Improving the Landing Precision of an MSL-Class Vehicle

IEEE Aerospace Conference – Big Sky, MT
March, 2012

Aron Wolf, Jordi Casoliva, Joel Benito,
Behcet Acikmese, Scott Ploen

Jet Propulsion Laboratory, California Institute of Technology

Copyright 2012 California Institute of Technology. Government sponsorship acknowledged.

Introduction

- **What is an "MSL-class" vehicle?**
  - Guided entry, 4.5-m diameter aeroshell
  - "Skycrane" configuration (descent stage w/8 engines + 900kg rover)
  - Single 21.5-m diameter disk / gap / band parachute

~10-12 km

MSL: Velocity trigger,
0.25-deg 3σ att init error

- **What can we change without violating "MSL-class" paradigm?**
  - Parachute triggering scheme
  - New powered descent guidance
  - Addition of terrain-relative nav
  - Substitution of star tracker for star scanner
  - Perhaps some extra prop?

How to get to 2 – 3 km (or less) from the target?

MSL Attitude Initialization Error Budget

MSL budget
(requirement = 0.25 deg,)

!"#$	%&&'&(*#+, -./01+$23
456 720#819#	
!"#$%&'#%&($	)*)+,
-&./0 /23/ $(&4/	)*))5
6"$ 4/$4(7 484%/9#%&: /77 ;(<4/7=/2>	)*+,5
6"$ 4/$4(7 %&9/%#3 $(&4/ /77	)*)))
6"$ /?@/9/7&4 /77	)*),)
ABB/:%4 (B 4%#7 4:#$$/7 %(4"$ 4/$4(7 9&4#0&3$	)*)CD
6"$ 4/$4(7 %(4%#7 4:#$$/7 #0&3$ E$(F0/23/	)*)5G
6"$ 4/$4(7 %(4%#7 4:#$$/7 #0&3$ 4%#<&0&%8	)*)5G
HIJ %(4%#7 4:#$$/7 #0&3$ E$(F0/23/	)*+))
HIJ %(4%#7 4:#$$/7 #0&3$ 4%#<&0&%8	)*+))
6"$ 4/$4(7 %&9/%#3 <&#4 #$3	)*)+,
HIJ %&9/%#3 <&#4 #$3	)*)+,
:55	**;,<==**

"What If" IMU align knowledge & stability were perfect (e.g. add "late cal")?

!"#$	%&&'&)*+ ,-.$/0
123 4/,#5-6# 789#&:#;" 5/"# ;/5-4&/"-'6	
!"#$%&'#%&($	)*)+,
-&./0 /23/ $(&4/	)*))5
6"$ 4/$4(7 484%/9#%&: /77 ;(<4/7=/2>	)*+,5
6"$ 4/$4(7 %&9/%#3 $(&4/ /77	)*)))
6"$ /?@/9/7&4 /77	)*),)
ABB/:%4 (B 4%#7 4:#$$/7 %(4"$ 4/$4(7 9&4#0&3$	)*)CD
6"$ 4/$4(7 %(4%#7 4:#$$/7 #0&3$ E$(F0/23/	)*)5G
6"$ 4/$4(7 %(4%#7 4:#$$/7 #0&3$ 4%#<&0&%8	)*)5G
HIJ %(4%#7 4:#$$/7 #0&3$ E$(F0/23/	)*)))
HIJ %(4%#7 4:#$$/7 #0&3$ 4%#<&0&%8	)*)))
6"$ 4/$4(7 %&9/%#3 <&#4 #$3	)*)+,
HIJ %&9/%#3 <&#4 #$3	)*)+,
<22	**=>?@A**

Attitude initialization error improvements with a "build to print" MSL system are limited by the sun sensor, which is used to define the coordinate frame used in cruise

Star Tracker w/Late Cal, Spinning or 3-Axis Stab

- **100 arcsec 3-sigma error is a conservative assumption for both spinning and 3-axis stabilized S/C configurations**
  - Results of investigation of 3 star trackers: Galileo Avionics A STR, Sodern SED26, Ball CT-633

!"#$	%&&'&)*+ ,-.$/0	
12-33-3.'& *+/4,"/5 6&7-,#,"/.#8,"/& "9& :;</"#6/<		
!"#$%&'#%&($	)*)+,	
-&./0 /23/ $(&4/	)*))5	
6%#7 %7#89/7 /77(7	)*),:	;($4/7<#%&</ 4%#7 %97 =/7>(7?#$8/
6%#7%97%&?/%#3/77	)*))@	, A-B 4=&$ 7#%/ .)*5 ?4/8 7?4 %&?&$3 /77(7
6"$ /=C/?/7&4 /77	)*)))	$(4"$ 4/$4(7
D>>/8%4 (> 66E %(F6E ?&4#0&3$	)*)))	
F6E %(66E #0&3$ 9$(G0/23/	)*)))	
F6E%(66E#0&3$4%#H&0&%I	)*)))	
FJBK%(4%#7%97#0&3$ 9$(G0/23/	)*),:	;#44&$& 7/LM% ($&$>0&3C%#0&3$M%N OP4&3?#=/7#.&4
FJBK%(4%#7%97#0&3$4%#H&0&%I	)*)))	E44"?/4 =/7>/8% 0#%/ 8#0
F6E %&?/%#3 H&#4 #$3	)*)))	
FJBK%&?/%#3H&#4#$3	)*)+,	
=11	>?>@@	

Reasonable to assume that when a star tracker is used, 0.06 deg. (3-sigma) is a conservative estimate of attitude initialization error

Achievable Dispersions at Ignition
MSL-Class Vehicle

Illustrative "cartoon"

~8km **Velocity trigger,**
0.06-deg 3σ att init error

~10-12 km **MSL: Velocity trigger,**
0.25-deg 3σ att init error

When Using Velocity Trigger, Winds Cause Range Errors at Chute Deploy

Winds assumed constant or nearly so throughout entry (

Targeted range at chute deploy

V trigger 25 m/s headwind deploys uprange
Pl-rel V = 450 m/s
Atm rel V = 475m/s

Direction of flight

No wind
Pl rel V = 450 m/s (nominal)
Atm rel V = 450 m/s

Altitude →

V trigger: deploy at desired ***planet-relative velocity****, as computed onboard by* ***integrating acceleration measured by the IMU***

V trigger 25 m/s tailwind deploys downrange
Pl-rel V = 450 m/s
Atm rel V = 425 m/s

Downrange distance →

Correlation Between Wind V and Planet-Relative V at Deploy w/Range Trigger

Winds assumed constant or nearly so throughout entry !

Targeted range at chute deploy

V trigger 25 m/s headwind deploys uprange
Pl-rel V = 450 m/s
Atm rel V = 475m/s

Headwind 25 m/s
Pl-rel V = 400 m/s
Atm rel V = 425m/s

Dispersion in atm-relative V = +/-25 m/s

Direction of flight

No wind
Pl rel V = 450 m/s (nominal)
Atm rel V = 450 m/s

Dispersion in planet-relative V = +/-50m/s

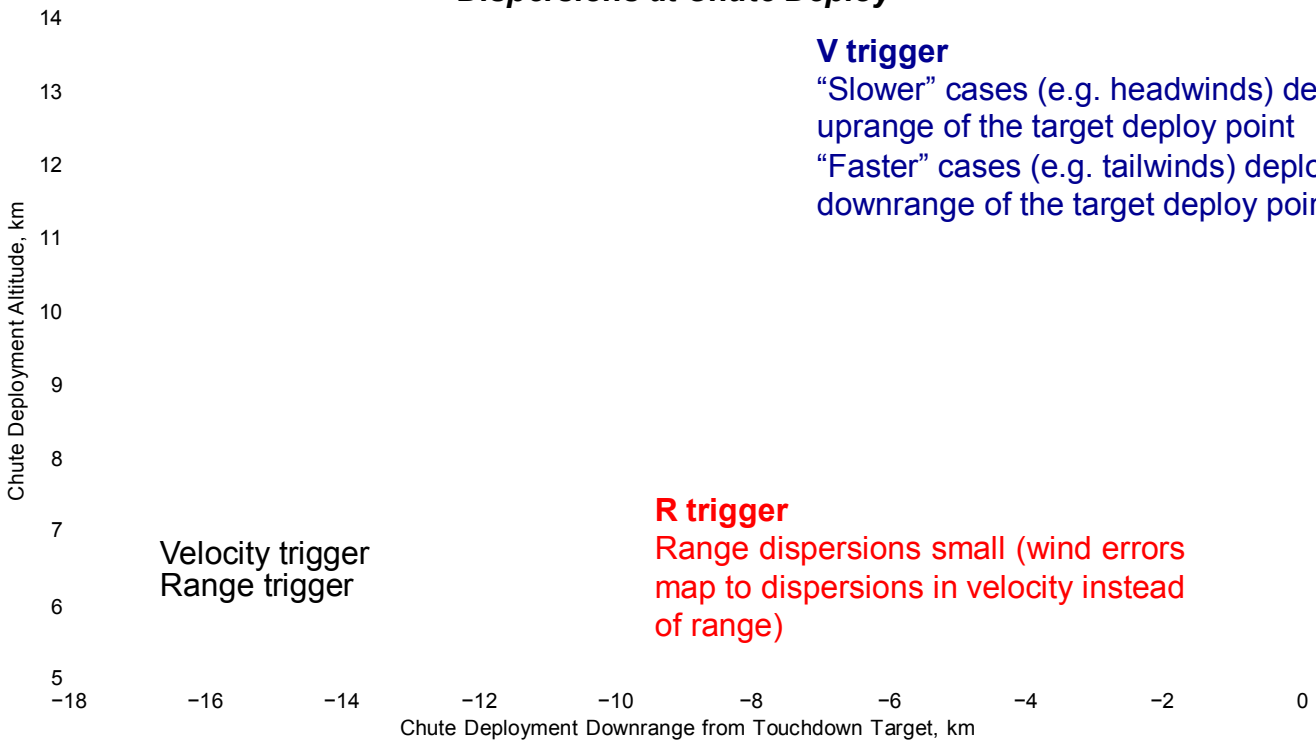
Tailwind 25 m/s
Pl-rel V = 500 m/s
Atm rel V = 475 m/s

V trigger 25 m/s tailwind deploys downrange
Pl-rel V = 450 m/s
Atm rel V = 425 m/s

- ***Increased planet-relative (IMU) V dispersions of range trigger don't map to increased dispersions in atm-relative V (and Mach)***

Range and Velocity Triggers: Monte Carlo Comparison

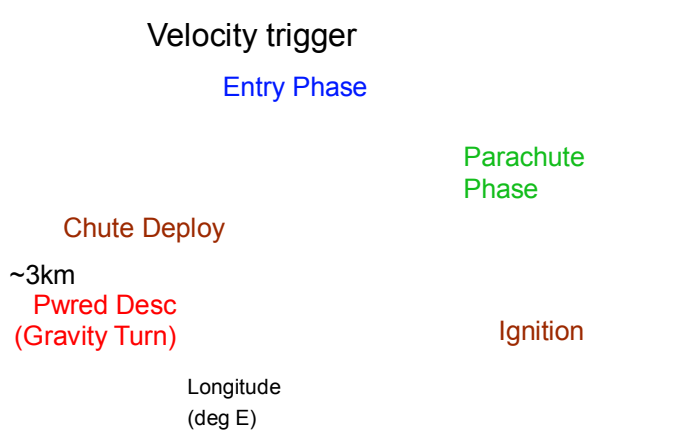
Dispersions at Chute Deploy

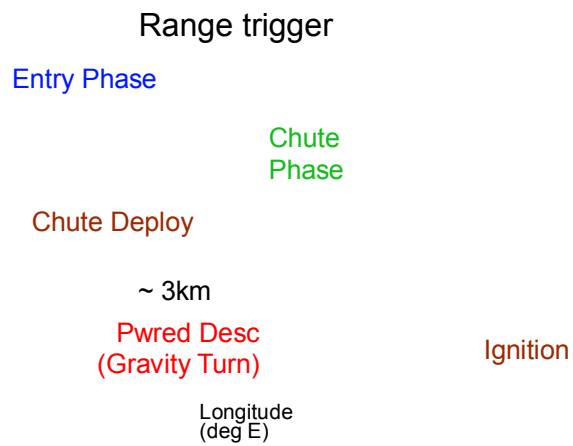


V trigger
"Slower" cases (e.g. headwinds) deploy uprange of the target deploy point
"Faster" cases (e.g. tailwinds) deploy downrange of the target deploy point)

R trigger
Range dispersions small (wind errors map to dispersions in velocity instead of range)

!"#"$% "' ()*'+ ,+-./0	1+./23'0 '#344+#	5"64+ 7#344+#
!"#$ &#"#' &#()		
()*'+ 8+-./0 9"2)		
*)+,	-./-	-./-
00.123	-.-4	-.-5
!."6+':#+."'3;+ %-++8 "' 2)*'+ 8+-./ 0		
6#78,+"	945.99	942.//
00.123	942.4/	905.04
:00.123;7)+,<	/.11	9/.=-
()*'+8+-./0".'3'*8+<>$		
*)+,	=/.>-	=/.>-
/.=>3	2.95	2.1-
,/?6#"64++##/#"'3463'3/6<>$		
:00.123;/.=>3<?-	2.15	>.11





Total Propellant Mass vs. Prescribed Landing Accuracy (MonoProp)

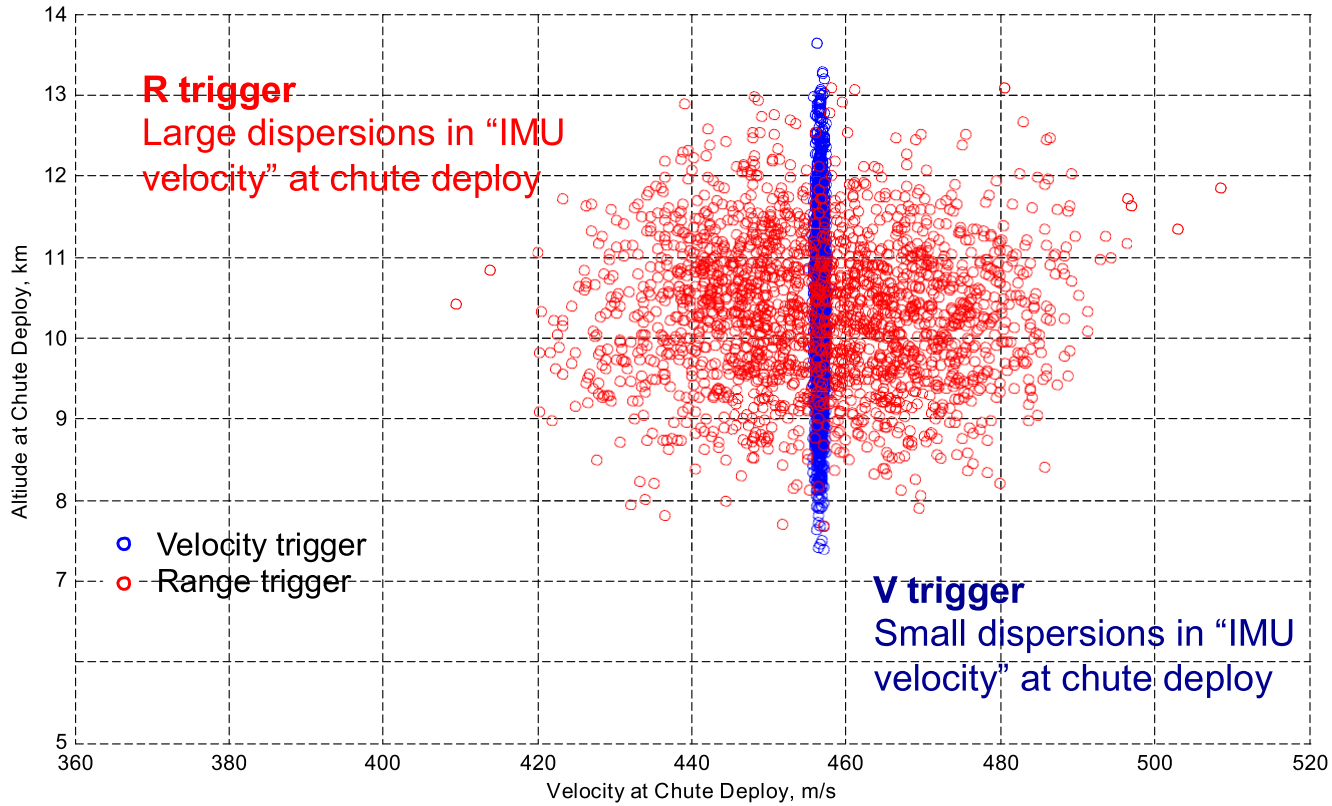
Isp = 210 sec

Assumed:
Wet mass at ignition = 2047kg (MSL)
Range Trigger
0.06-deg att init error
Perfect nav after heatshield jett+5 sec
MSL engrg wind

MSL

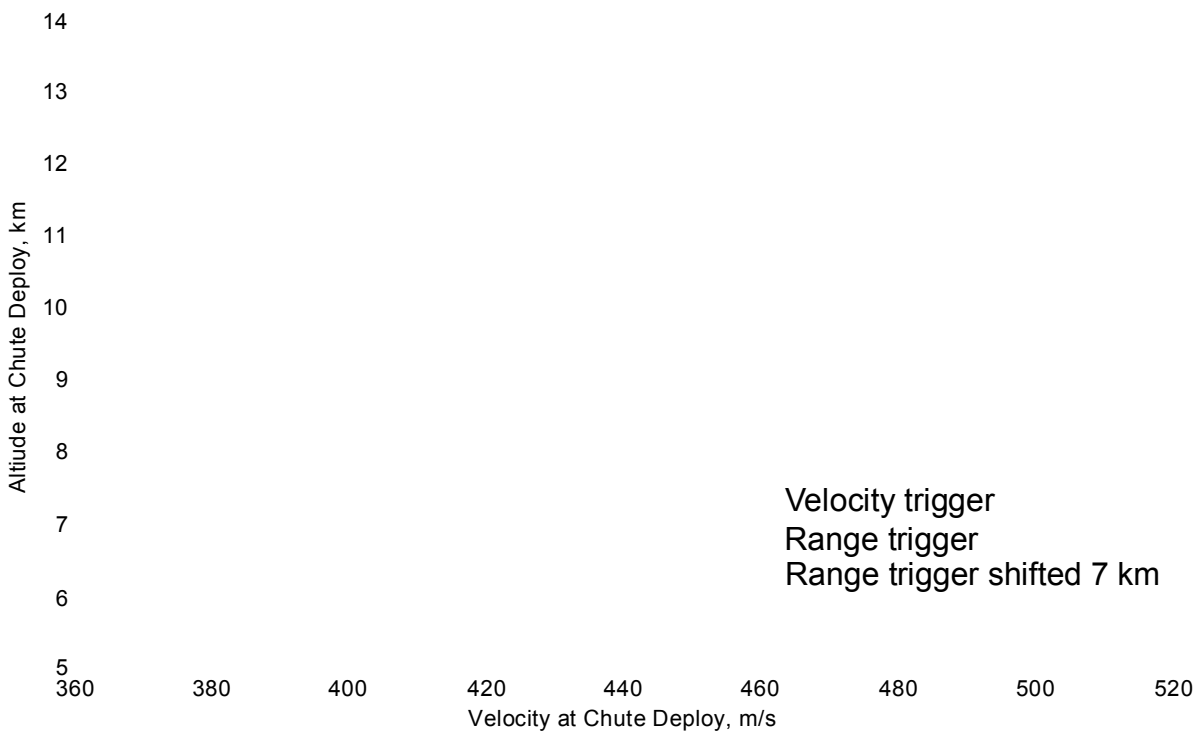
MSL
Total Fuel
400 kg

Chute Deployment Velocity Dispersions



Range Trigger caution: correlation effect only works if winds are constant - unmodeled change in wind close to deploy (e.g. tailwind => headwind) could cause deployment at excessive Mach

Chute Deployment Velocity Dispersions

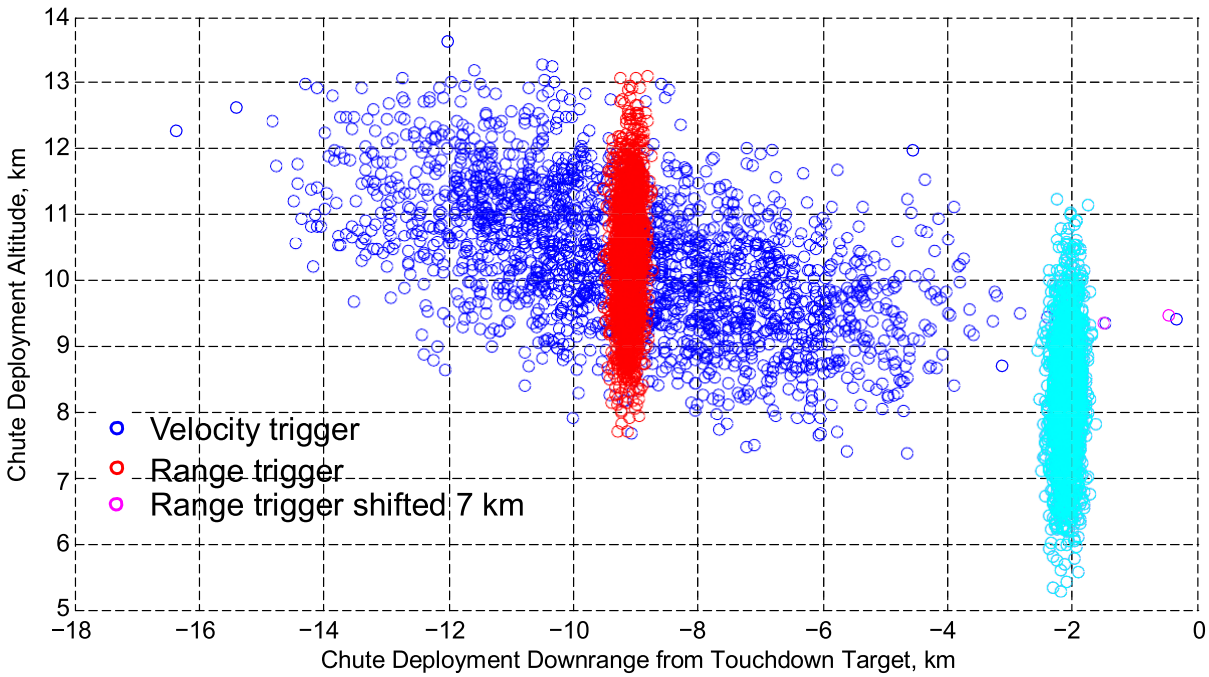


!"#"$%"'()*'+ ,+-./0	1+./23'0 '#344+#	5"64+ 7#344+#	5"64+ 7#344+# %)38'+9 :;$
!"#$ &#"#' &#()			
()*'+9+-./0<"2)			
*)+,	-./-	-./-	0.12
22.314	-.-5	-.-6	-./5
!."6+'=#+."'3>+%-++9"'2)*'+9+-./0?$@%			
7#89,+"	:56.::	:51.//	:00.:0
22.314	:51.5/	:26.25	:5:.5;
<22.314=8)+,>	/.33	:/.0-	::.//
()*'+9+-./0".'3'*9+?;$			
*)+,	0/.;-	0/.;-	3.--
/.0;4	1.:6	1.3-	5.::
,/A6#"64++##/#"'3463'3/6?;$			
<22.314=/.0;4>?-	1.36	;.33	;.-2

3-sigma high planet-relative deployment velocity same as that of V trigger (~457 m/s)

Suggested risk posture: Don't allow 99.87% IMU velocity w/range trigger to exceed value w/velocity trigger

Chute Deployment Range Dispersions



!"#"$%"'()*'+ ,+-./0	1+./23'0 '#344+#	5"64+ 7#344+#	5"64+ 7#344+# %)38'+9 :;$
!"#$ &#"#' &#()			
()*'+9+-./0<"2)			
*)+,	-./-	-./-	0.12
22.314	-.-5	-.-6	-./5
!."6+'=#+."'3>+%-++9"'2)*'+9+-./0?$@%			
7#89,+"	:56.::	:51.//	:00.:0
22.314	:51.5/	:26.25	:5:.5;
<22.314=8)+,>	/.33	:/.0-	::.//
()*'+9+-./0".'3'*9+?;$			
*)+,	0/.;-	0/.;-	3.--
/.0;4	1.:6	1.3-	5.::
,/A6#"64++##/#"'3463'3/6?;$			
<22.314=/.0;4>?-	1.36	;.33	;.-2

Result: shift deploy 7km downrange, reducing deploy altitude by ~2km, to protec againat a sudden wind shift of ~45 m/s (100 MPH!) at / near chute deploy

Ways to "Buy Back" Altitude

- **Throttle valve with no need for long (8 sec) priming time => ~800m**
- **Surface pressure uncertainty in atmospheric model (10% now, may be able to reduce after MSL landing to 5% or smaller) => ~500m**
- **Jettison heatshield earlier?**
  - MSL may show that there is no dip in drag performance at Mach 1 => **~500m** for 0.1 Mach increase
- **Increase chute diameter from 21.5m to 23m**
  - MSL vehicle was designed for 23m chute, 23m chute was tested in low-speed wind tunnel)

Potential to "buy back" all or nearly all of the altitude cost

Conclusions

- **Attitude initialization error of 0.06-deg., 3-sigma "reasonably conservative" for a future mission with a star tracker**
- **Need range trigger to achieve 3-sigma dispersions in the 4 – 5km class at ignition with an MSL-class vehicle unless winds assumed significantly more benign than "MSL engrg" model**
- **With range trigger, PDG, TRN, and 0.06-deg att init error, can get to ~2-3 km from the target with add'l ~few tens of kg prop**
  - Use of biprop buys back most of the prop cost, allows further improvemt
- **Range trigger improves precision perhaps at some cost in landing site elevation capability**
  - Suggested risk posture protects against sudden wind shift of ~45m/s during chute deploy (perhaps overly conservative?)
  - Multiple paths to "buy back" most / all the altitude cost if necessary

Backup

Achievable Dispersions at Ignition
MSL-Class Vehicle

Illustrative "cartoon"

~4km	**Range trigger, 0.06-deg 3σ att init error**
varies dep on trigger params	**Velocity-constrained range (VCR) trigger, 0.06-deg 3σ att init error**
~8km	**Velocity trigger, 0.06-deg 3σ att init error**
~10-12 km	**MSL: Velocity trigger, 0.25-deg 3σ att init error**

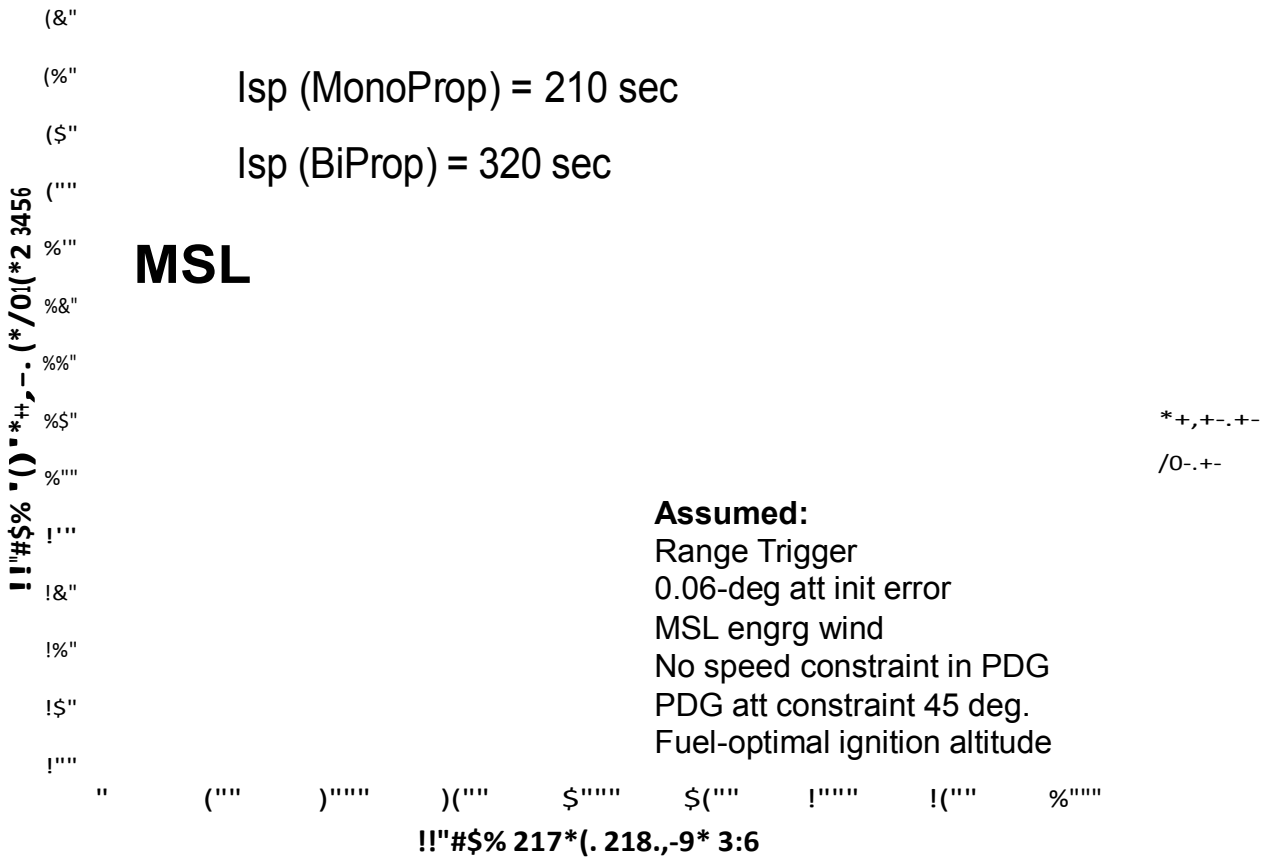
Prop Cost to Divert (Monoprop and Biprop)

Isp (MonoProp) = 210 sec

Isp (BiProp) = 320 sec

MSL

Assumed:
Range Trigger
0.06-deg att init error
MSL engrg wind
No speed constraint in PDG
PDG att constraint 45 deg.
Fuel-optimal ignition altitude



Conservatism in above results:

- Powered approach prop consumption not accounted for in computation of prop consumed in late phases (~15kg improvement?)
- Height of constant velocity “accordion” assumed 200m – could be less with TRN (~15 kg improvement?)

Why is Altitude Cost of Range Trigger Important?

- **Need range trigger for precision landing**
- **With same landed mass, may not be able to precision-land fetch rover at elevation of cached sample**

Velocity trigger

Range trigger

Altitude cost of range trigger

Cached sample

Sample collection mission (2018)

Max. site elevation with range trigger

Fetch rover + MAV mission

Mitigations:

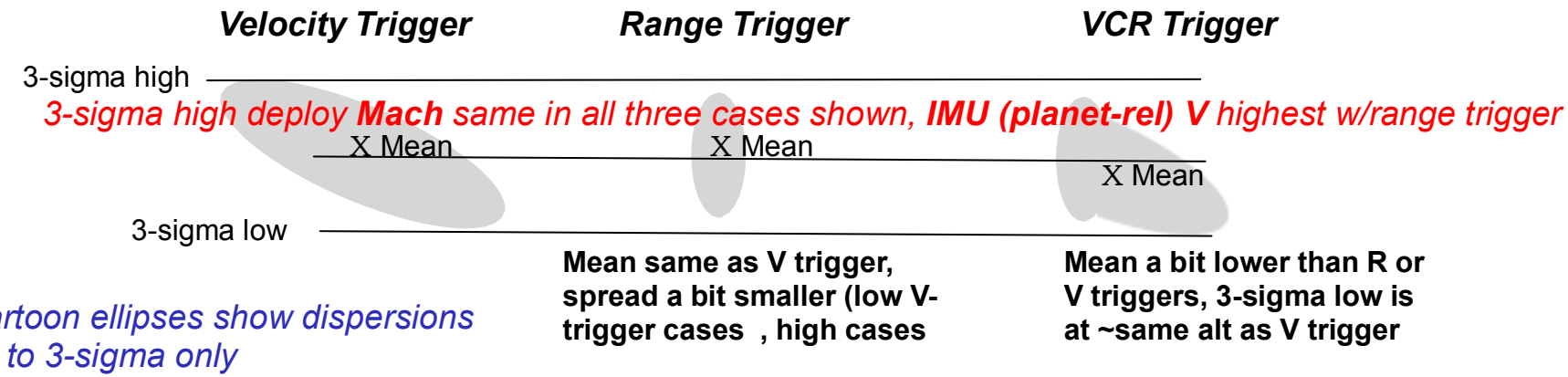
- Land 2018 mission at elevation which can be reached w/range trigger
- Limit or “buy back” alt cost of range trigger with various measures

Near-term need:

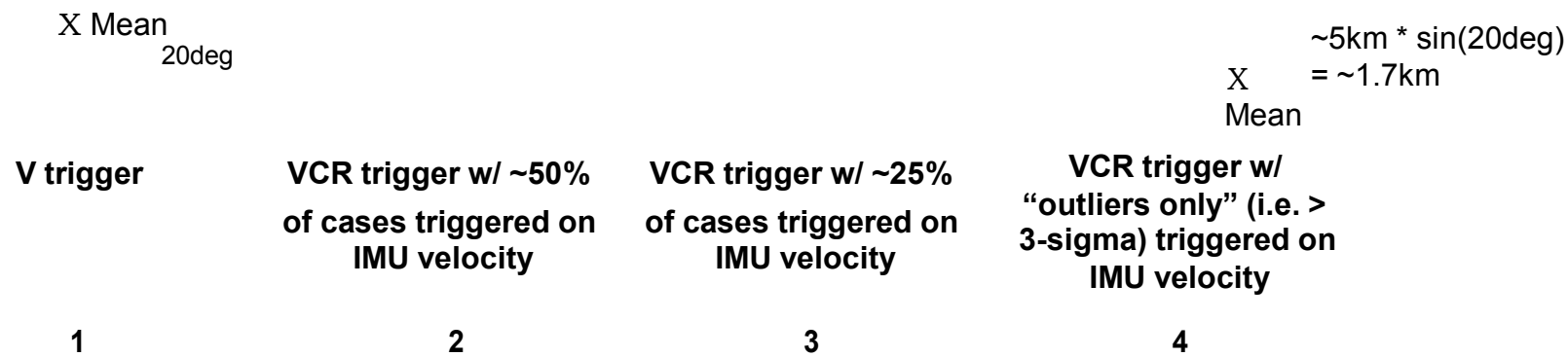
- Need to be able to quantify site elevation capability of lander system

Altitude Cost of Range Trigger (1)

- **Range trigger has no inherent altitude cost as modeled in sims**



- **Reduce alt to trigger +/- 3σ cases on range without increasing 3σ-high planet-relative (IMU) velocity**



*3-sigma high **IMU velocity** same in all illustrated cases, 3-sigma **Mach** lower for cases 3 & 4*

Introduction

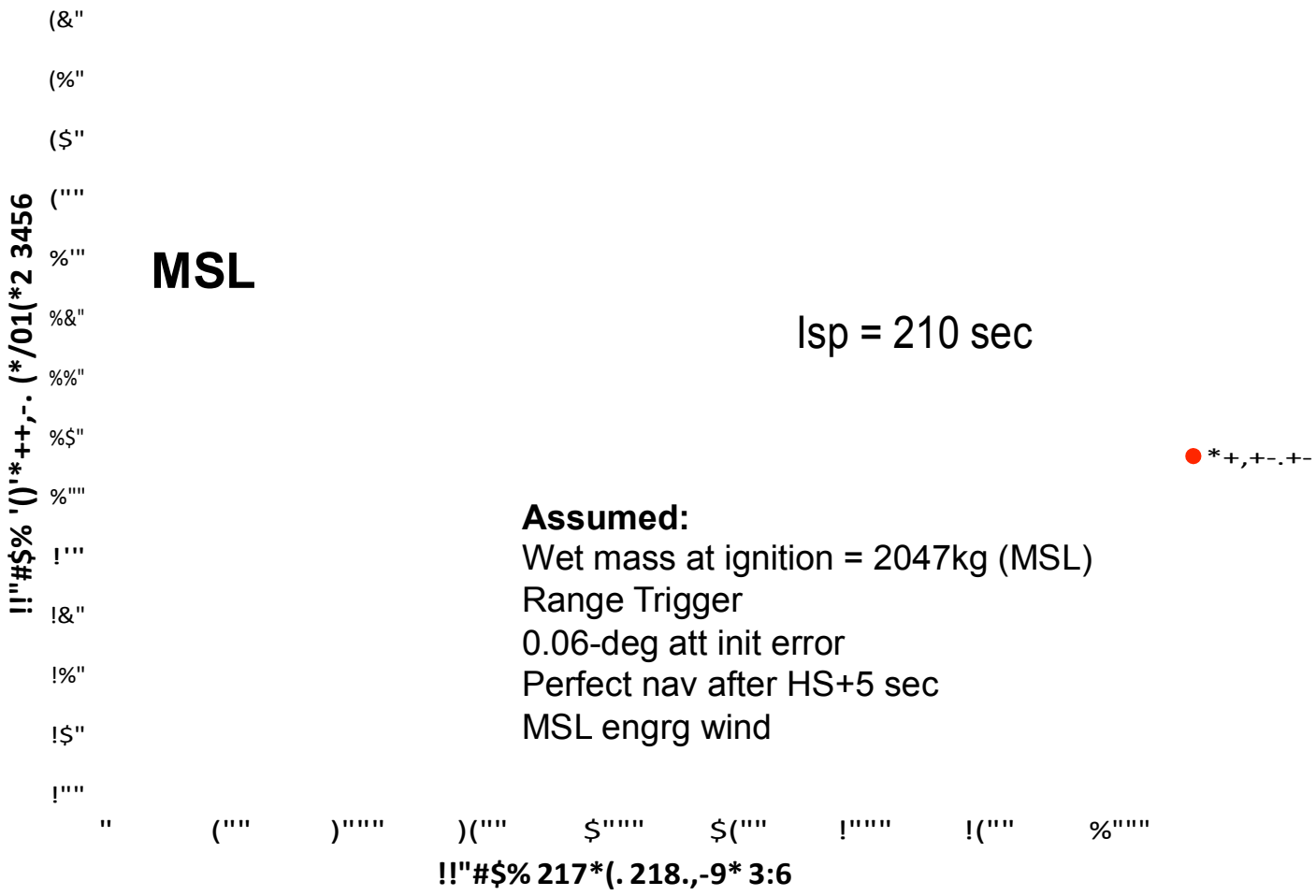
Historical landing precision capability

Mission	Landing ellipse semimajor axis (dist to target), 3σ (km)	Comments
Mars Pathfinder (1997)	150	Ballistic entry (no lift)
Mars Exploration Rover (2003)	~40 km	Ballistic entry (no lift), improved apch nav
Phoenix (2007)	~40 km	Ballistic entry (no lift), improved apch nav
Mars Science Laboratory	~10 km	Offset CG generates lift (constant AOA) which is used with entry guidance to null atmospheric and vehicle aerodynamics uncertainties

How to get to 2 – 3 km (or less) from the target?

- **What is an "MSL-class" vehicle?**
  - Guided entry
  - "Skycrane" configuration (descent stage + 900kg rover)
  - Single 21.5-m diameter disk / gap / band parachute
  - …
- **What can we change without violating "MSL-class" paradigm?**
  - Parachute triggering scheme
  - New powered descent guidance
  - Addition of terrain-relative nav
  - Substitution of star tracker for star scanner
  - Perhaps some extra prop?

Total Propellant Mass vs. Divert Distance (MonoProp)



Velocity-Constrained Range (VCR) Trigger

(credit: M. Ivanov)

Cases shown have 0.25-deg. att init err

= Velocity Trigger Cases
= VCR Trigger Cases

Guidance Target

"Real" Target

w/VCR trigger, "Slower" cases deploy at target range instead of up to several km uprange

~6 km ~6 km

"Faster" cases wait to reach Vhigh before deploying (at same velocity as w/V trigger)

VCR Trigger Range Statistics "Asymmetric"

	Vel Trigger	VCR Trigger
DRerror (3σ; km)	-10.0/10.1	-1.3/10.1
CRerror (3σ; km)	-3.6/3.7	-3.7/3.8
ALTerror (3σ; km)	3.0/-3.3	2.5/-3.3

Range Trigger Altitude Penalty Cases ("drop in" waiting for range)