.6 kb/s) out to 1 AU with low density parity check (LDPC)

**Meet deep space challenge with photon-efficient signaling**

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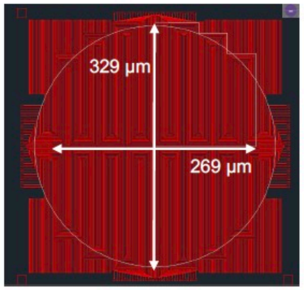
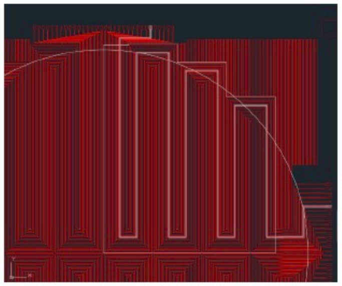
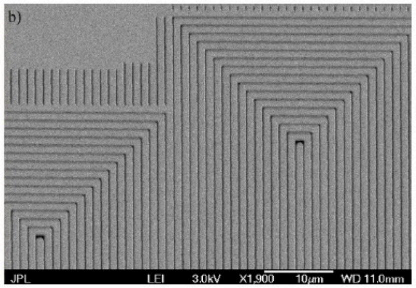
- SNSPD planned for DSOC Ground Laser Receiver at 200 inch Palomar telescope (5.1 m)
- 64-element WSi SNSPD array with >79,000 µm$^2$ area (equiv. to 318.5 µm diameter)
- Divided into four spatial quadrants for fast beam centroiding
- 160 nm WSi nanowires on 1200 nm pitch – each wire ~1 mm in length (~7000 squares)
- Free-space coupling to 1 Kelvin cryostat, with cryogenic filters and lens
- 78% system detection efficiency at 1550 nm
- < 80 ps FWHM timing jitter
- ~1.2 Gcps maximum count rate



CAD Design of SNSPD focal plane array



CAD Design showing one of 16 individual sensor elements per quadrant



Electron Microscope Image of Nanowire Structure

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*Shaw et al., IceQubes 2019: International Workshop on Cryogenic Electronics for Quantum Systems, Batavia, Illinois, June 17-20, 2019*

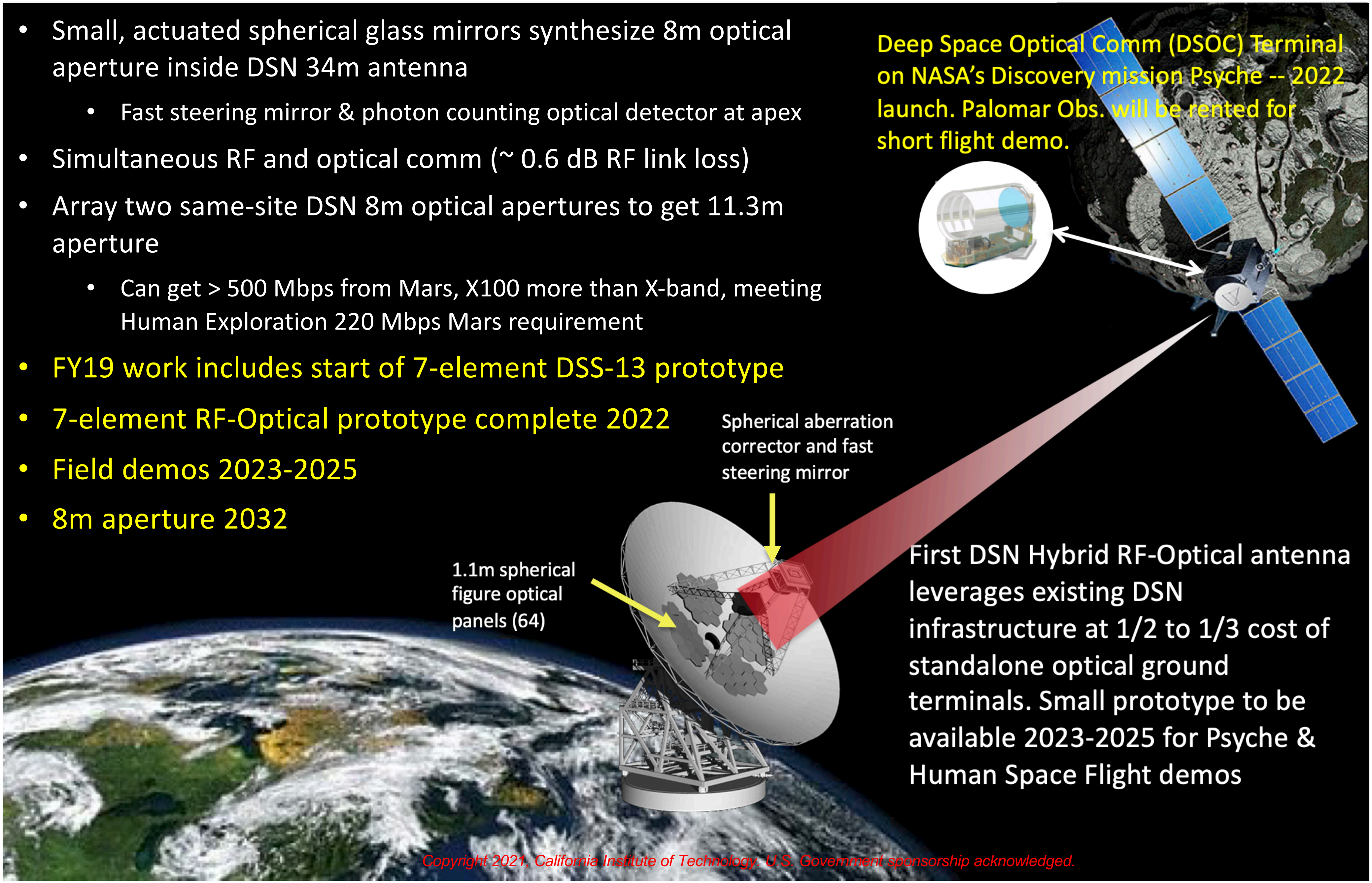
# Why Optical Deep Space Communications

$$\text{Data Rate} \propto \frac{P_T A_T A_R f^2}{T_S L_{TP} L_A L_{RP} R^2}$$

- RF: with some effort, we can increase $P_T$ by 3x to 10x
- RF: we can array DSN antennas – 2x to 4x
- **Optical (1550 nm) deep space downlink frequency is 6450x higher than 32 GHz Ka-band (0.01m)**

# DSN Hybrid RF-Optical Antenna Concept

- Small, actuated spherical glass mirrors synthesize 8m optical aperture inside DSN 34m antenna
  - Fast steering mirror & photon counting optical detector at apex
- Simultaneous RF and optical comm (~ 0.6 dB RF link loss)
- Array two same-site DSN 8m optical apertures to get 11.3m aperture
  - Can get > 500 Mbps from Mars, X100 more than X-band, meeting Human Exploration 220 Mbps Mars requirement
- FY19 work includes start of 7-element DSS-13 prototype
- 7-element RF-Optical prototype complete 2022
- Field demos 2023-2025
- 8m aperture 2032



Deep Space Optical Comm (DSOC) Terminal on NASA's Discovery mission Psyche -- 2022 launch. Palomar Obs. will be rented for short flight demo.

First DSN Hybrid RF-Optical antenna leverages existing DSN infrastructure at 1/2 to 1/3 cost of standalone optical ground terminals. Small prototype to be available 2023-2025 for Psyche & Human Space Flight demos

# The Future: Challenges of Deep Space Communications

- By using large antennas, high power transmitters, ultra-low noise receivers, and higher frequencies, the DSN can push RF link performance to tens of Mb/s over interplanetary distances
- Future robotic and crewed missions will need 100s of Mb/s to Gb/s
- Optical communications offers tens- to hundreds-fold higher data rates versus RF systems of comparable mass/size/power
- DSN's first optical/hybrid antenna, an 8m optical aperture “inside” a DSN RF antenna, is underway at Goldstone, CA (DSS-23), with potential for Gb/s capability at Mars
  - Reliable RF communications over long distances has always been challenging; optical systems will bring new challenges, including precise pointing, photon detectors, atmosphere/clouds, outdoors operation, and high power lasers on the ground and on the spacecraft

# The Future: Deep Space Optical Communications with the DSN