Enabling Pinpoint Landing (PPL) on Mars

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Outline

- Introduction
- Trajectory dispersion and control analysis
- Navigation analysis
- Mars wind effects study
- PPL decelerator considerations
- Conclusions and recommendations

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Some Assumptions

- PPL missions will deliver about 1000 kg of useful payload to the surface of Mars
  - Soft landings are of primary interest (<3 m/s)
  - The entry aeroshell will be a biconic similar to the Mars Science Laboratory (MSL) design (<4.5 m diameter)
- Mid-to-high latitude landing site compatibility is sought
- Should provide means to land at sites up to 2.5 km above Mars mean surface altitude

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Applicable Entry/Descent/Landing Phases and Notes

- Mars Approach:
  - For entry from Mars orbit, navigation and atmospheric condition knowledge may be enhanced from orbit using observations/soundings prior to entry
  - For direct entry, accuracy of transition to entry relies on approach navigation accuracy and late approach trajectory correction opportunities
- Mars Atmospheric Entry:
  - Guided aeroshell is the baseline for all candidate architectures
- Aerodynamic Decelerator Descent Phase:
  - Two-stage architectures considered
    - » Supersonic parachute plus guided subsonic parachute; or
    - » High-Mach inflatable decelerator plus guided subsonic parachute
- Powered Descent Phase
  - Uses propulsive descent stage for soft landing and final error reduction maneuver

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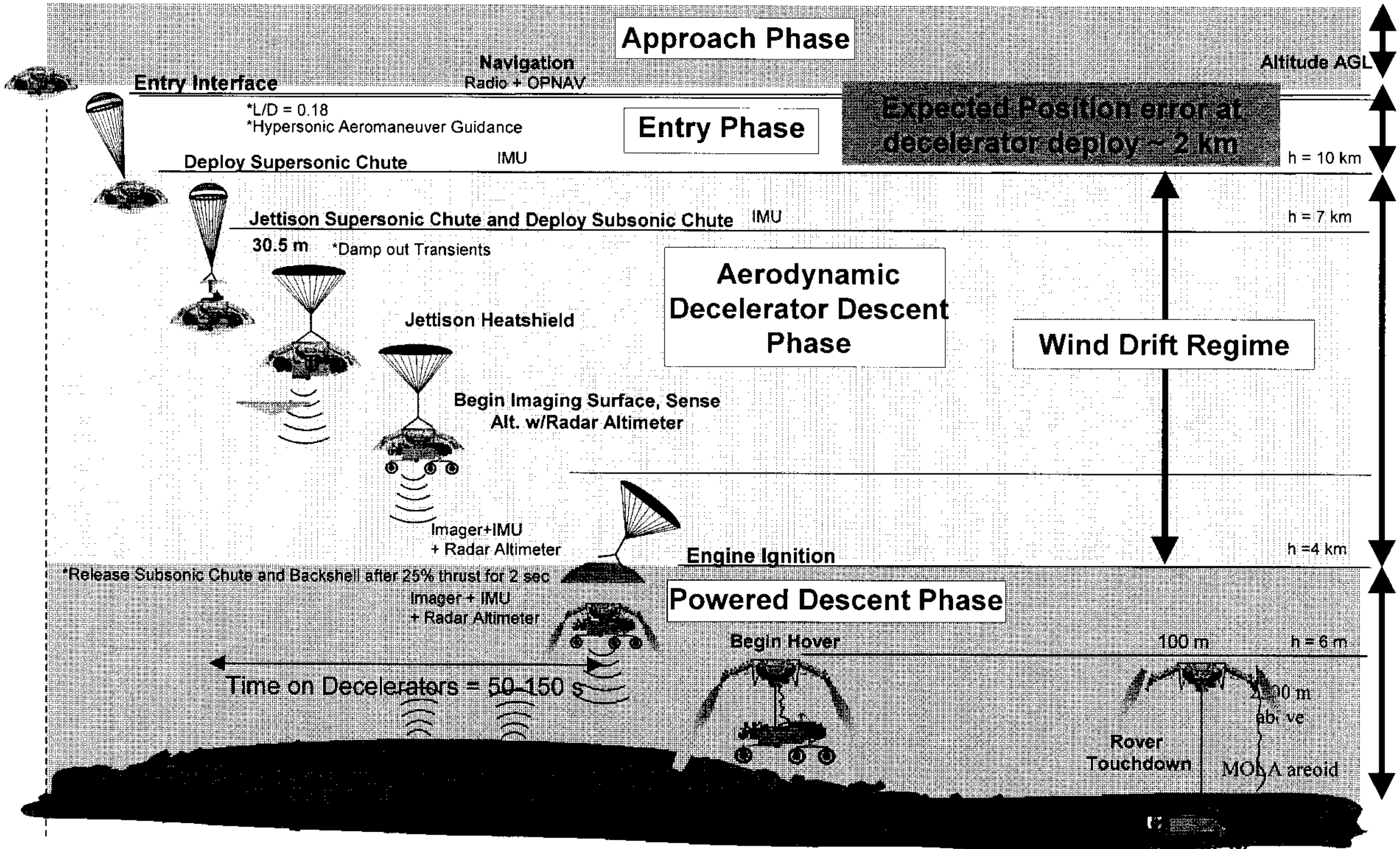
An Entry/Descent/Landing (EDL) Profile

(Based on an Early MSL Reference Mission)



Pinpoint Landing Evaluation Approach

Dispersion and Control Analysis Process

- Identify effects of pinpoint landing error drivers
  - Dispersion error sources
    - » Entry Interface (EI) Initial Conditions (ICs)
    - » Vehicle dynamics and atmosphere model uncertainty
    - » Navigation knowledge errors
  - Trajectory control error correction capabilities
- Quantify the effect of dispersions on landing error (i.e., project error to surface)
- Quantify landing position control capability/authority along entry path

Requirements for Accurate Landing

1. Keep composite of dispersion sources < trajectory control authority along entry path to landing
2. Assure final landing knowledge error < landing accuracy goal

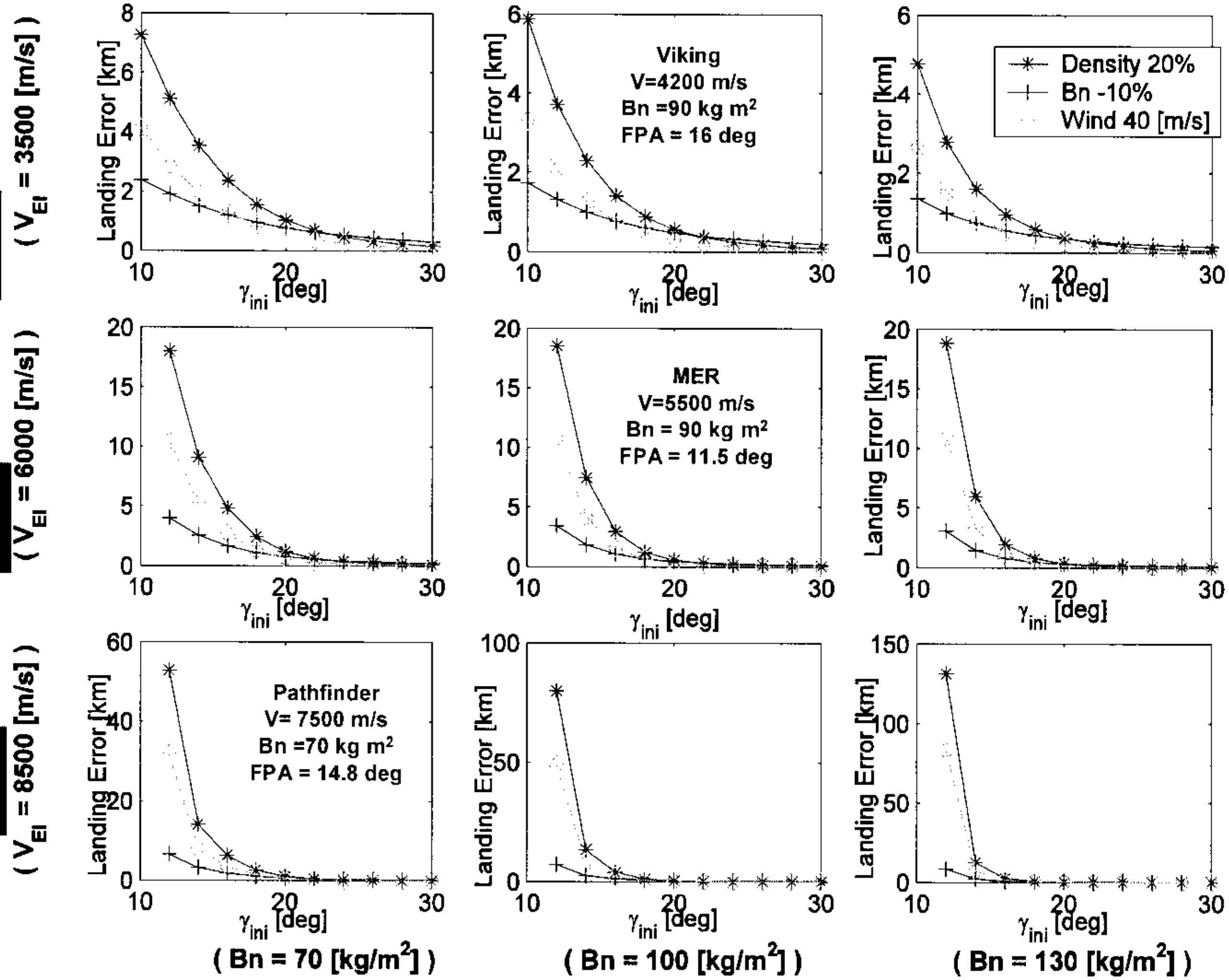
Unguided Aeroshell Entry Phase Dispersions Due to Trajectory and Ballistic Coefficient Variations

Summer Descent - 9 km Parachute Deploy

Entry from orbit

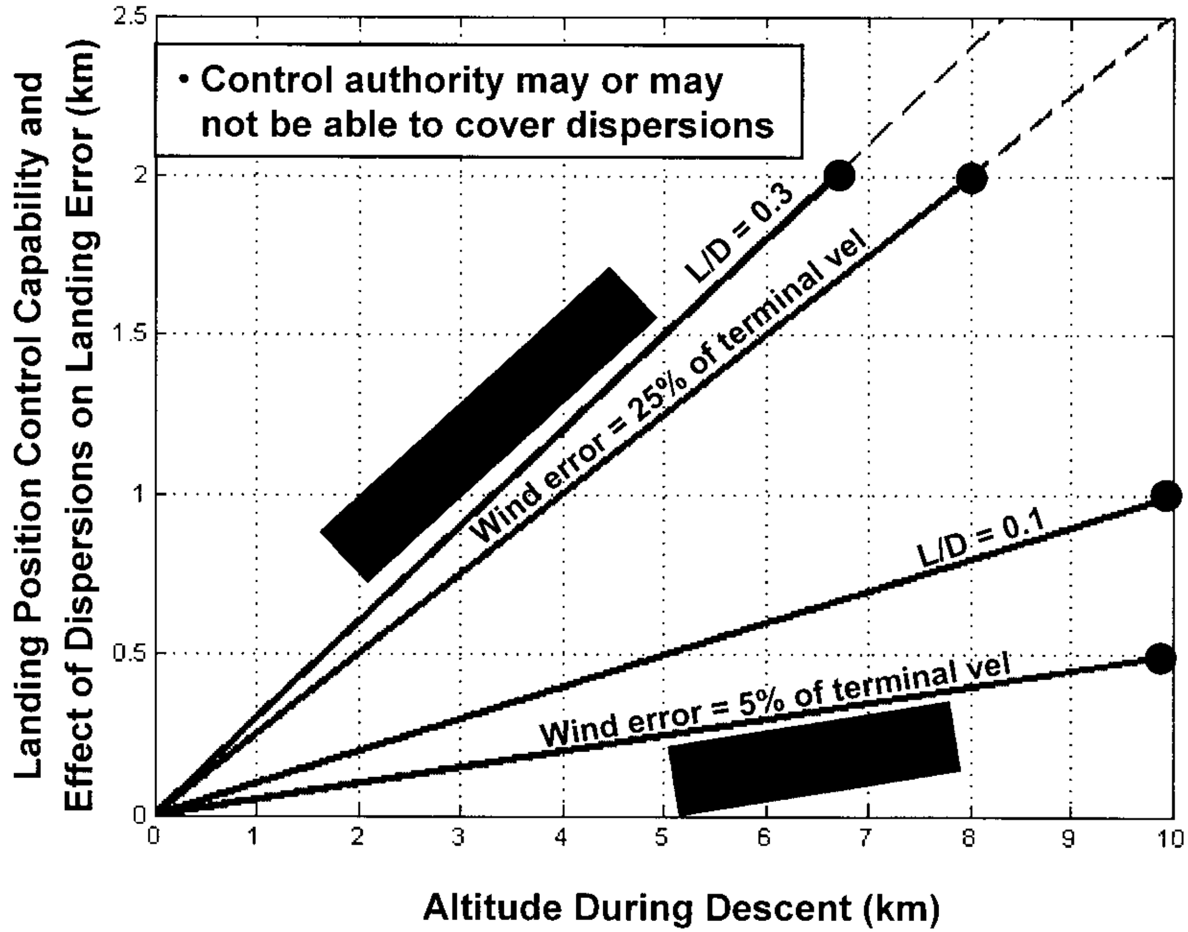
Direct entry (Type II)

Direct entry (Type I)



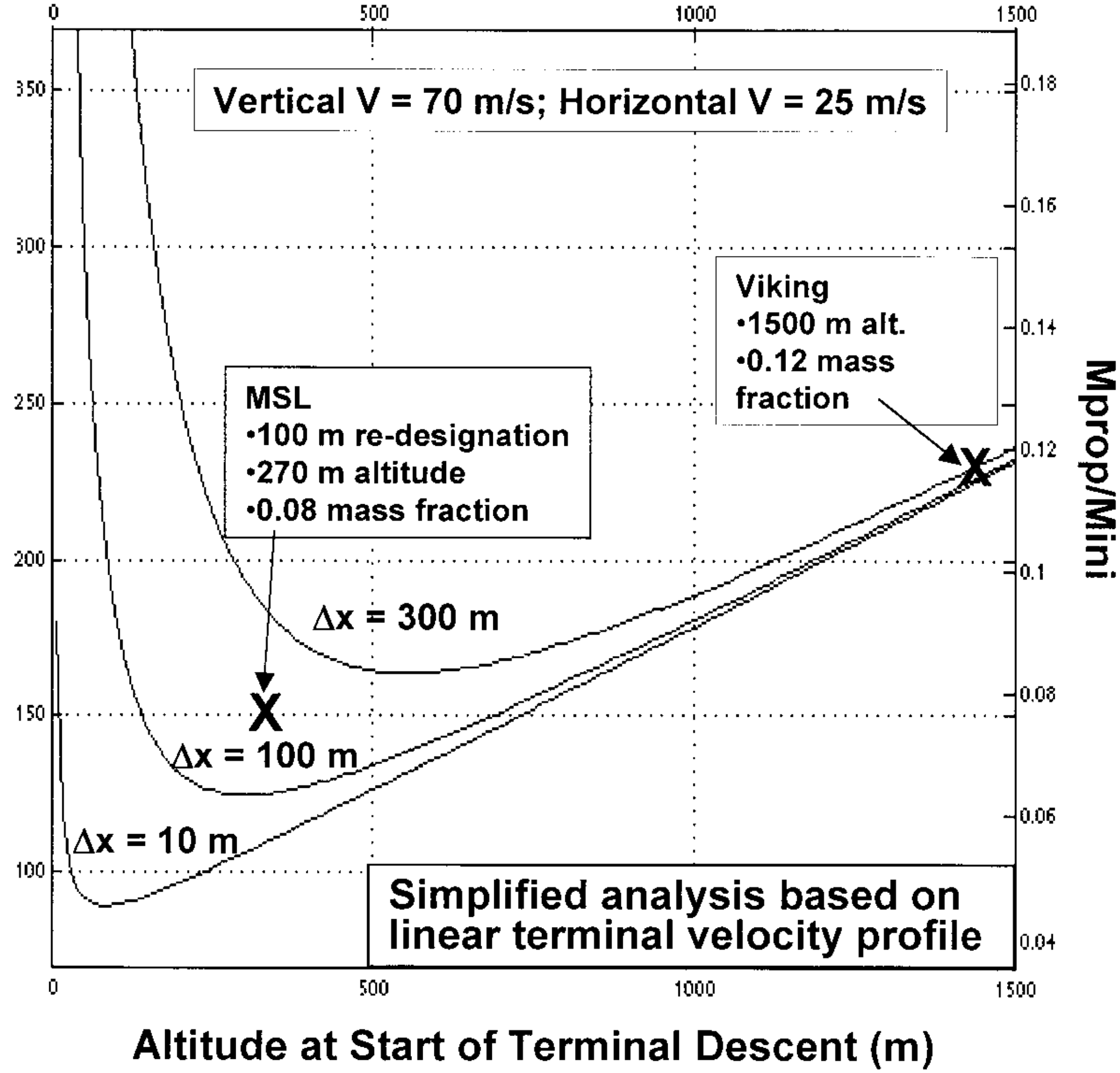
Steerable Subsonic Parachute Control vs. Dispersions

- Dispersions driven primarily by:
  - Persistent wind errors
  - Time of flight
- Landing site control authority driven by:
  - Steerable parachute's average L/D = 0.0-0.3
  - Descent phase time of flight
- Raise altitude of steerable parachute deploy (or lower terminal velocity) to improve control authority
- Lower parachute deploy altitude (or raise terminal velocity) to reduce dispersions



Propulsive Phase Δv vs. Dispersions

- **Dispersions are residuals after parachute release**
- **Landing site control authority driven by:**
  - **Initial powered flight altitude**
  - **Available propellant supply**
- **Adding propellant/ increasing maximum thrust increases control authority**



Example Unguided Dispersions (in Summer)

	Trajectory Phase	Max Acceleration	Max Dynamic Pressure	Altitude	Max Dispersion	Max Control
Direct Entry (Max Heat Load = 3118 J/cm^2) Max Heat Rate = 36.9 W/cm^2)	Aeroshell	9.9 g	10325 Pa	36.9 km	35 km	250 km
	Supersonic Chute	3.3 g	561 Pa	13.4 km	3 km*	0.0 km
	Subsonic Chute	4.0 g	110 Pa	10.0 km	5 km*	1.1 km**
Low Orbit Entry (Max Heat Load = 1271 J/cm^2) Max Heat Rate = 12.3 W/cm^2)	Aeroshell	2.6 g	2702 Pa	32.9 km	30 km	130 km
	Supersonic Chute	3.3 g	577.5 Pa	13.2 km	3 km*	0.0 km
	Subsonic Chute	4.1 g	112.0 Pa	9.9 km	6 km*	1 km**

* ***For worst case unknown winds and density effects (no descent initial position corrections based on forecast)***

** ***Based on an average subsonic parachute L/D for control of about 0.3***

Results

- Aeroshell entry phase dispersions can be large (10s of kilometers), but closed-loop guidance, to be first used on MSL, can null out resulting errors to within about 2 km
- Projected parachute control is inadequate to correct worst case dispersions without wind forecast data
  - Errors during unguided supersonic descent
  - This is assuming perfect navigation state knowledge
  - Would result in excessive use of propellant during terminal powered descent to meet sub 100-m landing accuracy
- Mitigation possibilities:
  - Reduce dispersions due to atmospheric uncertainty by providing on-board or external means to measure density and winds ahead of the vehicle
  - Investigate higher L/D control authority options for the subsonic parachute phase
  - Investigate decelerators with control authority options for the supersonic descent phase

Analysis Overview

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The Problem

- Prior analysis assumed perfect state knowledge
- Must take into account real-time state knowledge error

The Performed Analysis

- Determination of the navigation error footprint at landing for a vehicle with various sensor suites that include:
  - Baseline
    - » Inertial measurement unit
    - » Radar altimeter
  - Possible Additions
    - » Doppler ground speed measurement
    - » Two-way Doppler to an orbiting satellite
    - » ground relative navigation (e.g., imaging-based)
- Comparison of the effects of coarse (traditional DSN) and fine (Optical Navigation, about ¼ DSN) initial conditions at EI

Navigation Error Analysis Summary

- Even the best Inertial Measurement Unit (IMU) + radar altimeter + precision ICs at EI still yield position knowledge errors of about 3 km at landing
- Adding a measurement of ground speed can reduce the landing position knowledge errors to below 700 m
- Addition of ground-relative navigation aiding devices (e.g., imaging-based) can get error into the 100 m range
- Map-tie errors can also be important
  - Target inertial coordinate uncertainty adds (RSS) to navigation error
  - Map-tie error must be well below desired landing accuracy
  - Map-tie error is less significant with addition of imaging-based ground-relative navigation

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Assessment of Trajectory Biasing for Winds

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Can It Be Done

- Analysis of recent Mars landing sites show mesoscale models enabled predictions consistent with observed mean winds (within 4 m/s 1-σ) and wind shears
  - Applies where topographic features do not dominate wind behavior
- Would offset targeted decelerator deploy location based on a reliable wind forecast
- Would also use forecast to adapt transition to powered flight point to minimize offset correction propellant usage

Should it Be Done

- Landing accuracy benefits from trajectory biasing at sites with known persistent mean winds > 5 m/s
- Sites with high winds that fluctuate in space and time would preclude biasing benefits (also limiting any PPL potential)

Assessment of *In Situ* Wind Sensing

What Methods May Be Feasible

- Combine an IMU and terrain tracking camera to determine horizontal drift rates at the vehicle altitude
- Apply optical (Lidar) sensors with look-ahead wind measurement capability
  - Can only be done once a sensor window is exposed (after heat shield jettison)
- Apply predicted correlations of target site winds with current data from previously emplaced, spatially separated surface sensors
  - Depends on models derived from persistent measurements
  - Requires leveraging atmospheric models with underlying structure

How Is *In Situ* Data Useful

- Enables improved allocation of steerable decelerator control authority when response time constants are long
- Adds information for adapting the transition point to powered flight

Some Observations

- With a guided entry phase and unguided decelerator descent phase, the cumulative error at powered descent initiation can exceed 7 km
  - Assumes a supersonic parachute deploy at about Mach 2 – cumulative errors could be larger with unguided decelerators deployed at higher Mach numbers
- Total decelerator descent time is on the order of 50-150 seconds
  - Higher altitude (+2.5 km) landing sites and single stage decelerators limit the decelerator phase time to under 100 seconds
  - At least 20 seconds of the decelerator descent time is used to get to subsonic descent conditions suitable for subsonic parachute deployment and/or steering (M<0.8)
- The decelerator mass ratio on Mars is much higher than on Earth
  - The surface pressure is 3-9 milli-bars as a function landing site altitude (up to 2.5 km above the planet's mean)

Steerability/Control Issues

- Absent wind forecast and/or measurement data, an L/D of at least 1.5 is needed to negate decelerator initial condition and subsequent wind drift errors before powered descent
- Likely long control time responses in the low density Mars atmosphere precludes agile response to transitory wind dispersion effects
  - Makes correction for unmodelled wind effects difficult during decelerator flight
- Best use of decelerator steering may the following
  - Remove residual errors left after aeroshell entry
  - Correct navigation and map-tie errors detected when ground-relative imaging is initiated
  - Remove remaining expected wind drift effects not addressed by trajectory biasing
- May need to rely on powered descent to remove effects of unmodeled winds with applicable powered descent initiation adaptation
  - Required powered descent propellant impact will likely dictate use of best possible wind forecast data to enable PPL missions

Dispersion Observations

- While aeroshell entry dispersions can be large, closed-loop aeroshell guidance mitigates their impact (to within about 2 km)
- Unguided decelerator descent can leave errors of about 7 km at transition to powered flight
- A precision entry interface and high quality baseline sensors can leave a navigation error of almost 3 km at landing
  - Ground-relative navigation aiding is needed to get navigation errors into the PPL (< 100 m) box, and to also mitigate map-tie errors
- Wind forecasts and trajectory biasing can mitigate much of the decelerator-descent-phase wind drift
- Decelerator steering is needed to remove residual errors from aeroshell descent and navigation errors subsequently detected upon activation of ground relative (e.g., imaging) navigation aiding sensors
- Low Mars atmosphere density and short decelerator descent times make it difficult to use decelerator steering to remove unmodeled wind effects
  - Will need to rely on some powered descent capability to fly out remaining wind-driven errors

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