



Flight Mechanics Simulations: Trajectory and Testing Guidance, Navigation, and Control Algorithms in-the-loop

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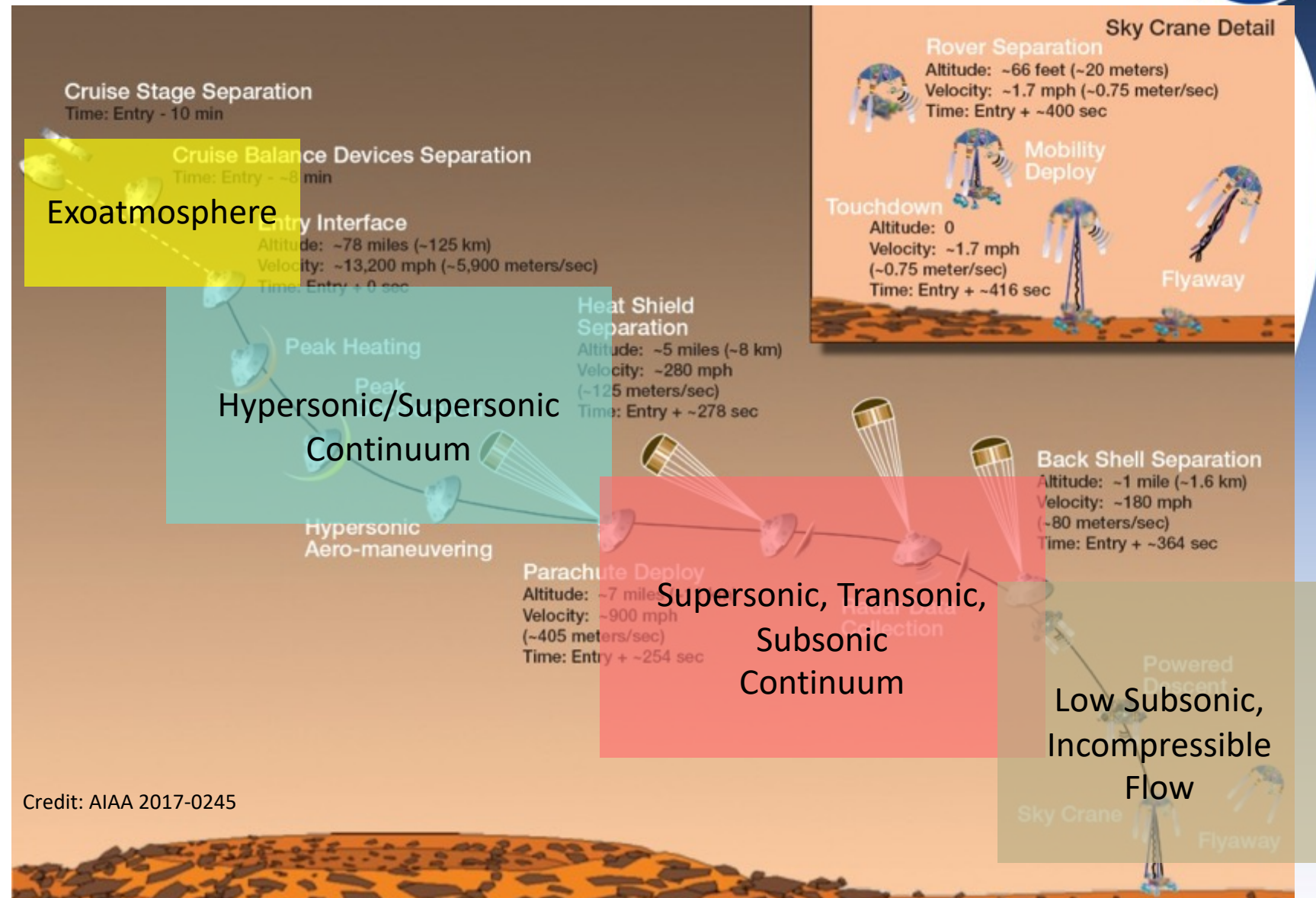
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Why Model Entry, Descent, and Landing?



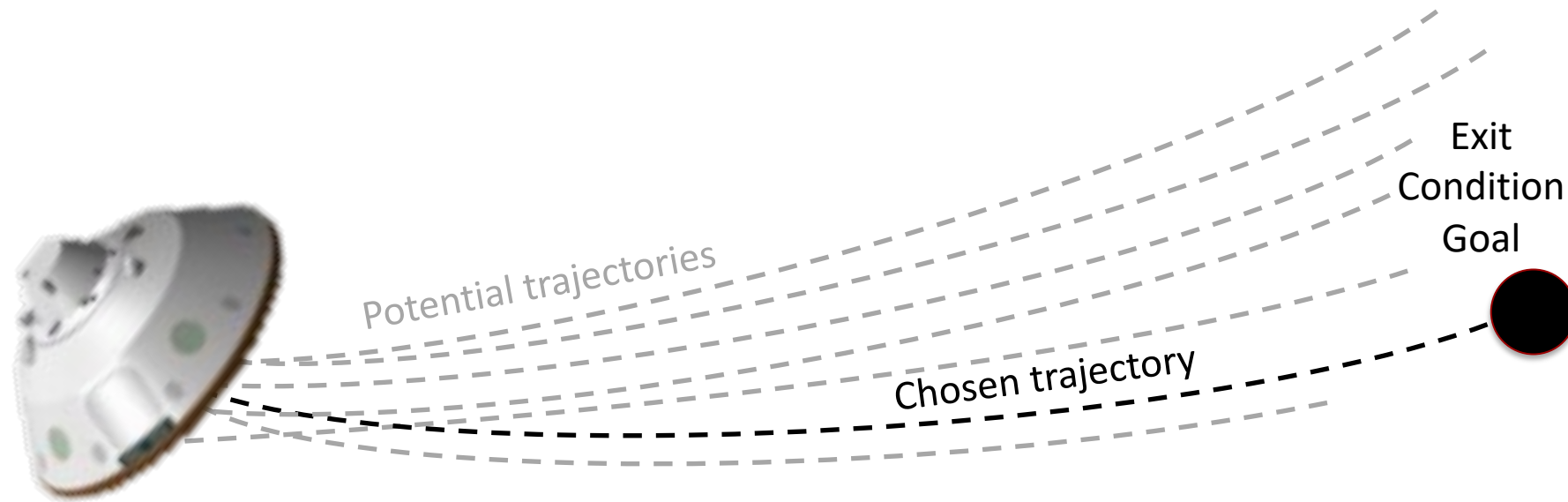
- We want to “Test as you fly, fly as you test”
- EDL spans many different regimes of flight
- End-to-end modeling through multiple flight regimes possible using flight mechanics simulations



Why Model Entry, Descent, and Landing?



- Parameter choice and tuning ease



Aeroshell Credit: AIAA 2017-0245

Why Model Entry, Descent, and Landing?



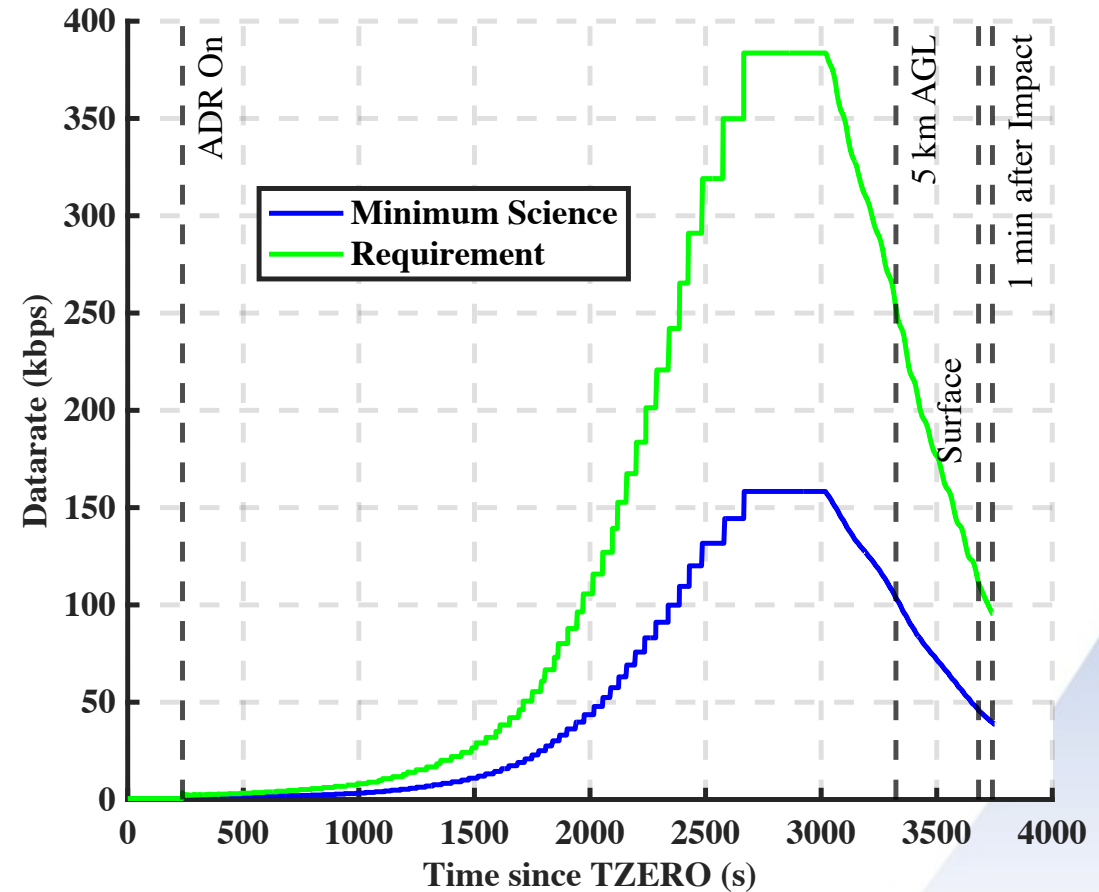
- Parameter choice and tuning ease
- Flight mechanics simulations give detailed insight into trajectory conditions – for a single run

TZERO = Sequence time = 0. Entry Interface – 60 s

ADR = Adaptive Data Rate

AGL = Above ground level

Kbps = Kilo bits per second



Credit: AIAA 2023-1165

Why Model Entry, Descent, and Landing?



- Parameter choice and tuning ease
- Flight mechanics simulations give detailed insight into trajectory conditions – for a single run
- Through Monte Carlo analyses, one can also understand the performance in statistical sense

Table 2 Monte Carlo parameters and variations

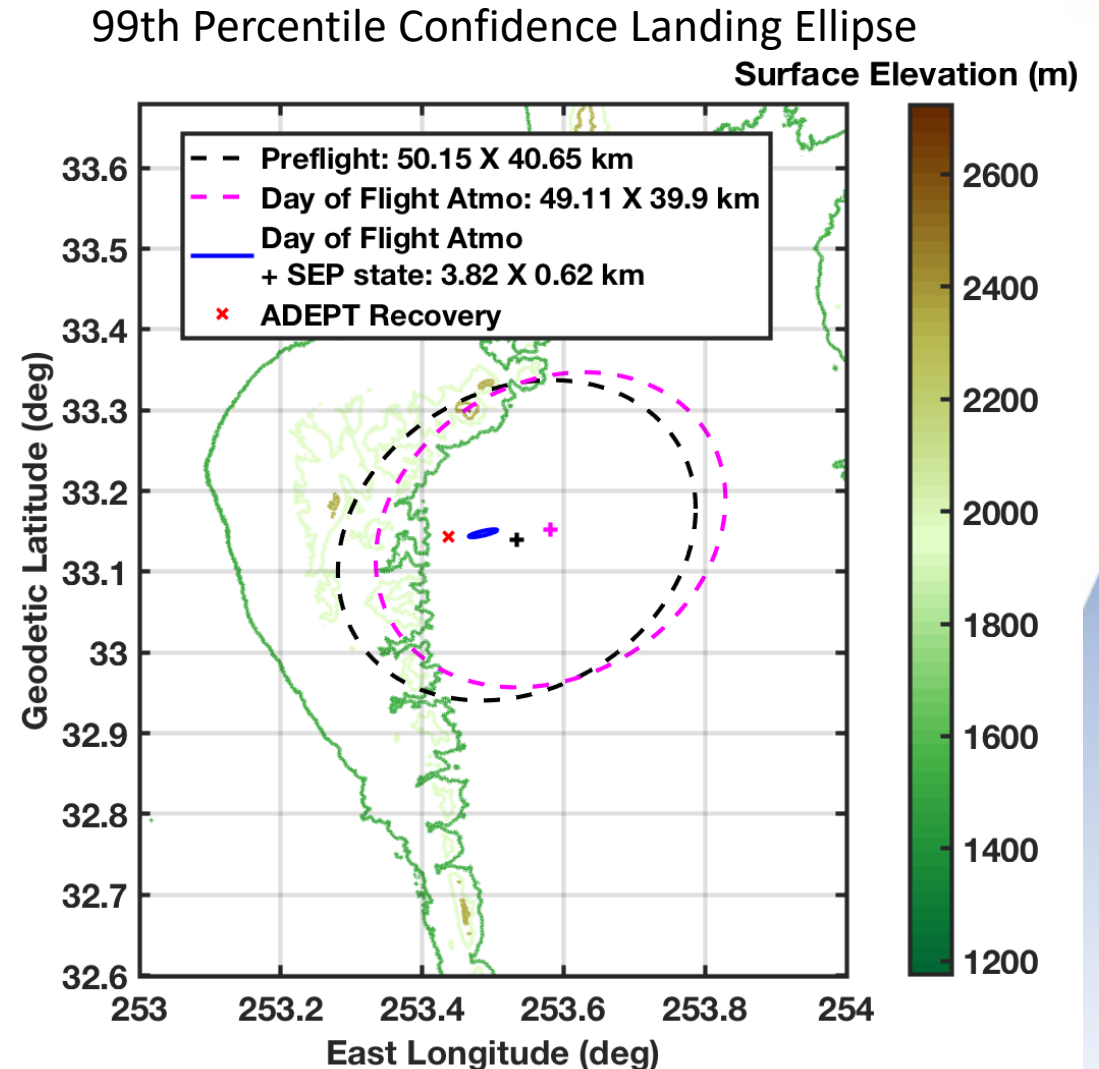
Parameter	Nominal	Distribution	3- σ or min/max
Entry flight-path angle, deg	-14.0	Gaussian	0.60
Initial state knowledge error	0.0	Gaussian	~1/5 delivery error
Entry mass, kg (c.g. offset config)	2196 (1883)	Gaussian	2.0
Entry X c.g., m (c.g. offset config)	1.296 (1.125)	Uniform	± 0.0318
Entry Y c.g., m (c.g. offset config)	0.0 (0.0)	Uniform	± 0.0069
Entry Z c.g., m (c.g. offset config)	0.0 (0.04936)	Uniform	± 0.0069
Terminal descent X c.g., m	0.0	Uniform	± 0.0318
Terminal descent Y c.g., m	0.0	Uniform	± 0.0318
Terminal descent Z c.g., m	0.0	Uniform	± 0.0318
Atmosphere dispersion seed	0	Uniform	1/29999
Atmosphere update distance, km	0.5	Uniform	0.5/5.0
Atmosphere dust opacity	0.45	Uniform	0.1/0.9
Entry maximum bank acceleration, deg/s ²	5.0	Gaussian	10%
Inertial measurement unit (IMU) initial seed	0	Uniform	1/29999
IMU initial angular misalignment	0.0	Gaussian	200
IMU gyro bias drift, deg/h	0.0	Gaussian	0.05
IMU gyro scale factor, ppm	0.0	Gaussian	100
IMU gyro nonorthogonality, ppm	0.0	Gaussian	60
IMU gyro random walk(PSD), deg/rt-h	0.0	Gaussian	0.025
IMU accelerometer bias, milligees	0.0	Gaussian	0.1
IMU accelerometer scale factor, ppm	0.0	Gaussian	240
IMU accelerometer nonorthogonality, ppm	0.0	Gaussian	210
Axial-force coefficient multiplier (Knudsen ≥ 0.1)	1.0	Gaussian	5%
Normal-force coefficient multiplier (Knudsen ≥ 0.1)	1.0	Gaussian	10%
Axial-force coefficient multiplier (Mach > 10)	1.0	Gaussian	3%
Normal-force coefficient multiplier (Mach > 10)	1.0	Gaussian	5%
Axial-force coefficient multiplier (Mach < 5)	1.0	Gaussian	10%
Normal-force coefficient multiplier (Mach < 5)	1.0	Gaussian	8%
Trim angle-of-attack increment, deg	0.0	Gaussian	2.0
Supersonic parachute drag coefficient	0.61	Uniform	$\pm 10\%$
Subsonic parachute drag coefficient	0.85	Uniform	$\pm 5\%$
Axial-force coefficient multiplier (Mach < 0.8)	1.0	Uniform	$\pm 20\%$
Normal-force coefficient increment (Mach < 0.8)	0.0	Uniform	± 0.03
Pitching-moment coefficient increment (Mach < 0.8)	0.0	Uniform	± 0.03
Parachute separation attitude of lander (per axis), deg	0.0	Uniform	± 30
Parachute separation attitude rates of lander (per axis), deg/s	0.0	Uniform	± 20
Terminal descent engine thrust variation, N	3047/609	Uniform	$\pm 5\%$
Terminal descent engine specific impulse, s	194/210	Uniform	$\pm 0.67\%$
Radar altimeter altitude bias	0.0	Gaussian	3%
Radar altimeter altitude noise	0.0	Gaussian	1%
Radar velocimeter velocity noise	0.0	Gaussian	4%

Credit: Striepe et al., JSR, 43(2), 2006

Why Model Entry, Descent, and Landing?

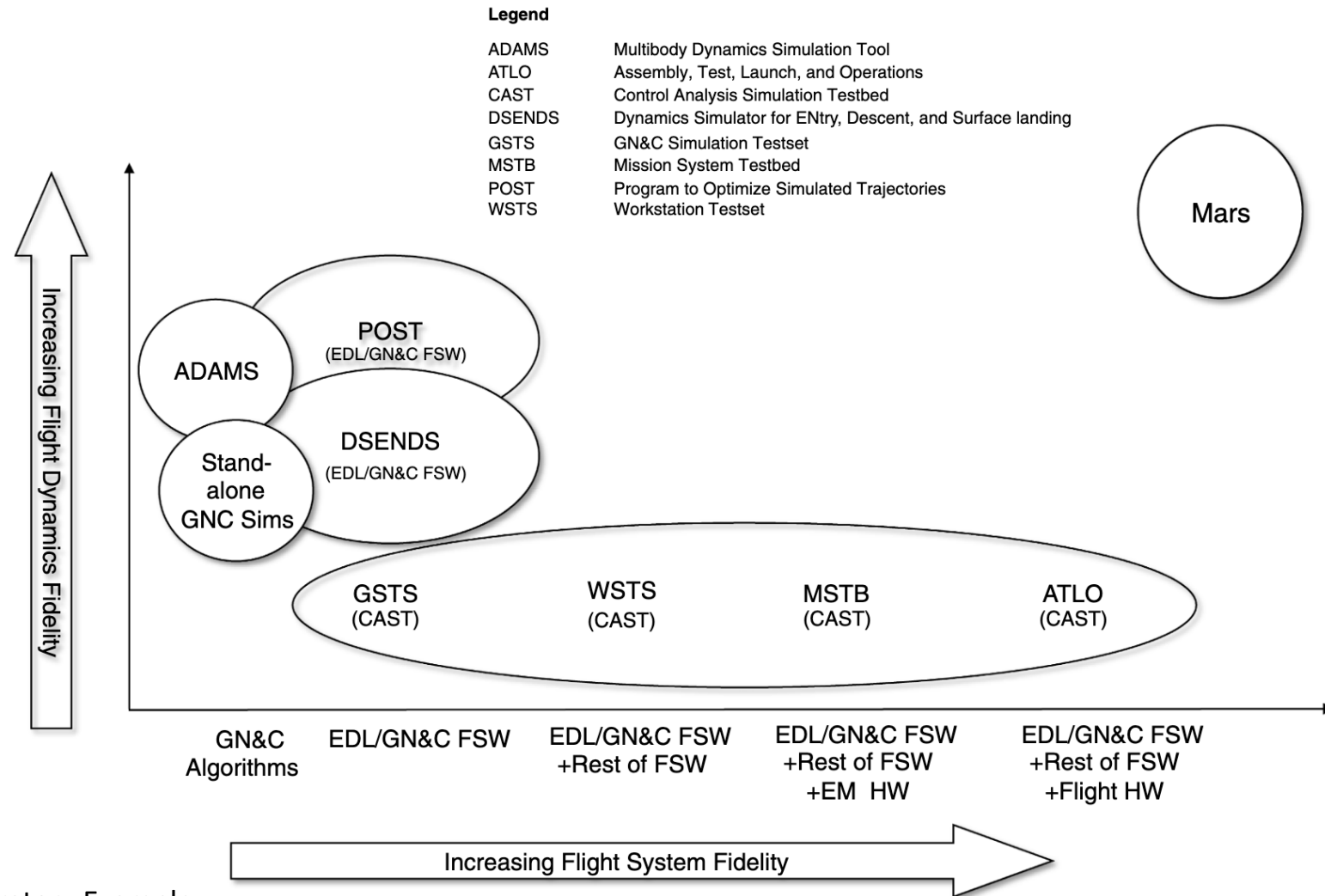


- Parameter choice and tuning ease
- Flight mechanics simulations give detailed insight into trajectory conditions – for a single run
- Through Monte Carlo analyses, one can also understand the performance in statistical sense



Credit: AIAA 2019-2900

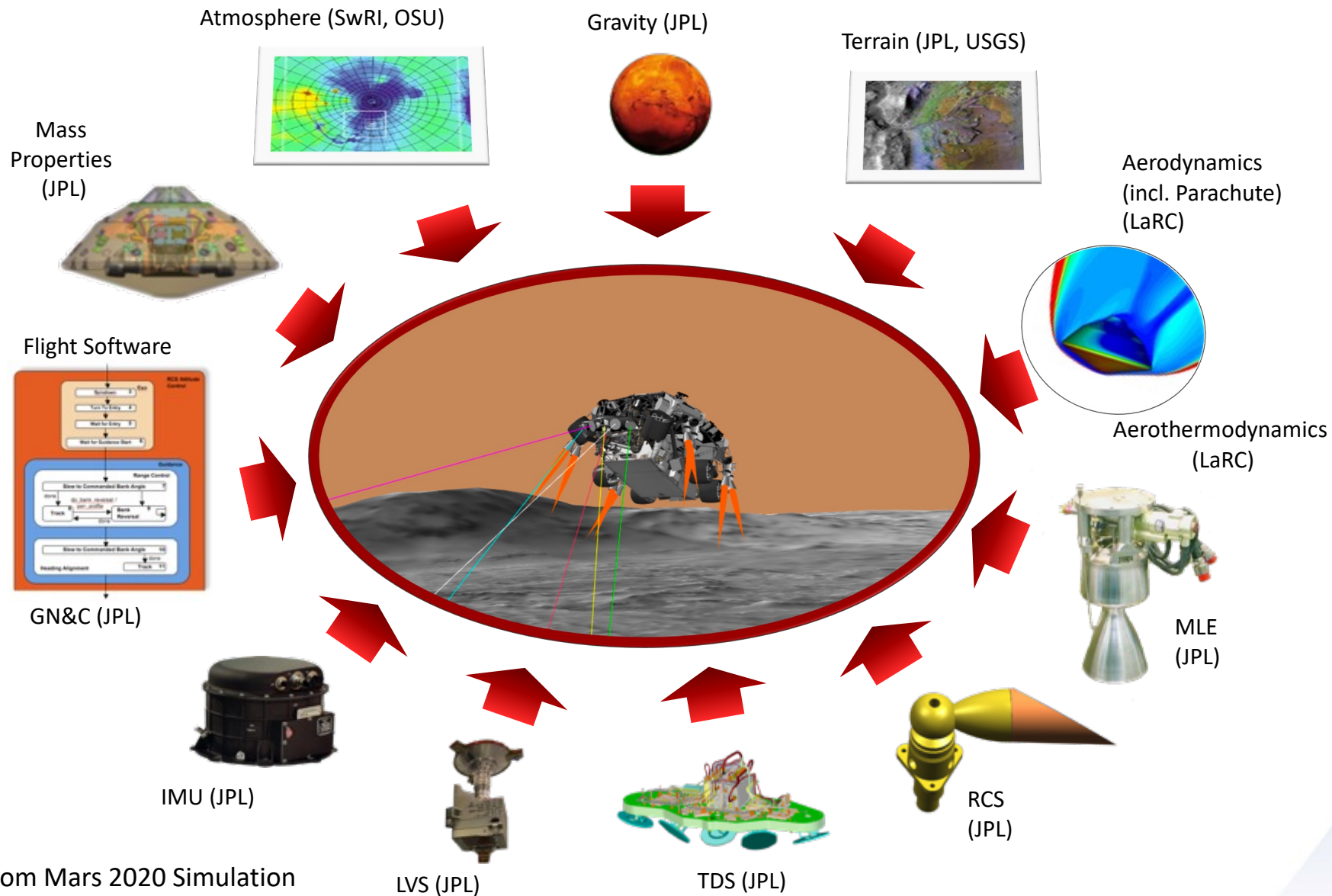
Flight Mechanics Simulations with Various Fidelity



Credit: Mars Science Laboratory Example
Kornfeld et al., JSR, 51(4), 2014

Fig. 6 The “L chart”: flight dynamics and flight system testing venues.

Model Integration: Mars 2020 EDL Simulation

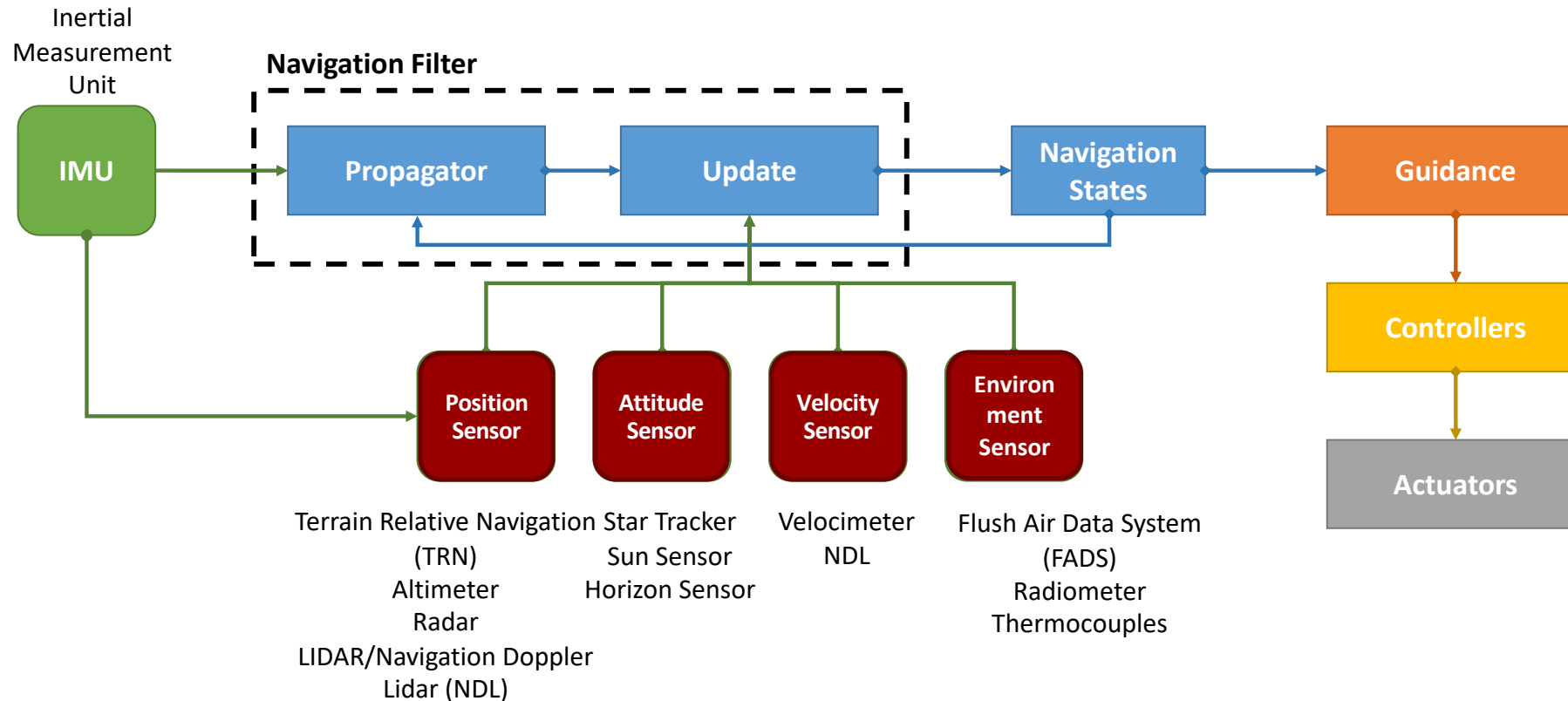


Credit: Example from Mars 2020 Simulation
(AIAA 2022-0421)

Guidance, Navigation, and Controls Relationship



Credit: Adapted from AIAA 2022-0609



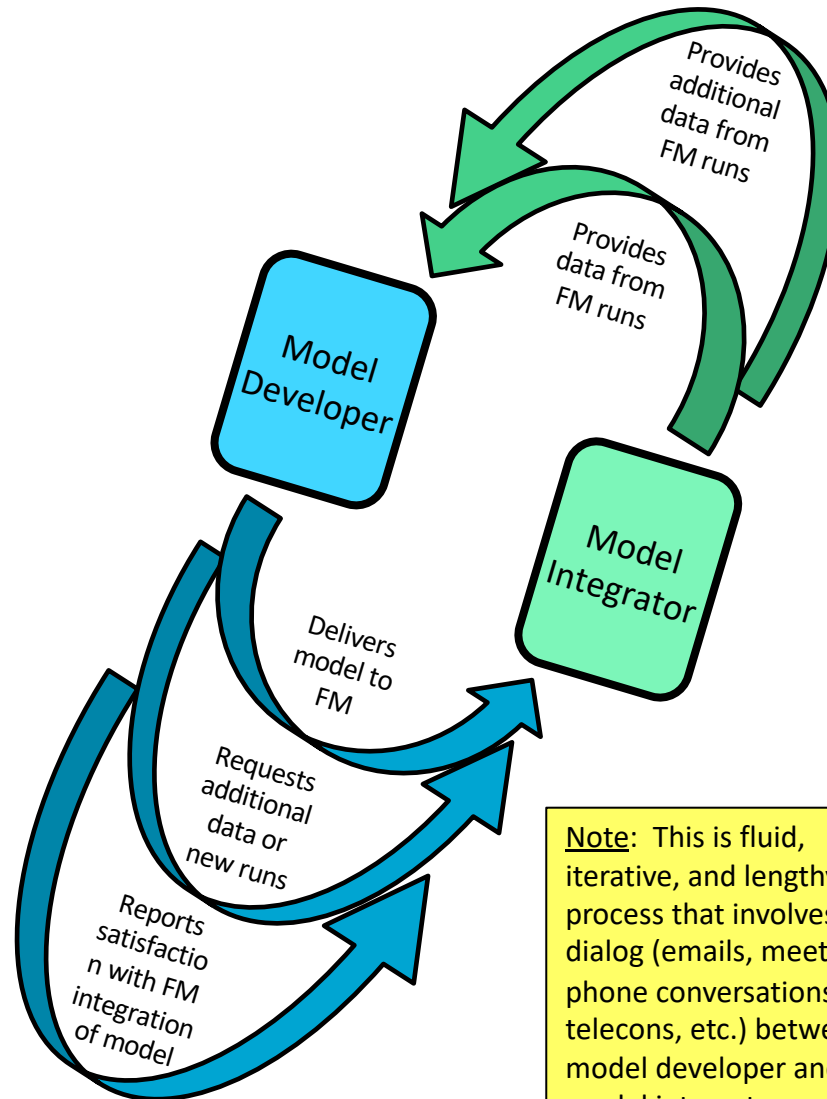
Model Integration/Checkout Process



Model Developer

(Subject Matter Expert)

- Develops and delivers model to simulation & model integration team
- Evaluates data returned by simulation & integration team
 - Data is compared with the developer's own stand-alone version of the model, data produced by other simulations, physical test data of the modeled system, or simplified problems where the expected outcome is either known or easier to comprehend
- Requests additional data or simulation cases based on model-specific needs or diagnostics
- When developer is satisfied with the simulation outputs from the implemented model, they report satisfaction to the model integrator



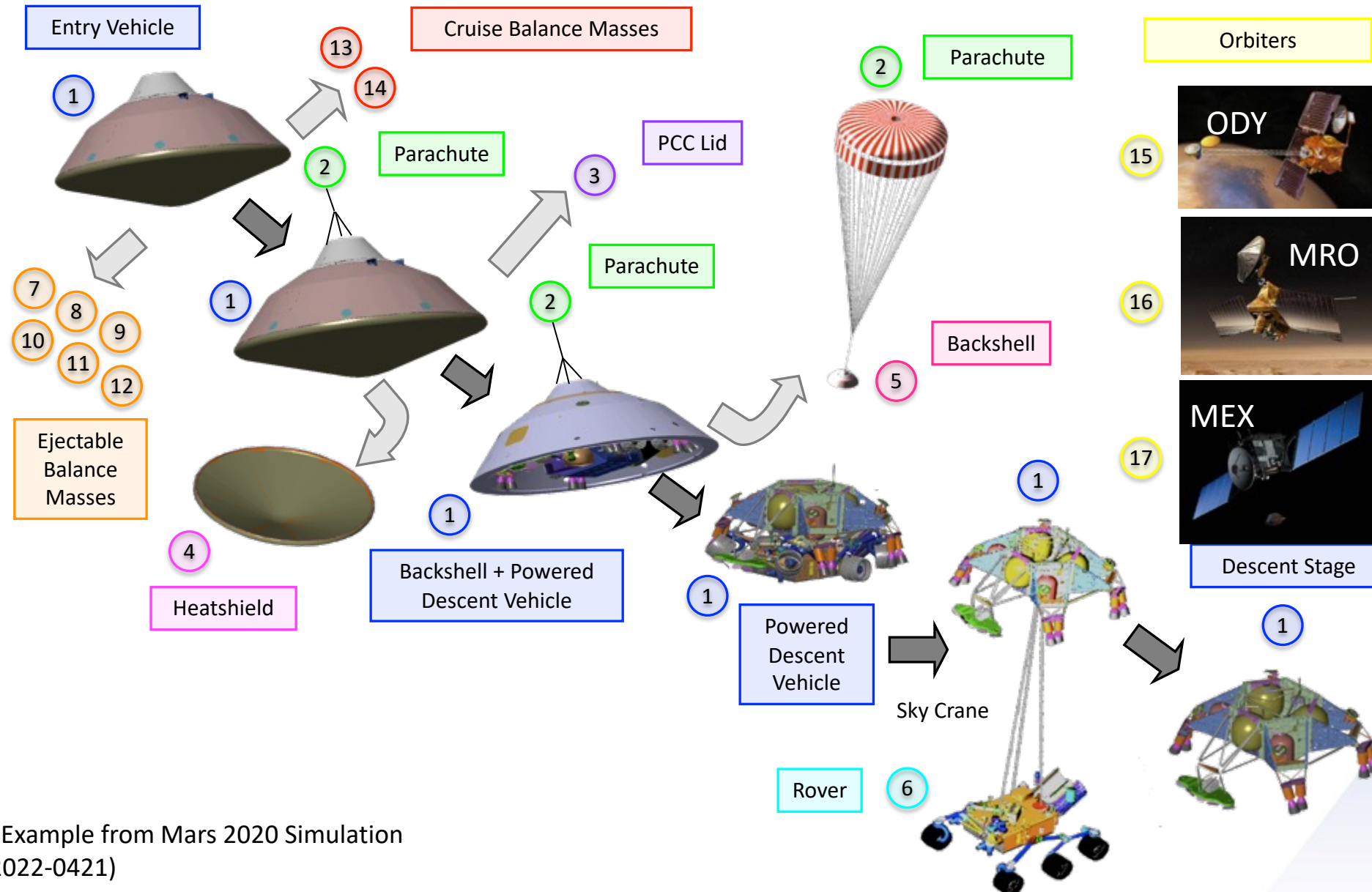
Note: This is fluid, iterative, and lengthy process that involves open dialog (emails, meetings, phone conversations, telecons, etc.) between the model developer and model integrator over a significant amount of time.

Model Integrator

(Simulation and Flight Mechanics Team)

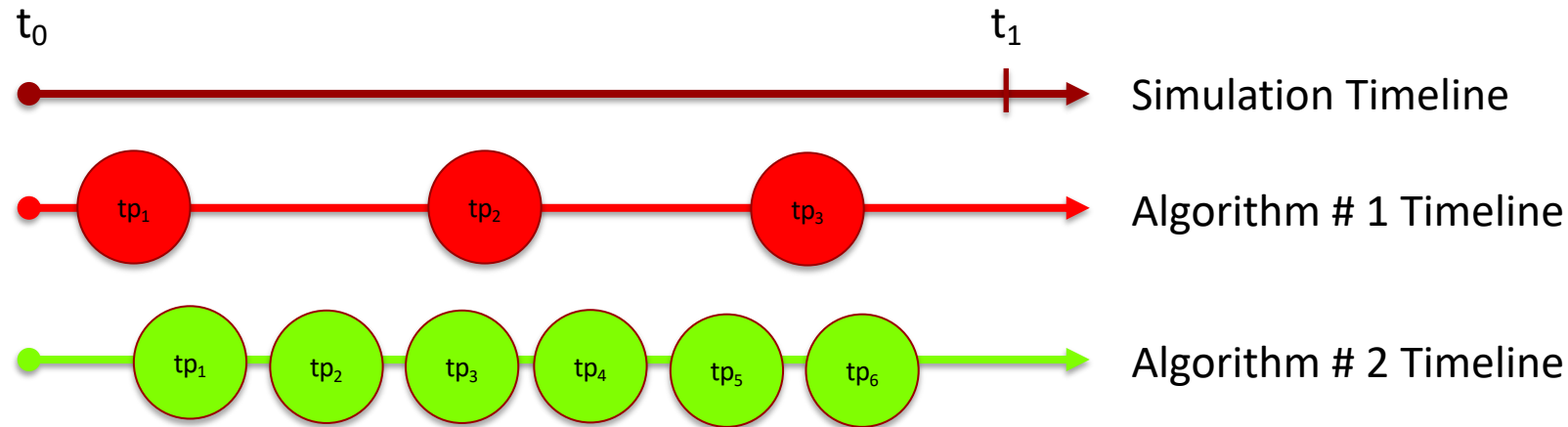
- Integrates the received model into a specialized, branched version of simulation source code that is used for model integration and testing
- Compiles simulation code into a new executable that is then used to generate large quantities of data that is delivered back to the model developer for evaluation
 - Format of data delivery and type of simulation flight cases run are discussed between model developer and model integrator before hand
- Provides additional data, as requested by the model developer, until the model developer states they are satisfied the model is functioning as intended within the simulation
- Integration branch of source code is merged into production branch and re-tested for functionality and compliance
- Successful integration of the model is then reported to the EDL design team
- Future data products presented to the EDL design team will include references (by version number) of the model used during the run

Capabilities for EDL Simulations – Multi-body Modeling



Credit: Example from Mars 2020 Simulation
(AIAA 2022-0421)

Capabilities for EDL Simulations – Multi-rate Modeling

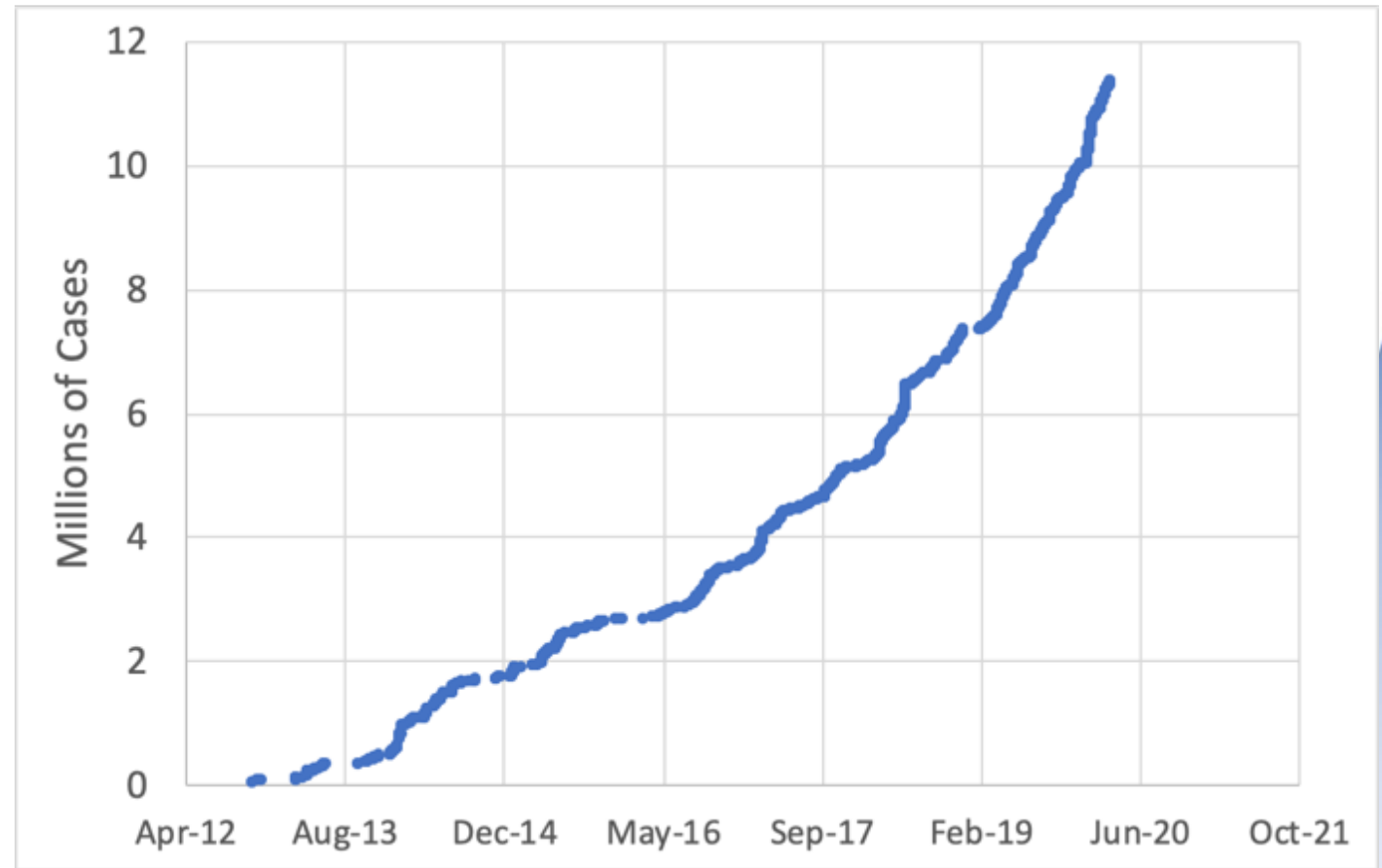


- With simulation-in-the-loop testing, flight mechanics simulations have to provide multiple timelines for execution of code
- Not even discussed: Hardware-in-the-loop – real-time execution of code necessary

Capabilities for EDL Simulations – Length of Checkout



- Saddle-time with GNC algorithms and models over long time span, repeated testing

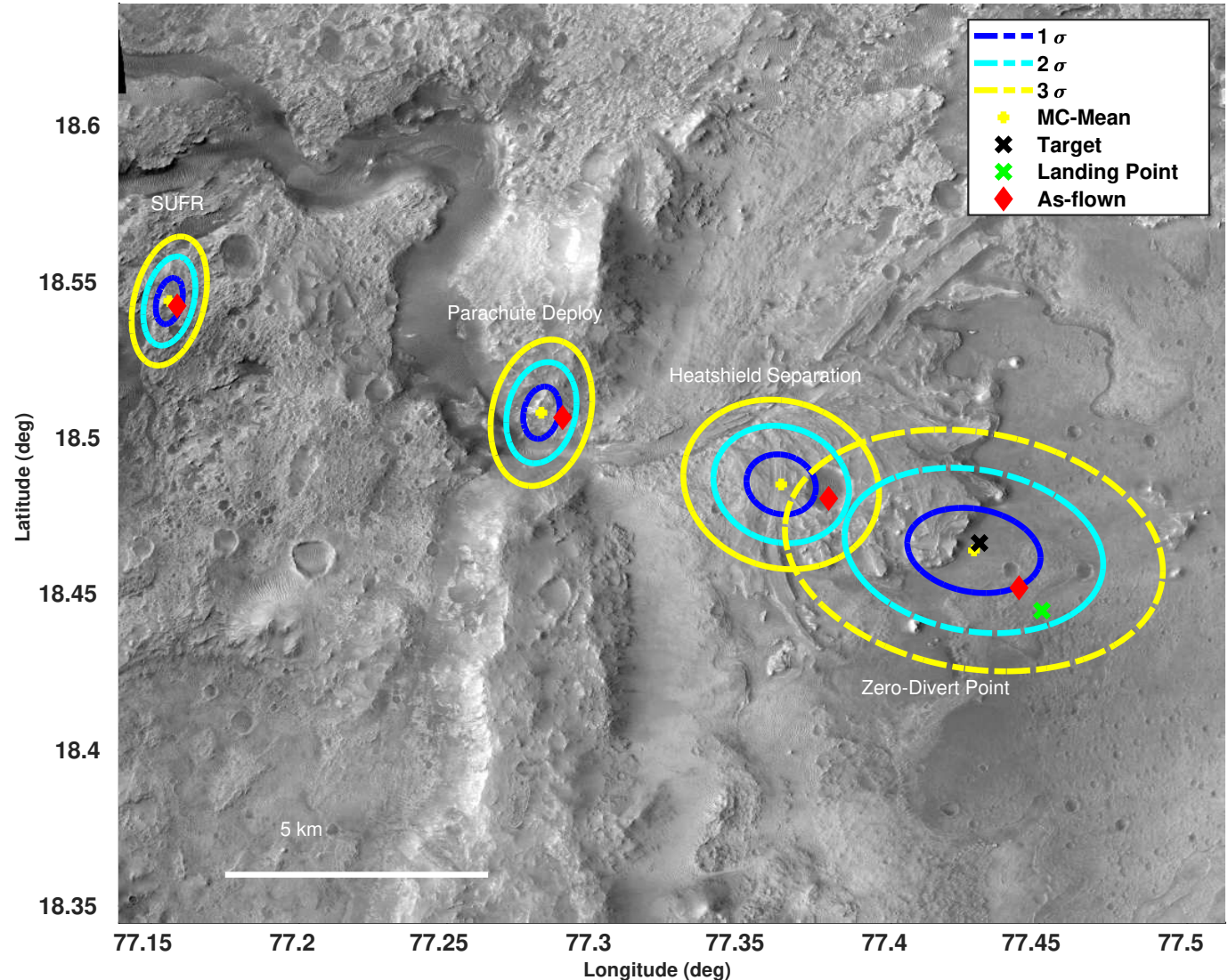


Credit: Example from Mars 2020 Simulation
(AIAA 2022-0421)

Capabilities for EDL Simulations – Length of Checkout



- Saddle-time with GNC algorithms and models over long time span, repeated testing
- Reconstruction of conditions and comparison with pre-flight simulations



Credit: AIAA 2022-0421

Summary



- Entry, Descent, and Landing involves many different regimes of flight
- “Test as you fly, fly as you test” is sometimes not possible outside of an end-to-end flight mechanics simulations
- Simulations offer advantages in tuning for desired conditions, insight into the trajectory, and looking at statistical analyses
- Flight mechanics simulations integrate models from many sources
- Verification and validation is an iterative step between model developer and integrator
- Key relationship is testing Guidance, Navigation, and Control algorithms and flight software and how they operate in various flight conditions
- Modern EDL flight mechanics tools need many capabilities