How to get your Motorhome on Mars in one piece

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NASA Systems Webinar

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Jet Propulsion Laboratory
California Institute of Technology

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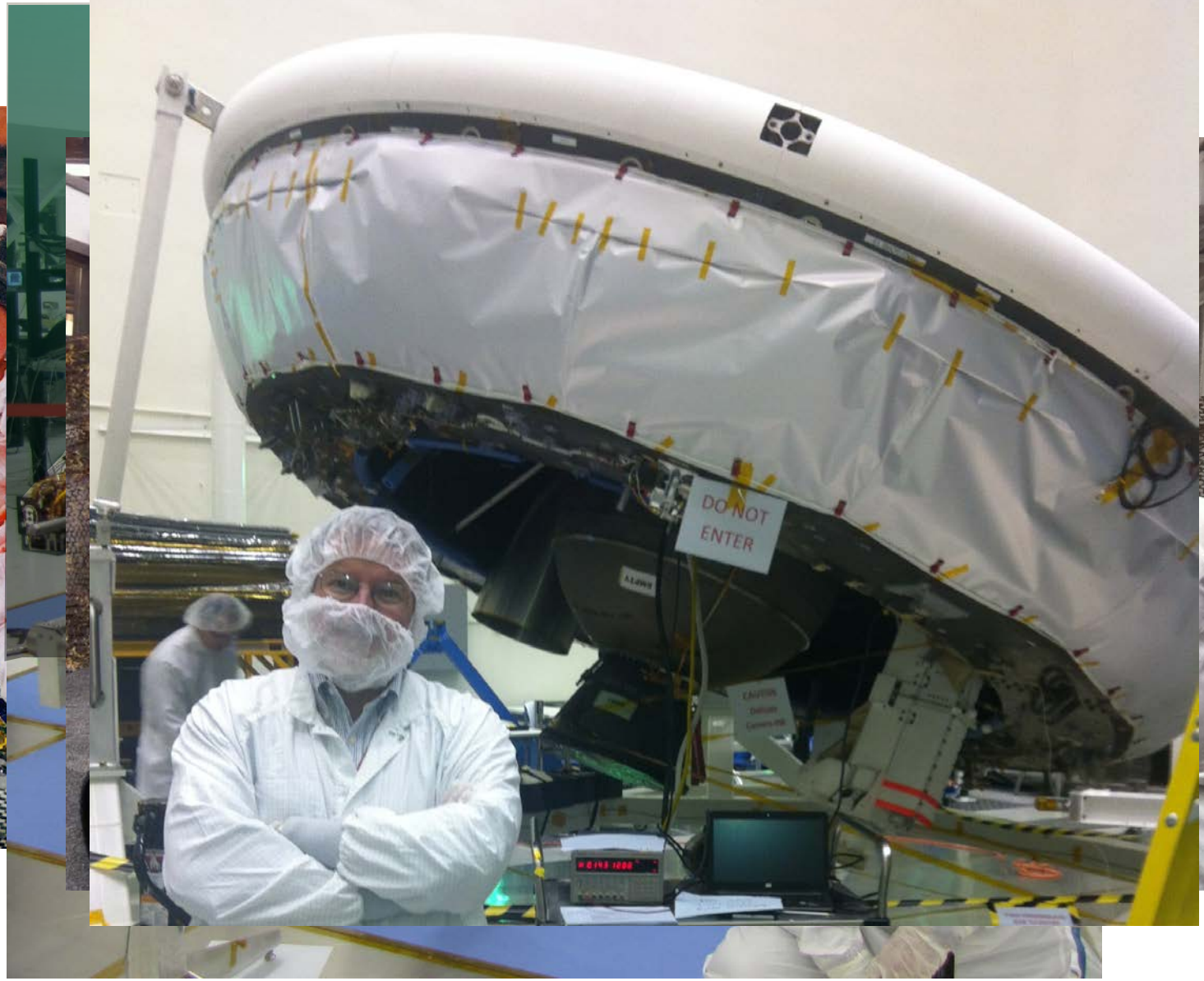
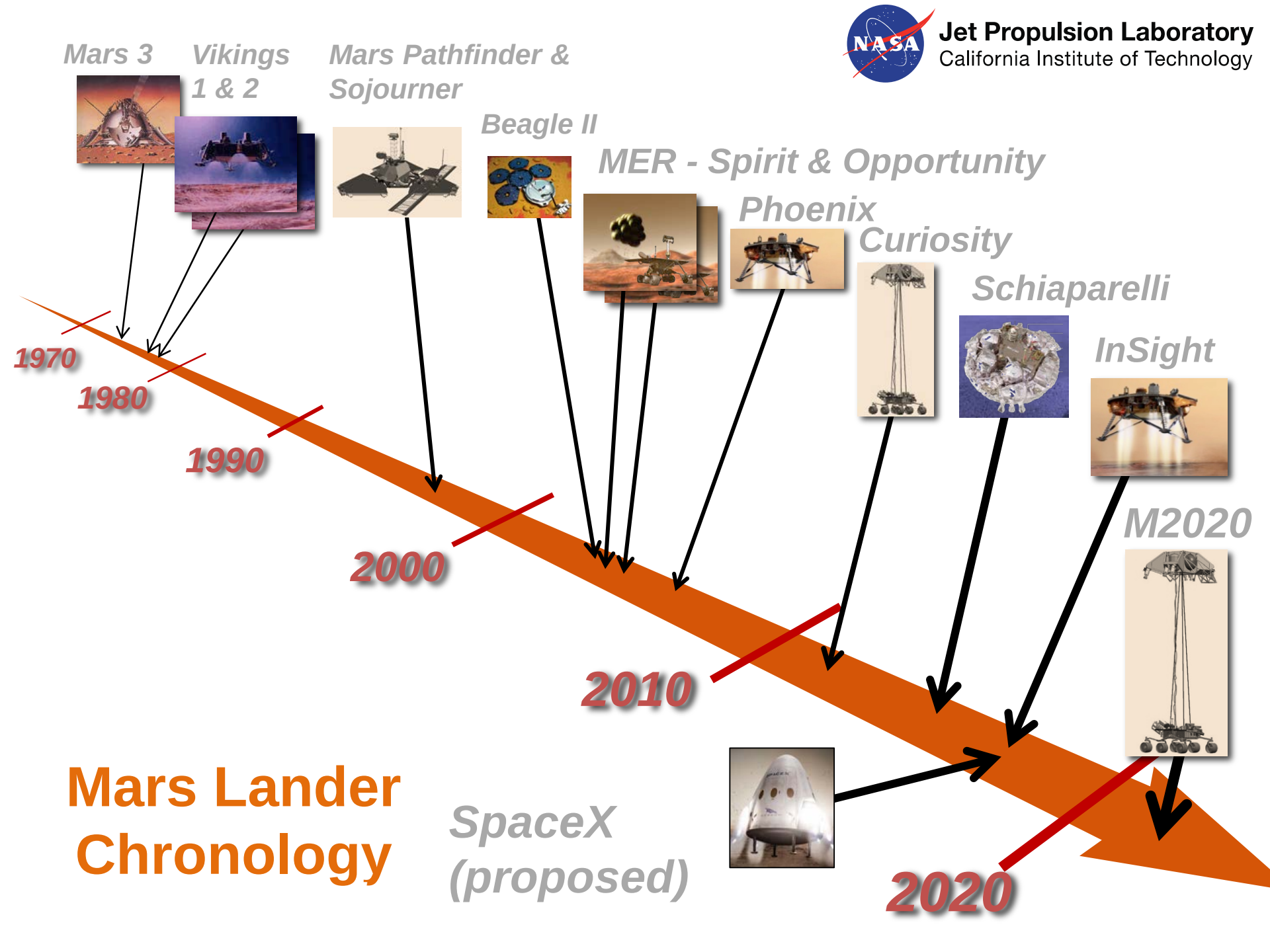
My life on Mars




Jet Propulsion Laboratory
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Mars 3
Vikings 1 & 2
Mars Pathfinder & Sojourner
Beagle II
MER - Spirit & Opportunity
Phoenix
Curiosity
Schiaparelli
InSight
M2020
1970
1980
1990
2000
2010
2020
Mars Lander Chronology
SpaceX (proposed)

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Invasion of the Mars Rovers

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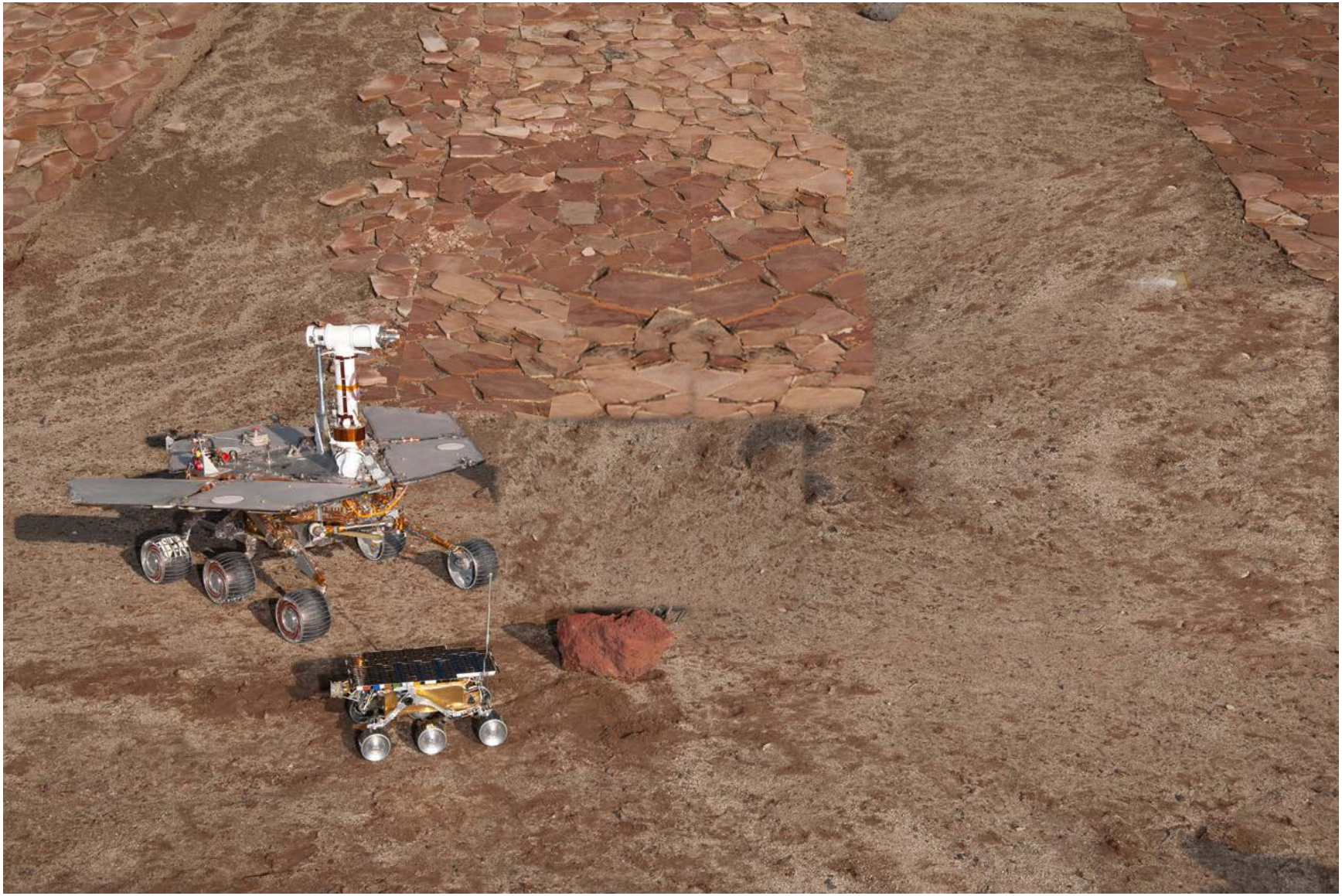
Invasion of the Mars Rovers



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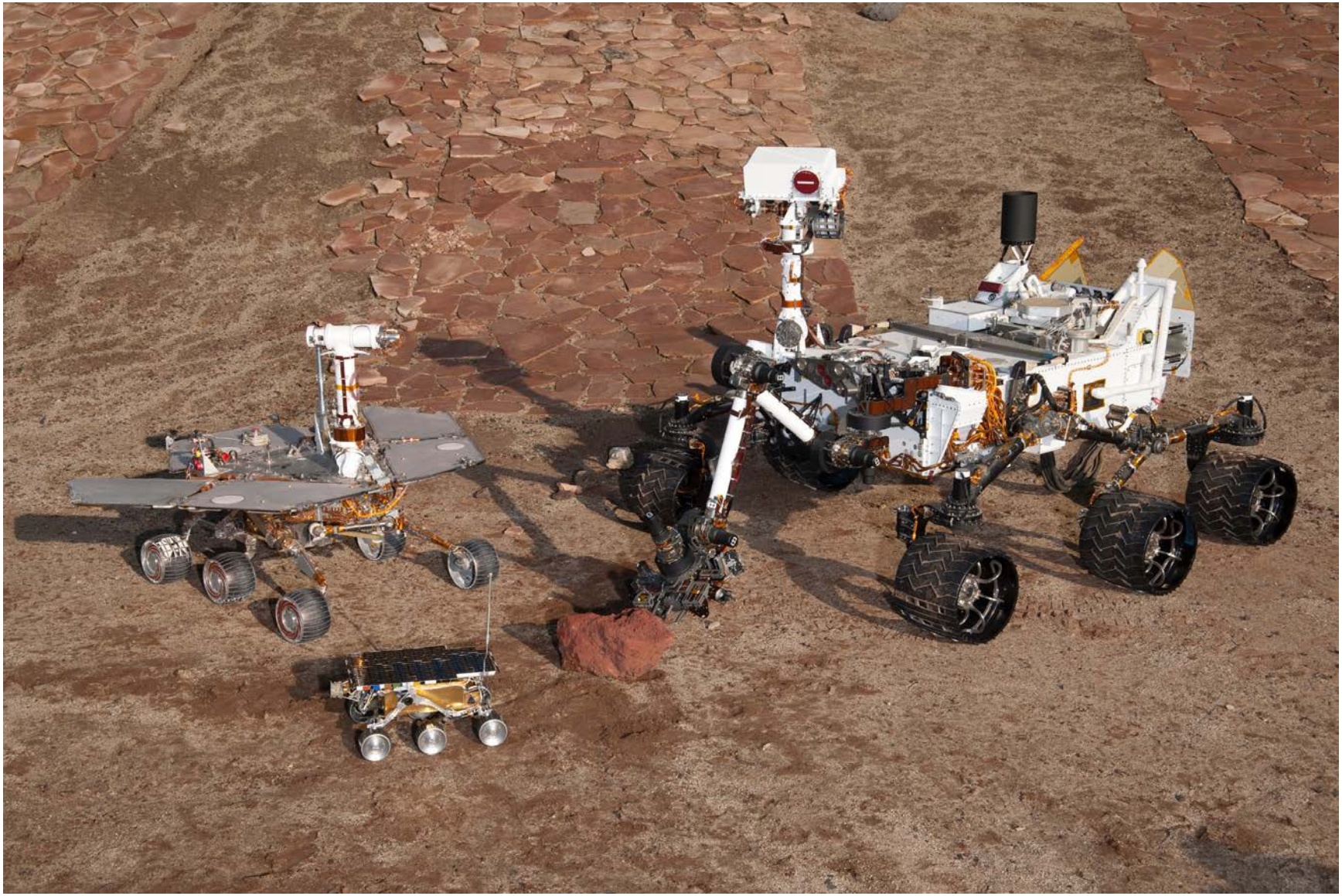
Invasion of the Mars Rovers



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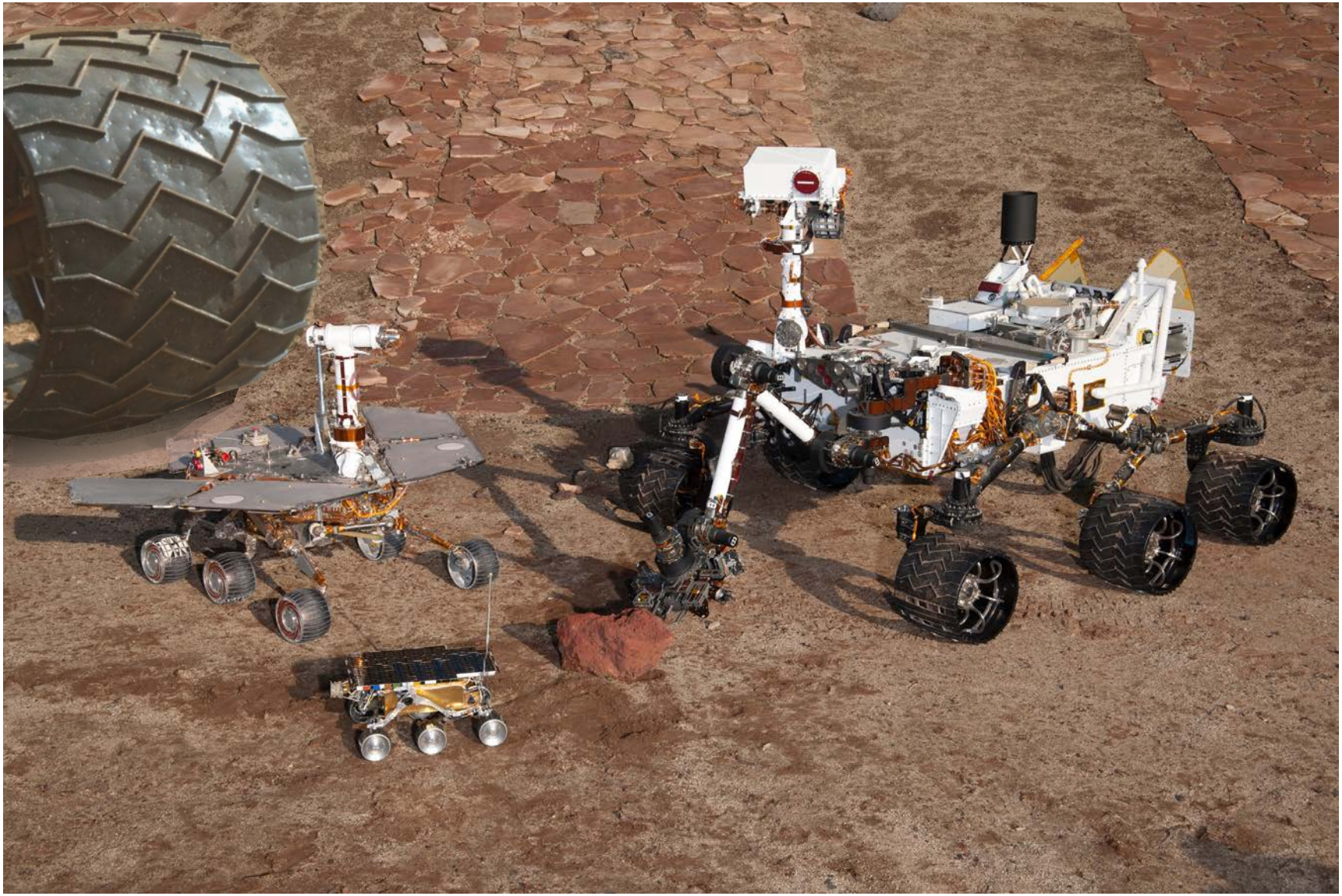
Invasion of the Mars Rovers



Big Picture

This is NOT a talk about SysML, MagicDraw, requirements-driven approaches, system visualization.

It is about how to convince yourself that your spacecraft won't crash onto Mars.

Divide and Conquer

- As good system engineers and system architects you all understand functional decomposition and why we do it.
  - Per JPL SE, PM and retiree John Casani:

    "We create subsystems so that we don't fall over each other working on the spacecraft at the same time!"

- We have used the traditional (text-oriented) systems engineering approach (and now the computer aided MBSE approach) to help systematically specify relationships, definitions and viewpoints.
  - This talk is not about that either.

Dividing E, D, & L

- On Earth (and moon) we can sub-divide EDL into sub-phases with relatively clean state envelopes that define interfaces between phases.
  - Divide and conquer is a good thing if the physics and system design allow it.
  - Allows for “separation of concerns” and parallel development and test.
- For example:
  - Entry can be simulated down to some altitude (or other criteria) where specialty analysis can be performed (long range sensing kicks in, change in guidance mode/law).
  - The descent phase is typically the “targeting” phase that tends to use on-board GNC to get knowledge and control into some box.
  - The terminal phase is the “prox-ops” subphase (e.g. eliminate the horizontal velocity - constant velocity phase)
  - Landing (“oh, the variety!!”)
- Viking was the last (and only) Mars mission to have successfully sub-divided Mars EDL into separate subphases with clean input specs between phases.

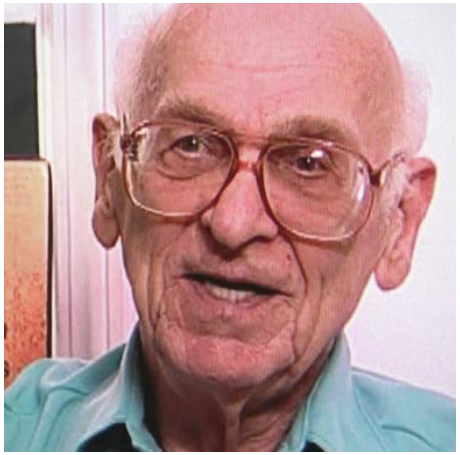
Viking EDL

- Viking (1971-1976)
  - No real end-to-end EDL simulation
  - Many separate single-pass (none of this Monte Carlo stuff!) simulations (and designs) for various mission phases
    - Entry 6-DOF until Parachute deployment
    - Parachute through lander-backshell sep
    - Local dynamics sims for separation
    - G&C focused lander simulations (uncoupled with entry and descent).
    - Separate touchdown test program (very simple simulation)
    - Separate site alteration (prop-soil) test programs
    - Very large environmental uncertainty (density, winds, rocks, slopes)
  - Each subphase was handed worse-case bounding box initial conditions and imposed requirements on phase exit conditions.
  - Viking incorporated DESIGN features so that it was possible to break EDL into separate subphases (“designed for test” or “fly like you sim”).
    - Fixed lift-up entry
    - Long range radar for parachute deployment
    - Heatshield-mounted entry reaction control subsystem

21 years later…
Mars Pathfinder comes along

- One of Dan Goldin's 1st (FIXED PRICE) faster better cheaper missions.
  - Budget was 1/10th of Viking.
  - Average age of team was about 30 (but experienced enough to be afraid)
  - Had essential help from LaRC, Ames, LMA, universities etc.
- Skeptical Ex-Vikings are on our review boards critiquing EVERYTHING.
  - Dang. They had good memories.
  - They expected us to divide and conquer.
  - We fail. Badly. Why?

Jim Martin

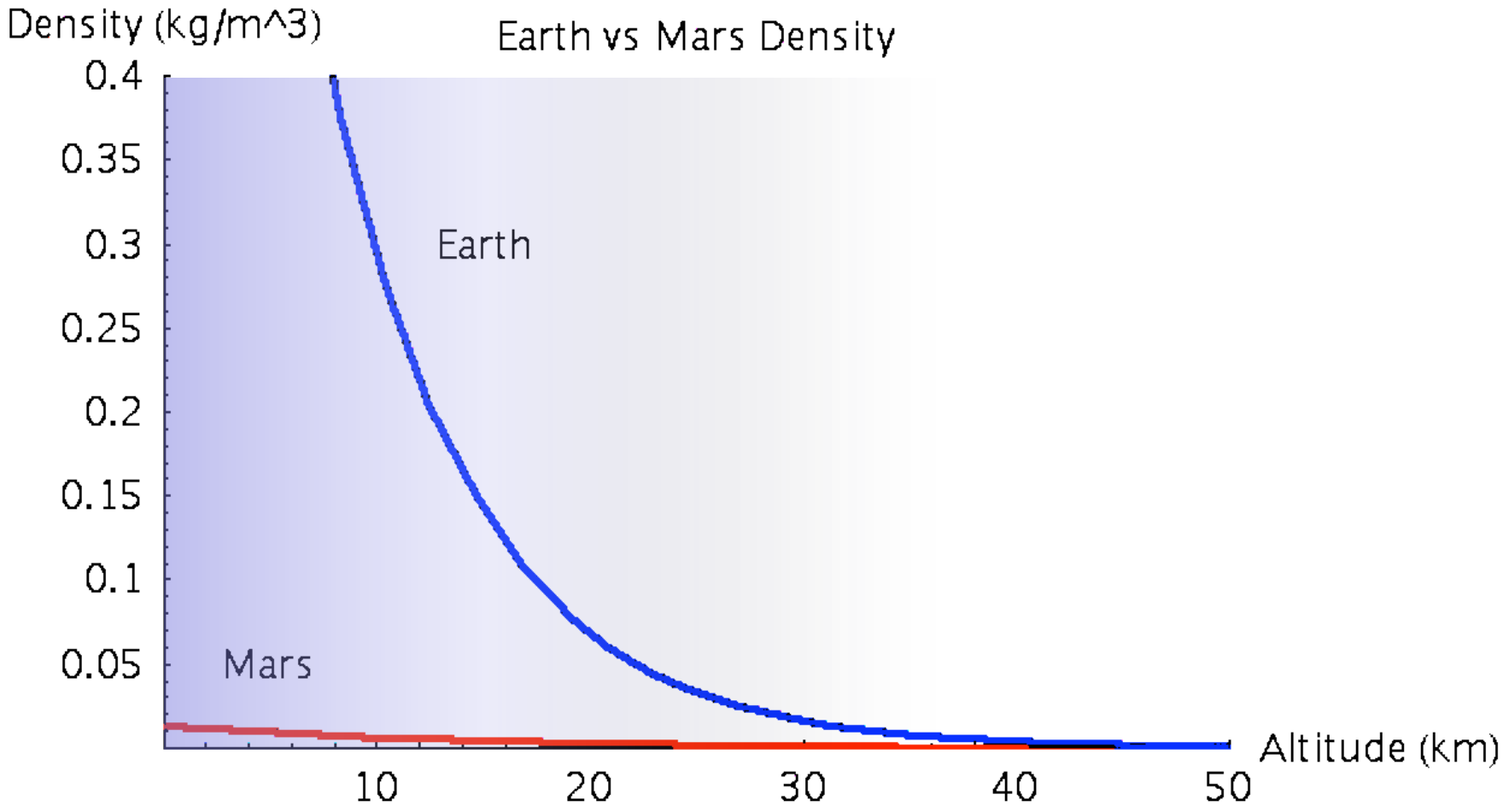


Iz Taback

Gentry Lee

Tom Young

The root of the problem



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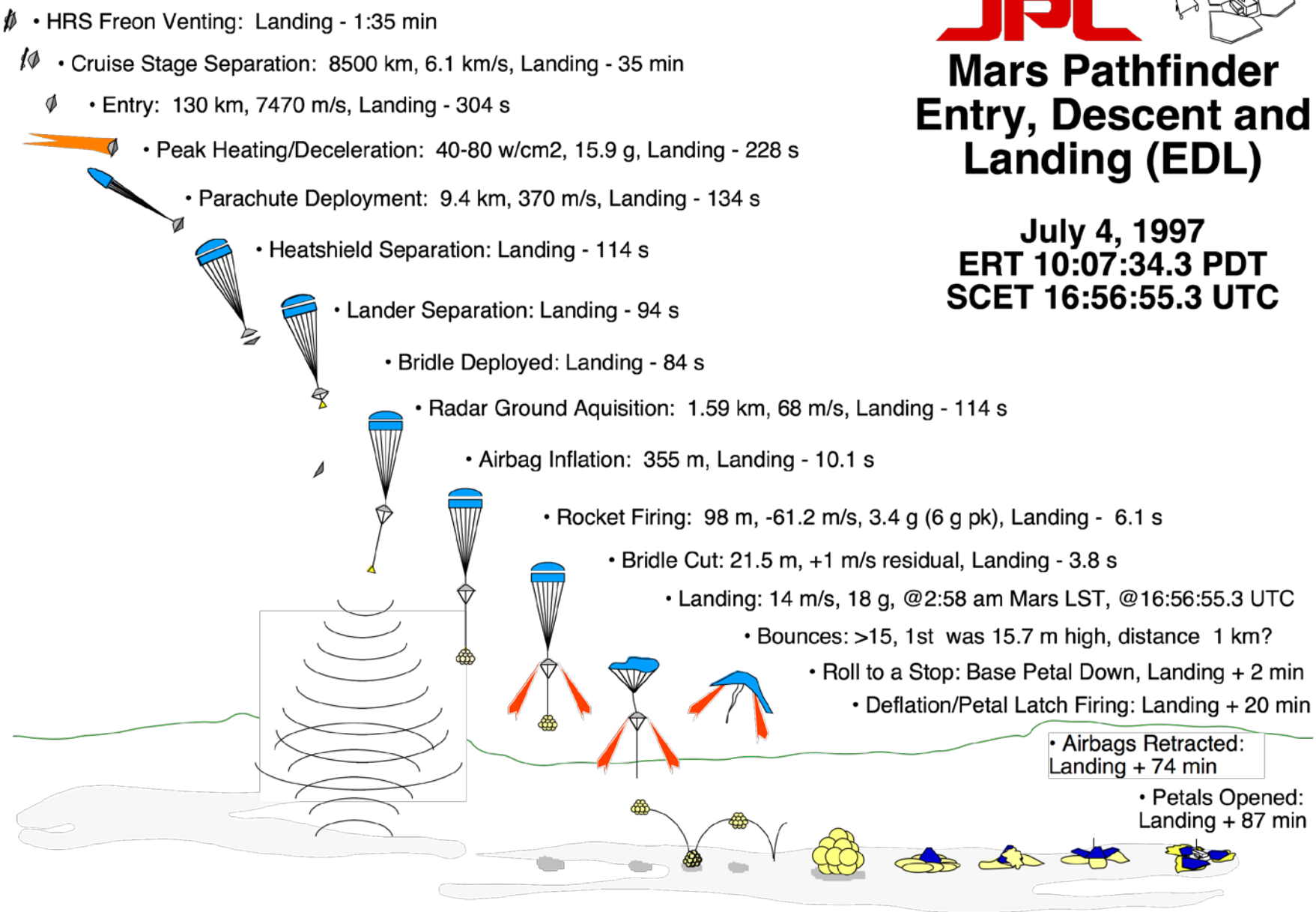
Mars Pathfinder Entry, Descent and Landing (EDL)

July 4, 1997
ERT 10:07:34.3 PDT
SCET 16:56:55.3 UTC



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8/3/97 RMM

Mars Pathfinder deviates from Viking

- First hyperbolic entry (7.4 km/s) at Mars
  - Spin stabilized (no RCS therefore no lift)
  - No attitude control at all. No IMU (just accelerometers).
  - No long range radar for Parachute deploy timing
  - Needed about 60 sec “hang time” on chute for HS sep, lander sep and radar sensing before rocket firing.
  - Used cheap ($13,000) short range (1 mile) C-band radar altimeter for altitude and rough velocimetry to time final (terminal) events: Airbag release and inflation, solid rocket ignition, bridle cut.
  - Could not afford to re-create Viking throttled engines so we used 3 inexpensive Thiokol solid rockets (which drove the need for 4-pi st Vectran airbags).
    - We stole the rocket-on-a-rope-under-chute idea from the US Army
    - Our inability to get venting timed right led us to multi-bounce landing.

We discover that Mars is irritating

- At first we tried the divide and conquer approach.
  - We thought that this approach might also make EDL at the system level more testable on Earth.
- We fail! We could NOT get the design to close!
  - Worst case analysis could not work. We did not have the $ for the hardware that Viking used to get and enforce margin.
  - We discovered that the velocity when only 170 m above the ground was a function of entry flight conditions!!
    - Waaa??? How can that be?
    - Easy! Mars has practically no air.
- Worse yet we keep discovering that the Mars-Earth differences prevented us from doing any real system-level flight testing.
  - Great. We are going to Mars without a flight test.

Time to re-think

- This sad state of affairs did not sit well with the Viking gods (especially Jim and Iz).
  - If we didn't come up with a design that closed we would be canceled.
- I was frustrated but we noticed that the design seemed to close *on average* (and not a worst case sense).
  - If instead of bounding boxes we used dispersed states and ran Monte Carlo of the whole dang EDL machine, perhaps we could count the number of times that it "crashed" in the sim. If that number was small enough maybe the we had a story after all.
  - For a low budget FBC mission, what do you think a good calculated system design "failure rate" might be?
- In Spring 1994 we decided that we needed to couple our various separate simulations into a single "Mother-of-all-EDL simulations" and run it in a Monte-Carlo mode.

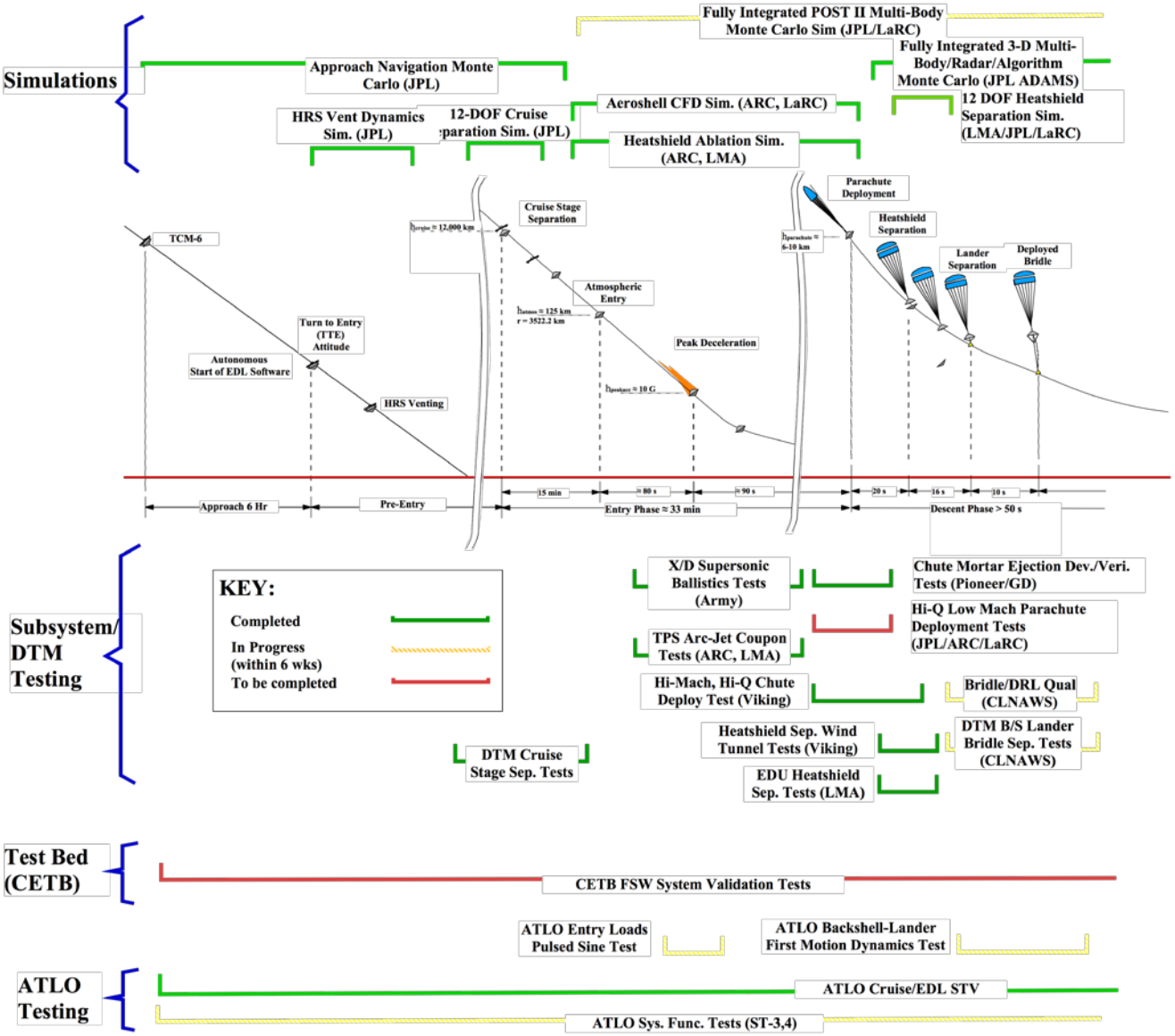
What was being modeled?

- Our navigators were simulating entry targeting conditions.
  - At Mars, entry is defined at 3522.2 km from center of planet (well above the atmosphere).
- The ACS team was modeling attitude dispersions at entry.
- My friends Bobby Braun and Bob Mitcheltree at LaRC where running the original FORTRAN Lockheed Martin POST (Program for Optimization of *Shuttle* Trajectories) trajectories of the entry phase up until parachute inflation.
- The Ames folks (Mike Tauber) were running aerothermal sims locally (mostly convective but some radiative heating) and doing TPS characterization.
- The JPL mechanical team was using multiple ADAMs simulation (running on a single Apollo workstation) of the multi-body dynamics from parachute deployment through HS sep through lander sep bridle deploy.
- The JPL G&C avionics and radar guys were modeling the radar and the accelerometer (with entry decelerations from LaRC) as well as the flight software.
- The JPL EDL com guys were modeling the link dynamics (Direct to Earth com)
- Rockwell modelled the airbag impacts using Dyna (but did not work).
- The atmospheric science team was busy making density (& wind) models
- The surface morphologists were making slope and rock models

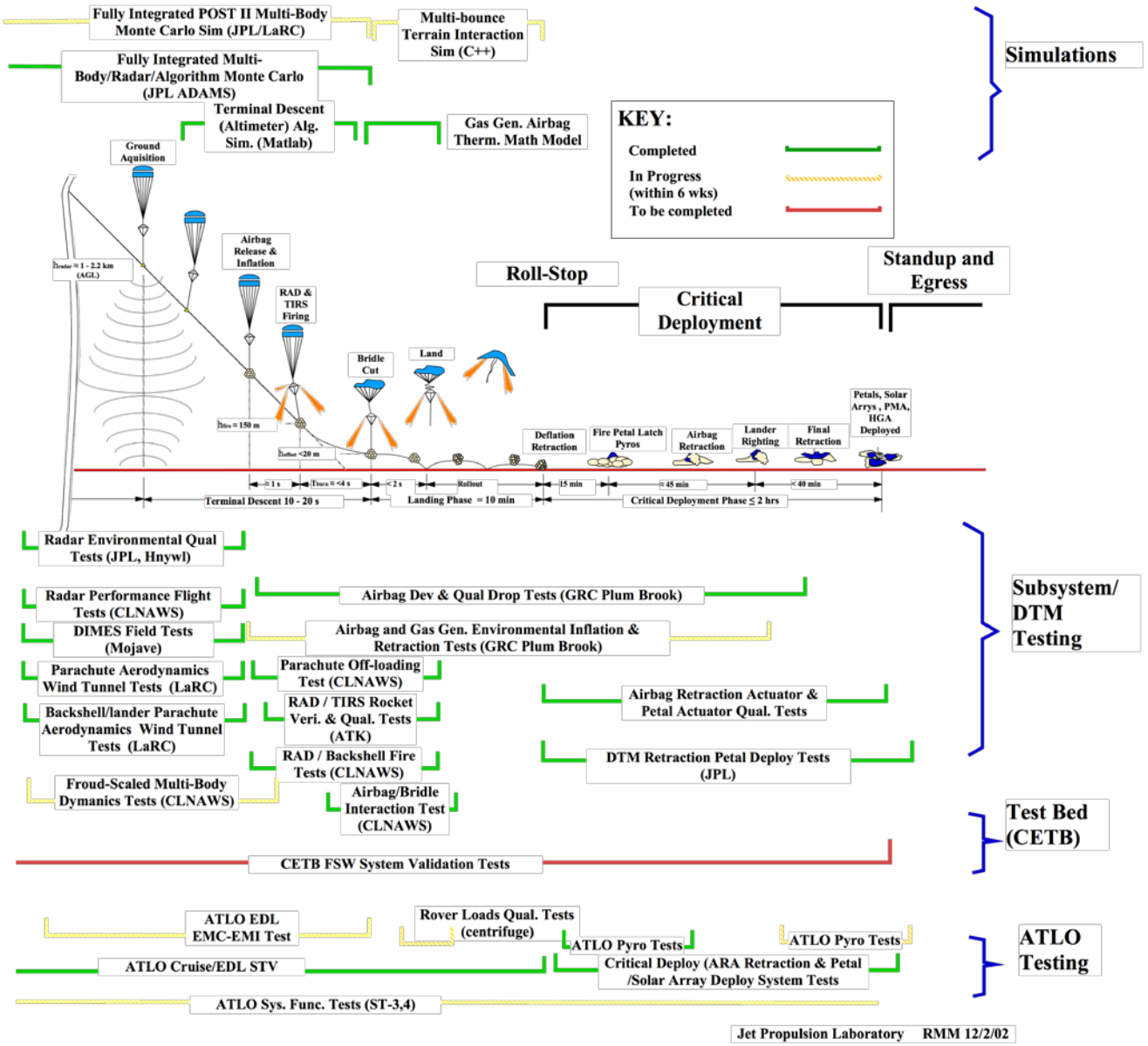
One team to rule them all

- We created a single, inter-disciplinary, mult-org team involving ARC, LaRC, LMA, JPL div 31 (systems), div 32 (science), div 33 (radar), div 34 (avionics and software) and div 35 (mechanical).
- Not only did we need to stitch these sims together but we needed to randomize key input parameters so that these could be run over and over again with different randomized inputs.
  - Eventually leading to 1000s of random variables each with a PDF (millions if you include the environment models).
- Each parameter and model needed a validation program! (garbage in = garbage out, right?).
  - A massive effort to design and implement a model validation effort using real physical test of subsystems in earth environments.
- From here on out all of our end-end system tests for all of our EDL missions would be flown in virtual reality.
  - This is BEFORE “The Matrix”
- We finally got our answer.
  - These sims told us that EDL will work about 90% of the time.
  - The 10% failures included running out of time, and impacts exceeding tested airbag capability envelope.

MER EDL Test/Simulation Coverage: Approach thru Descent



MER EDL Test/Simulation Coverage: Descent thru Critical Deployments



The Spectrum of EDL V+V

Flight Vehicle Dynamics
Environmental Models
- Atmoshperes
- Winds
- Terrain

Parachute
Aerodynamics
Propulsion interaction with environment.
.
Separations
IMU interaction with environment
Radar interaction with environment
.
Propulsion internal function
.
GNC Algorithms in FSW
.
EDL Sequencing
.
IMU interaction with avionics
Radar interaction with avionics

Phasing and timing
.
Pyro function
Thermal conditioning
1553 Bus function
RCE function
Telecom function
.
Power system function
.
FSW utility function
Individual avionics card function
Internal Spacecraft Function

EDL Systems Engineering team execution

Modeled and tested in high fidelity in simulation, field tests and subsystem test beds

Overall EDL V+V Responsibility

Tested in high fidelity within FS test beds and ATLO

Flight System Systems Engineering team execution

EDL V+V Venue Taxonomy "Trilogy"

Flight Vehicle Dynamics
Environmental Models
Atmoshperes
Winds
Terrain
Parachute
Aerodynamics
Propulsion interaction with environment.
.
Separations
IMU interaction with environment
Radar interaction with environment
.
Propulsion internal function
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IMU interaction with avionics
Radar interaction with avionics
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Phasing and timing
.
Pyro function
Thermal conditioning
1553 Bus function
RCE function
Telecom function
.
Power system function
.
FSW utility function
Individual avionics card function
Internal Spacecraft Function

"Simulate as you fly, fly as you simulate"

Flight Dynamics
(External Behavior/Environmental Interaction)
End-to-end Simulation
fed by validated models

Hardware (Unit-Software) Verification
(Unit and Assembly Level Function)
Subsystem Verification
ATLO

Command and Response
(Internal Behavior/HW-SW Interaction)
Testbeds
ATLO

"Test as you fly, fly as you test"

EDL V+V Trilogy (examples)

Will the entry guidance design deliver the vehicle within the ellipse?

Will the heat shield separation devices performance as expected?

Will the terminal descent sensor (TDS) function as expected?

All event tree nodes are V+Ved through one or more of these methods

Does guidance design handle full range of initial states, vehicle characteristics and atmospheric conditions?

Does during TDS flight, are the terrain properties as expected?

Does the command reach the gyros at appropriate time/condition?

Are the flight dynamics operation as expected?

Do the individual devices perform as expected?

Is TDS data acquired properly and delivered to nav filter as expected?

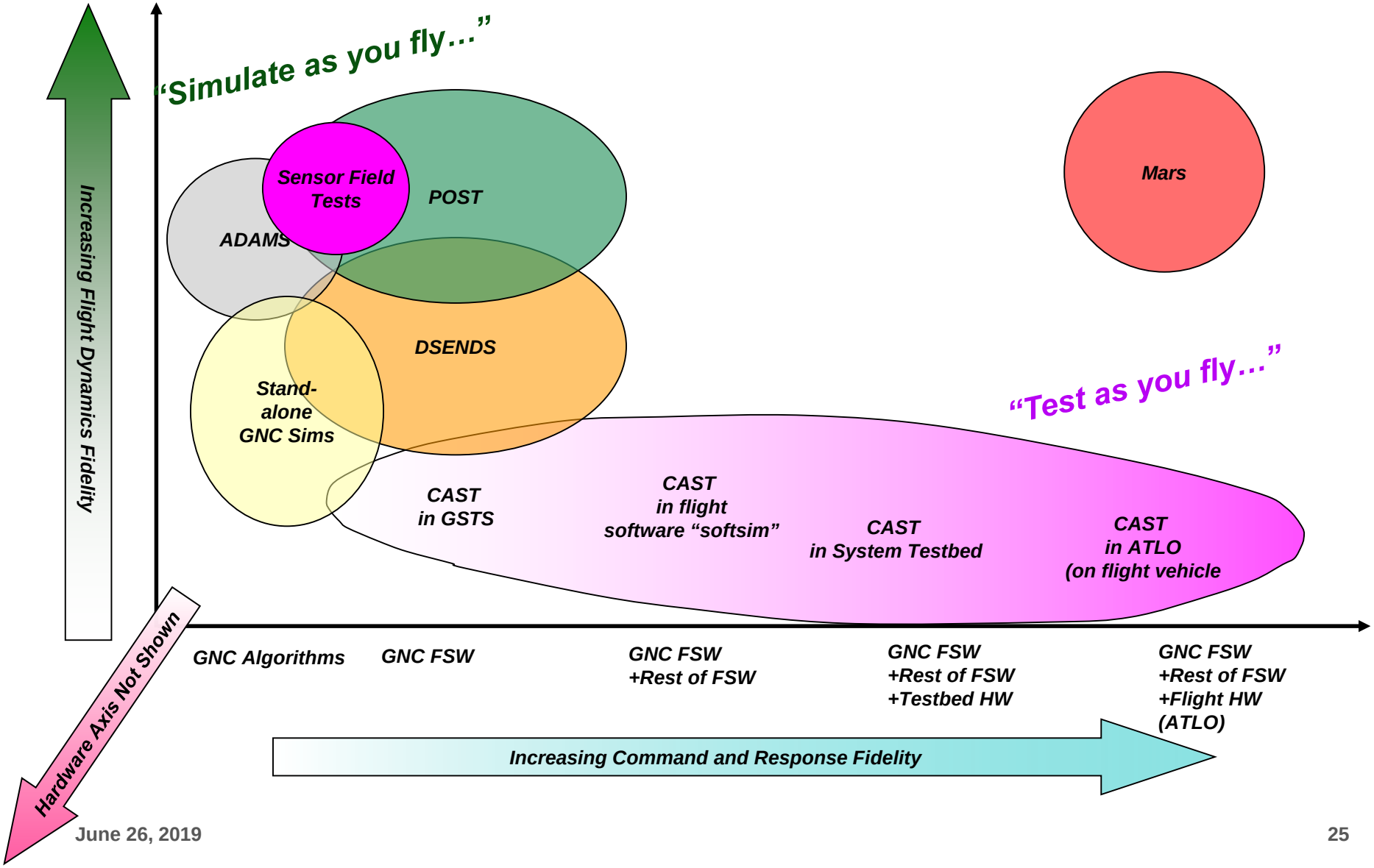
Does the TDS function properly through the flight regime(dynamics)?

Flight Dynamics
(External Behavior/Environmental Interaction)
End-to-end Simulation
fed by validated models

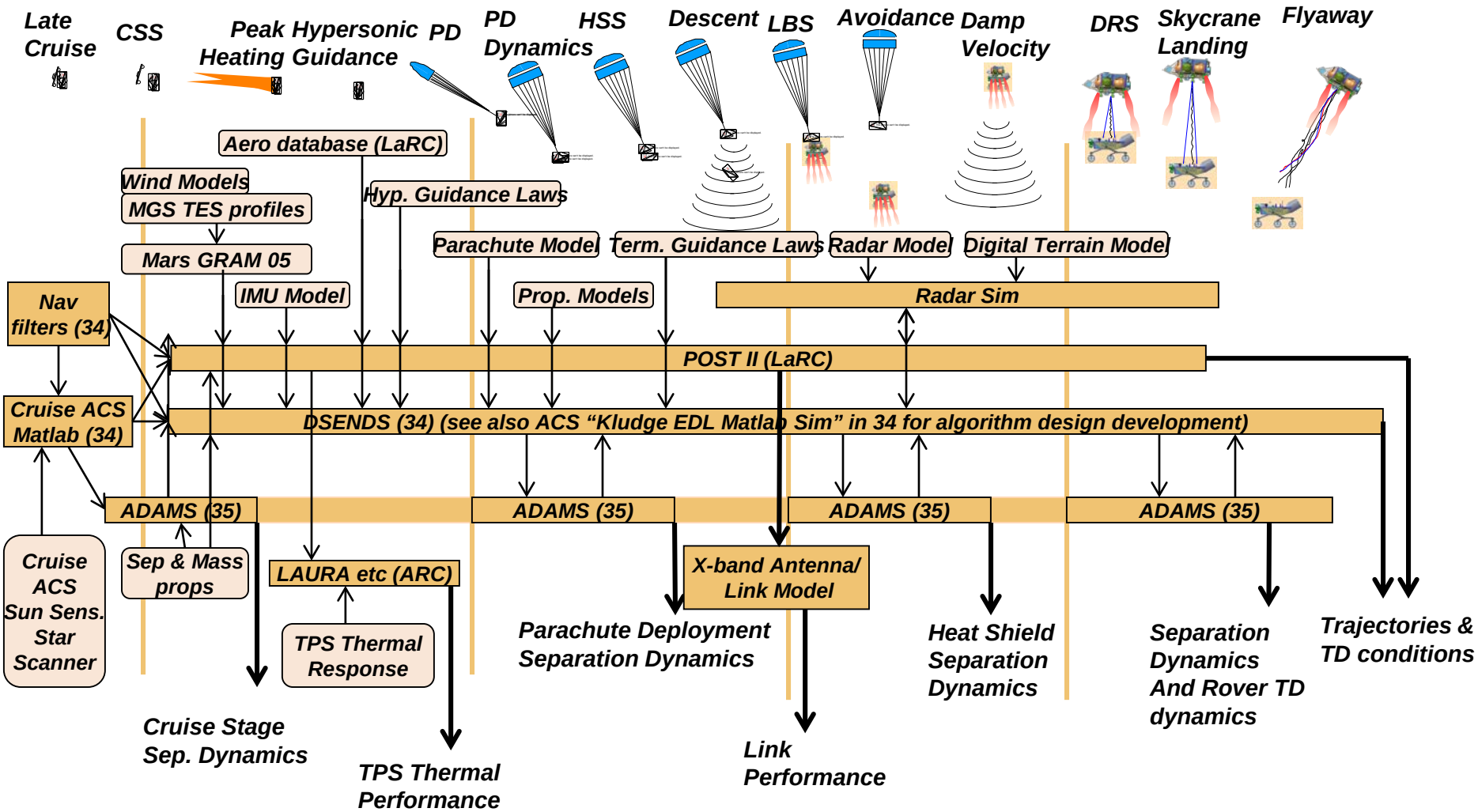
Command and Response
(Internal Behavior/HW-SW Interaction)
Testbeds
ATLO

Hardware (Unit-Software) Verification
(Unit and Assembly Level Function)
Subsystem Verification
ATLO

V+V Fidelity, Coupling and Risk



Some EDL Tools & Models

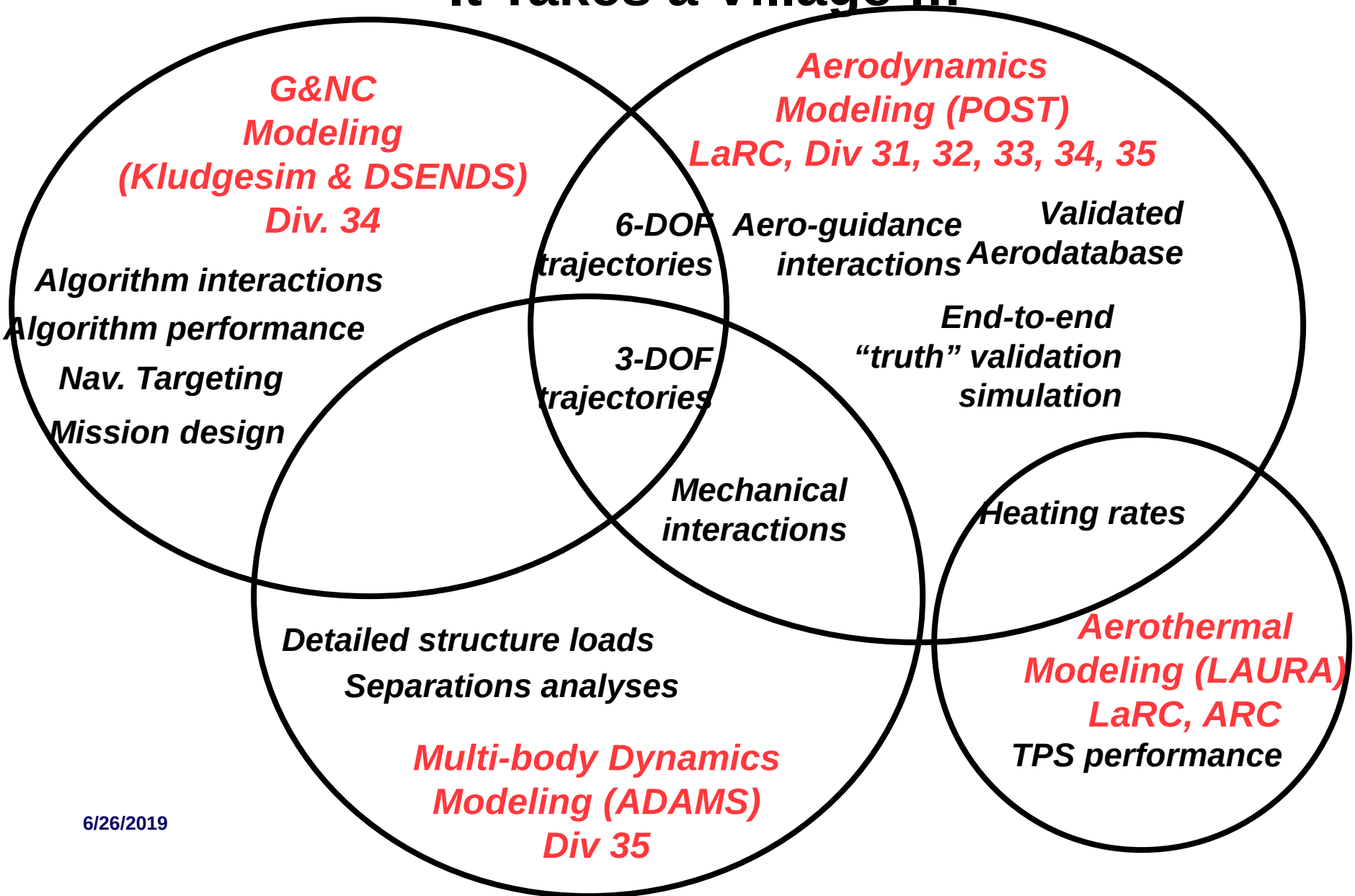


6/26/2019

= Executable Tool

= Model (data)

It Takes a Village …

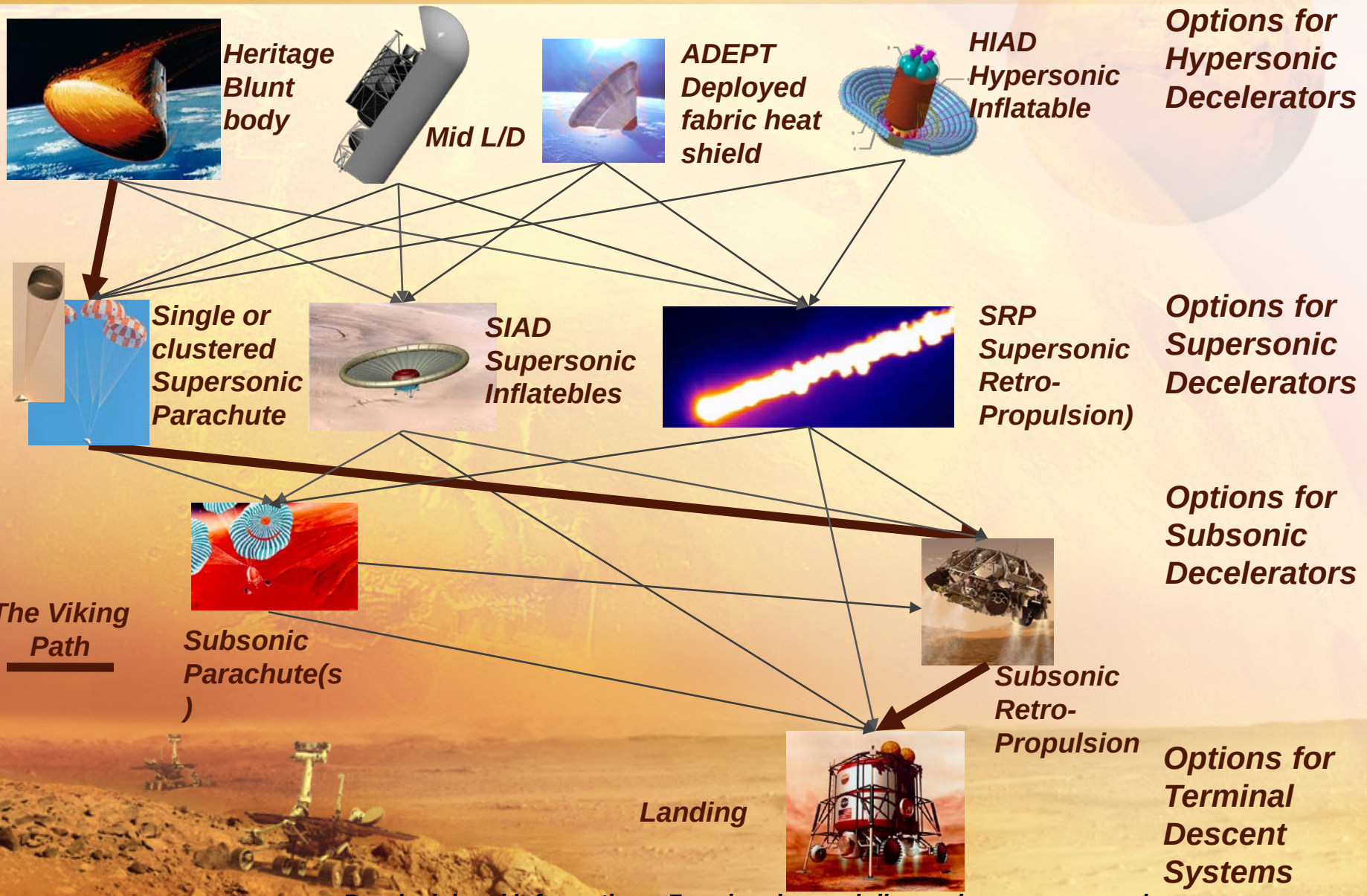


Today's EDL Simulations

- We now run these simulations with gradually increasing fidelity from initial 3-DOF sims in pre-phase A to many many DOF by the time of launch.
  - 100 models. 1000s of parameters. Millions of runs.
- We even run Monte Carlo sims to help us tune our final commanded pre-entry parameters using redundant supercomputers in the days and hours before landing.

- Validated, integrated EDL simulations are our ONLY way to convince ourselves that EDL will work.

Without a doubt the Human Mars EDL architectures will be different. But system modeling is here to stay.



Tomorrow's EDL

- Although we have not yet settled on an EDL architecture we do know that certain technologies will not work.
  - Even large deployed heatshields can not get your vehicle down below the speed of sound on Mars (about 240 m/s).
  - Huge or clustered supersonic parachutes are too hard to test.
- Supersonic Retro-Propulsion (SRP) is key
  - It has rarely been used anywhere but SpaceX used it to slow the Falcon 1st stage for return (thank you).
- It demands a lot more fuel, but fuel is cheap and packs well.
  - SRP on Mars lights up at Mach 3-4 about 1-5 km above the ground.
  - SRP-touchdown lasts about 60-90 seconds.
  - Overall gear ratio (entry mass/useful payload mass) = 2-3. Not bad.
- EDL of the future will be 7 min of entry terror and another 1-2 min of SRP terror.

Should be fun!

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