Post-Flight EDL Entry Guidance Performance for the 2011 Mars Science Laboratory Mission

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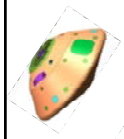
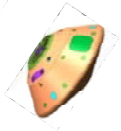
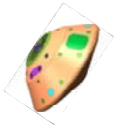
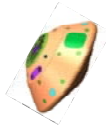
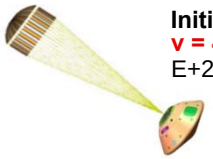
Introduction

- Mars Science Laboratory landed Curiosity in Gale Crater on 5 Aug 2012
  - First Mars guided entry to a touchdown ellipse of 19 x 7 km, landing 2.2 km away from the expected target

- Entry guidance is derived from the Apollo capsule “final phase” logic and adjusts the range flown during entry by varying the direction of the lift vector (i.e., bank angle)
  - Flight proven algorithm with minor modifications
  - Algorithm consistently met ellipse size requirements and performance constraints since conceptual development in 2000

Guided Entry Phases

Mars Science Laboratory

Event Description & Nominal State	Phase	Guidance Actions
 **Maneuver to Attitude Hold After Cruise Stage Separation** **Prior to EI-9 min**  **Entry Interface Occurs** E+0 sec, h=126km, range=632 km, inertial vel=5845 m/s, inertial FPA=-15.47 deg	**Pre-Bank**	• Attitude hold at a ground-commanded bank angle until Range Control Phase starts
 **Begin Range Control Phase** **Filtered drag acceleration ≥ 0.2g** E+51 sec, h=52km, range=350 km, M=29, relative vel=5839m/s  **Peak Heating Occurs** E+63 sec, h=39 km, range=283 km, M=24, v=5606 m/s, load=4g  **Peak Loading Occurs** **Load = 12.5 g** E+80 sec, h=23 km, range=200 km, M=19, v=4189 m/s	**Range Control** *(Start of Guided Entry)*	• Command bank angle magnitude to minimize predicted downrange error at deployment • Command bank reversals to manage crossrange error
 **Begin Heading Alignment Phase** **v = 1100 m/s** E+136 sec, h=14 km, range=83km, M=5, load=1.7g	**Heading Alignment**	• Command bank angle to minimize residual crossrange & maximize deploy altitude
 **Initiate Chute Deploy Sequence** **v = 406 m/s** E+259 sec, h=12 km, range=5 km, M=1.7	**Chute Sequence** *(End of Guided Entry)*	• Initiate sequence on velocity trigger to prepare for chute deploy

MSL Telemetry

Range Control Logic Overview

- Apollo final phase controls to terminal range and velocity target using pre-derived influence coefficients with respect to errors about a nominal reference trajectory that ends at parachute deploy
- Reference trajectory defined by range-to-go, drag acceleration, and altitude rate as a function of relative velocity
- Commanded bank angle varies to control range based on deviations in predicted range, altitude rate, and drag from a reference trajectory

Predict Current Range:

$$R_p = R_{ref} + \frac{\partial R}{\partial D}\left(D - D_{ref}\right) + \frac{\partial R}{\partial \dot{r}}\left(\dot{r} - \dot{r}_{ref}\right)$$

Find Commanded Vertical L/D Required to Converge Range to Target:

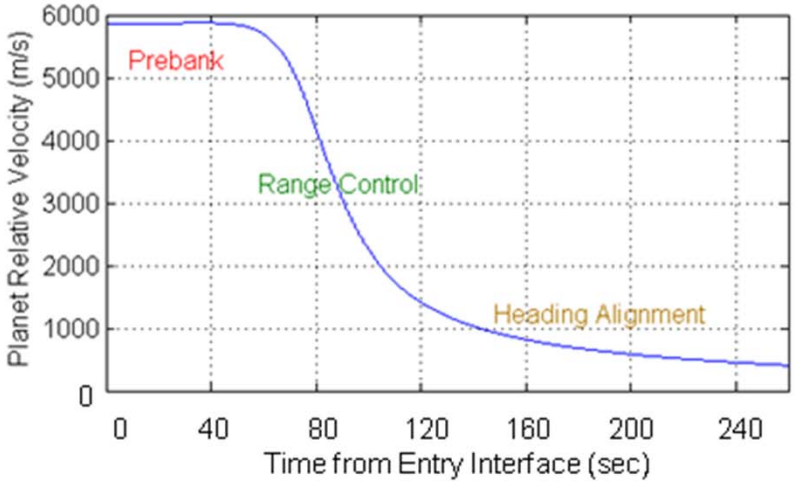
$$\left(\frac{L}{D}\right)_{v,c} = \left(\frac{L}{D}\right)_{v,ref} + \frac{K_3\left(R - R_p - R_{dep}\right)}{\partial R / \partial\left(L/D\right)_v}$$

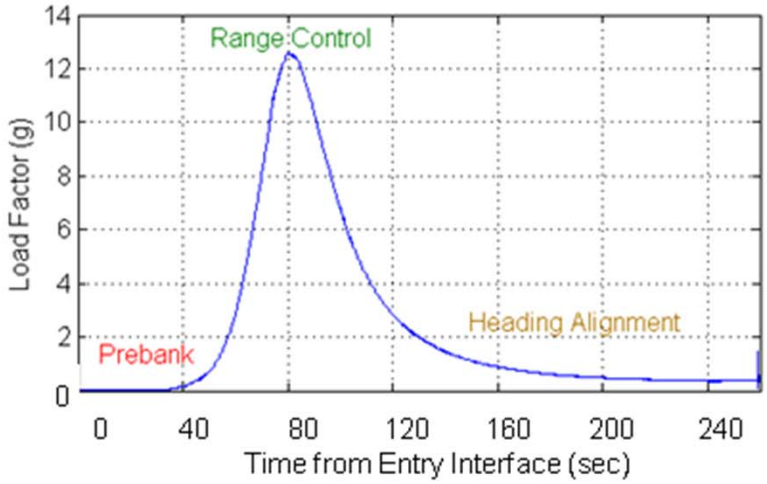
Bank Required For Commanded L/D:

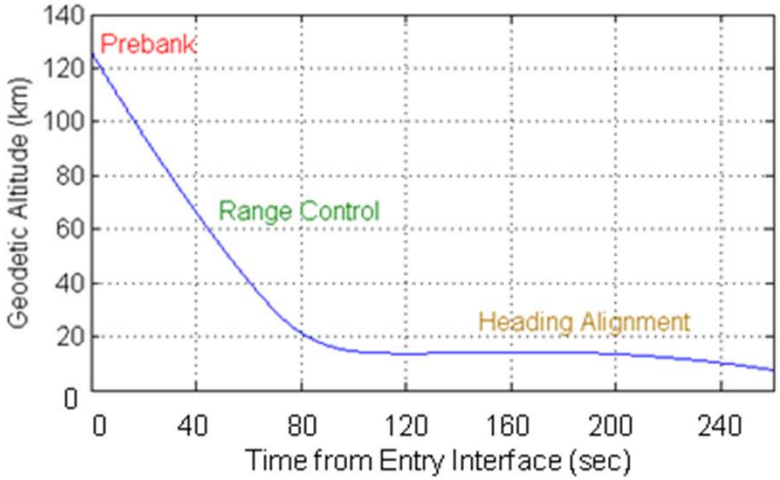
$$\Phi_C = \cos^{-1}\left(\frac{\left(L/D\right)_C}{\left(L/D\right)}\right) \times K_2$$

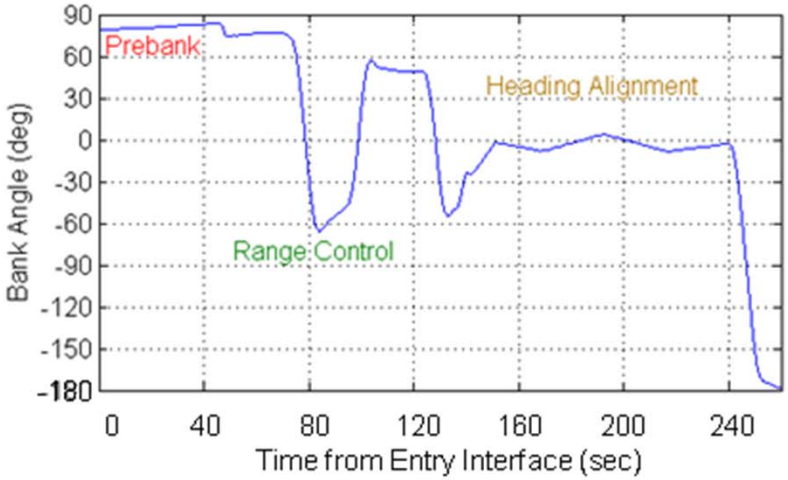
R	Range to Target
R_p	Range, predicted
R_{ref}	Range, reference
R_{dep}	Range, deploy bias
D	Drag
D_{ref}	Drag, reference
L	Lift
r	Altitude Rate
r_{ref}	Altitude Rate, ref
$\dot{K}_3$	L/D over-control gain
$\dot{K}_2$	Bank left/right control

MSL Reconstructed Entry Trajectory





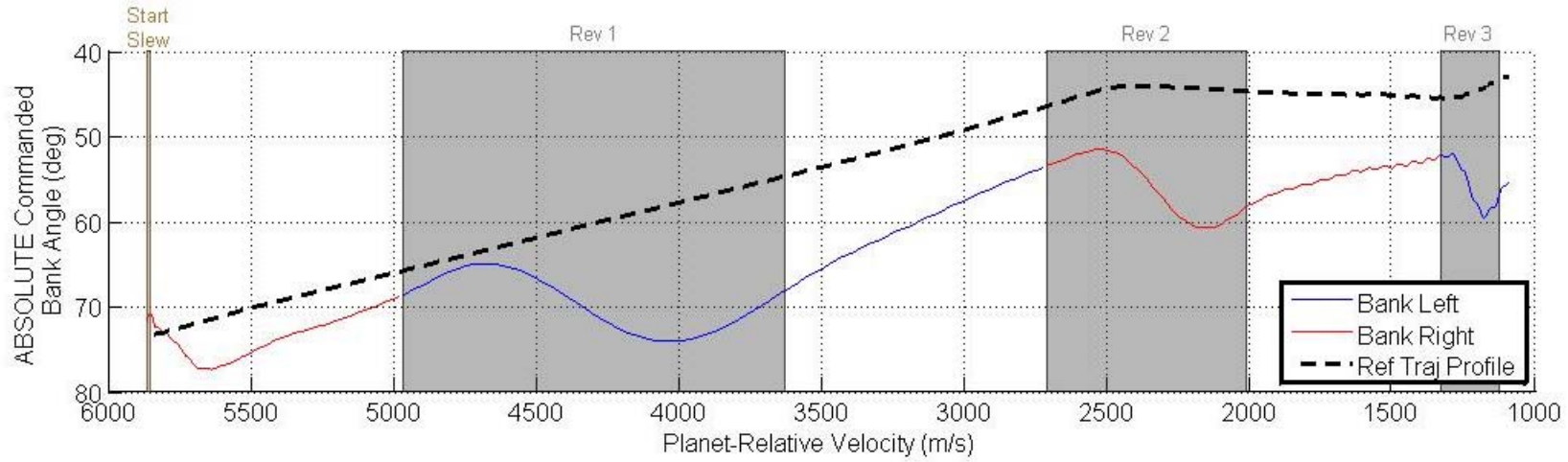




Commanded Bank Angle Telemetry

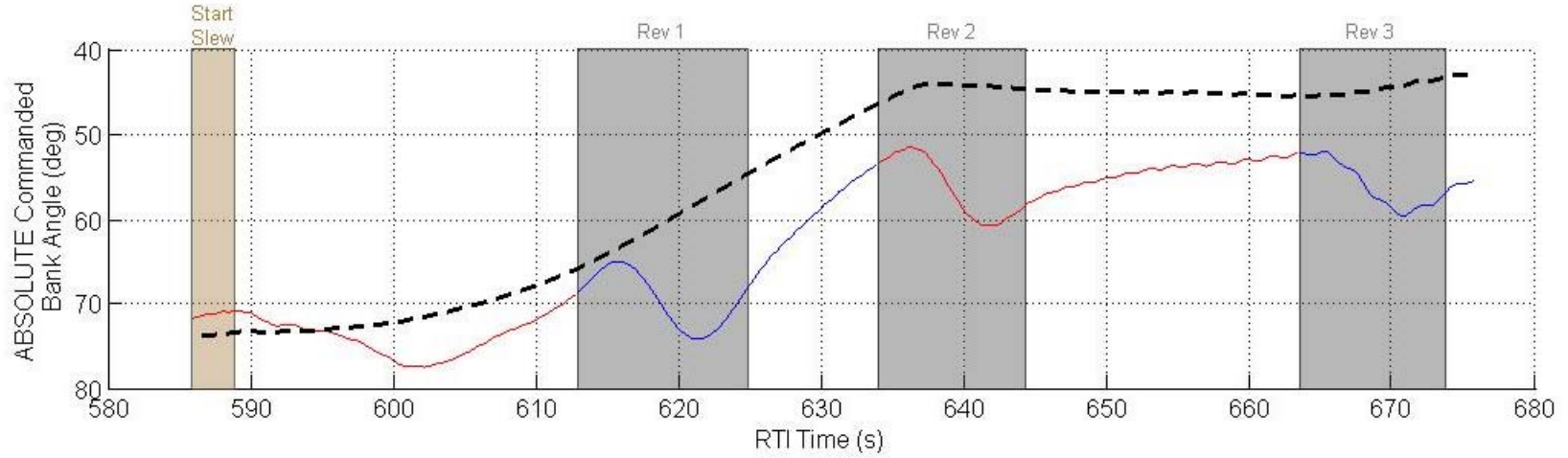
If Landing Short

If Landing Long



If Landing Short

If Landing Long

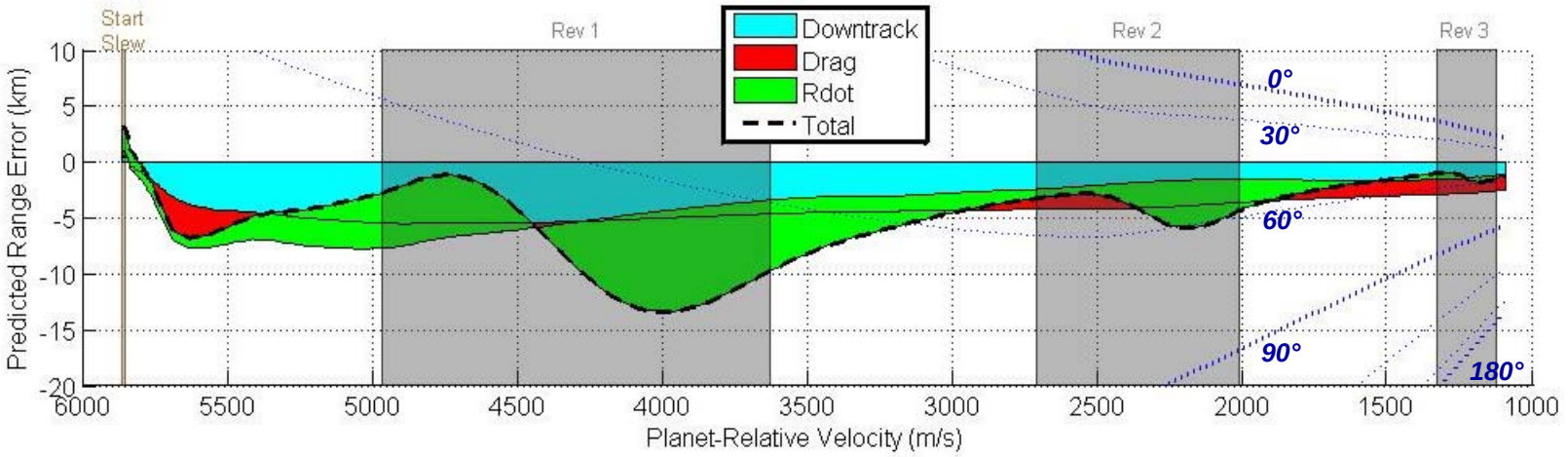


Range Error Components Telemetry

$$R_{error} = \left(R - R_{ref} - R_{dep}\right) - \frac{\partial R}{\partial D}\left(D - D_{ref}\right) - \frac{\partial R}{\partial \dot{r}}\left(\dot{r} - \dot{r}_{ref}\right)$$

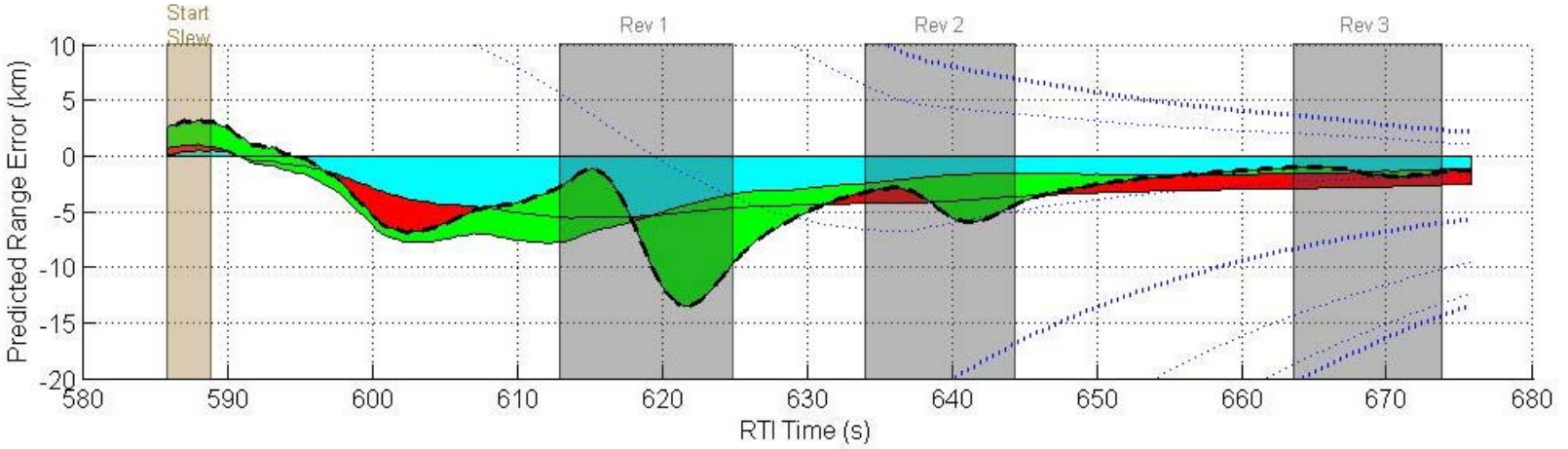
If Landing Short

If Landing Long

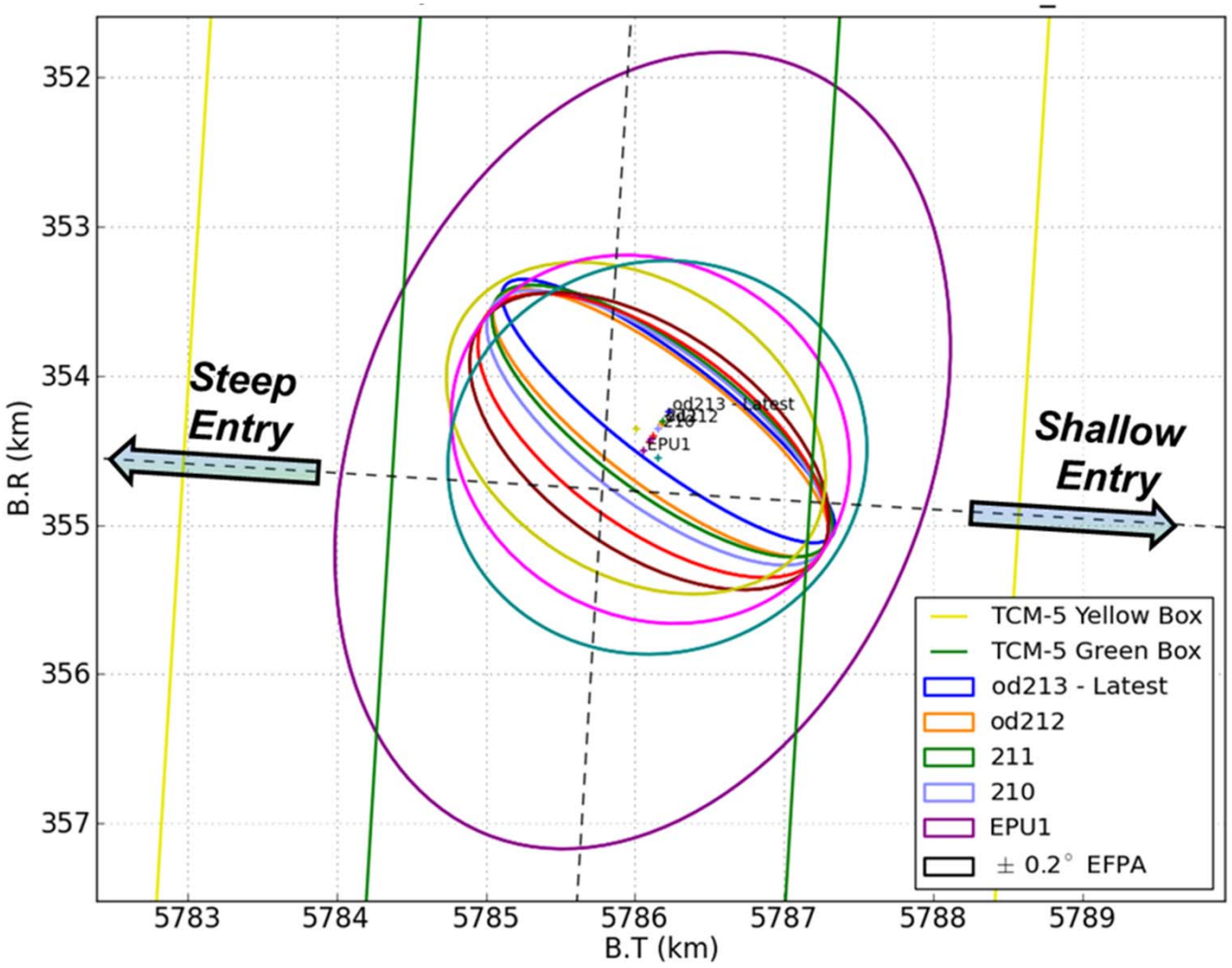


If Landing Short

If Landing Long

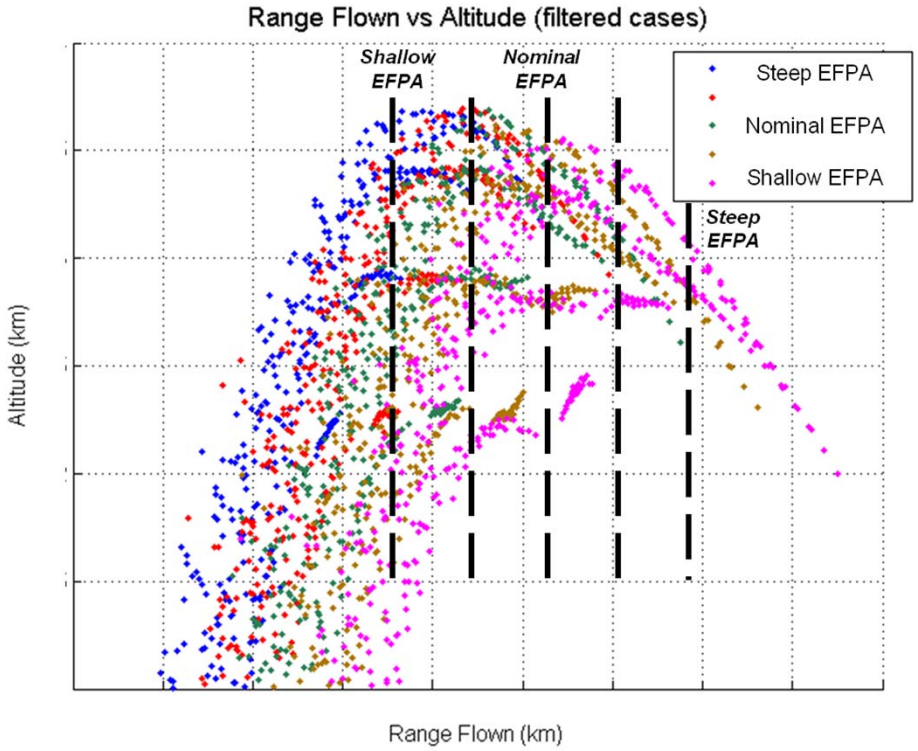


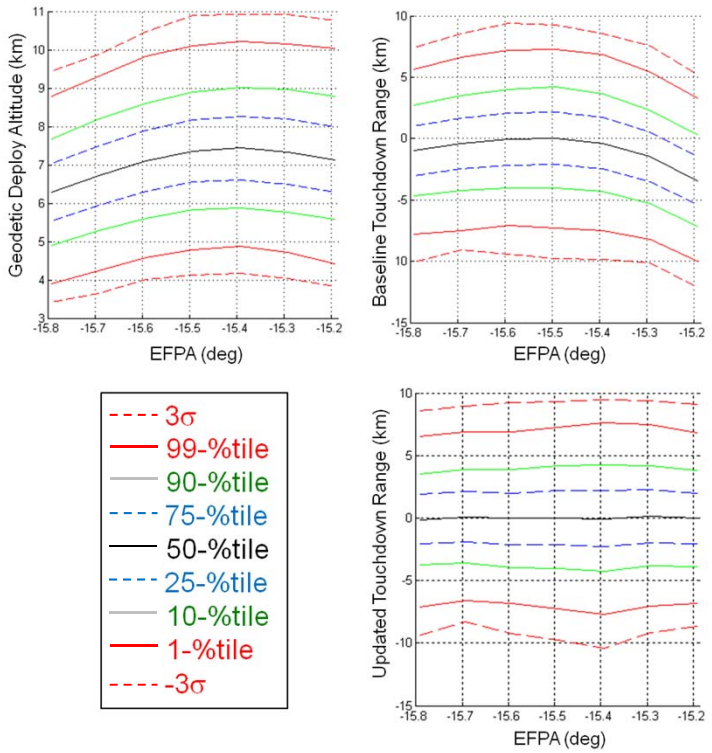
Delivery Uncertainties from Entry -8 to -1 days



Operations Planning for Delivery Errors

- For a given atmospheric entry point, what guidance reference trajectory will perform well to reach the intended landing site?
- Evaluated thousands of combinations before settling on a small number of different guidance gain sets to be chosen via the predicted entry flight path angle (EFPA)



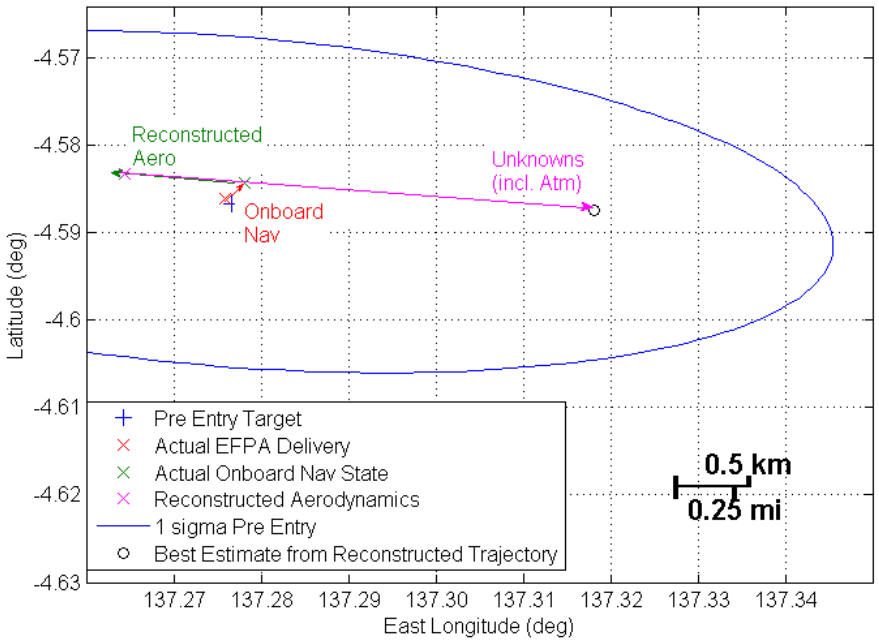


Contributions to Landing Site Error

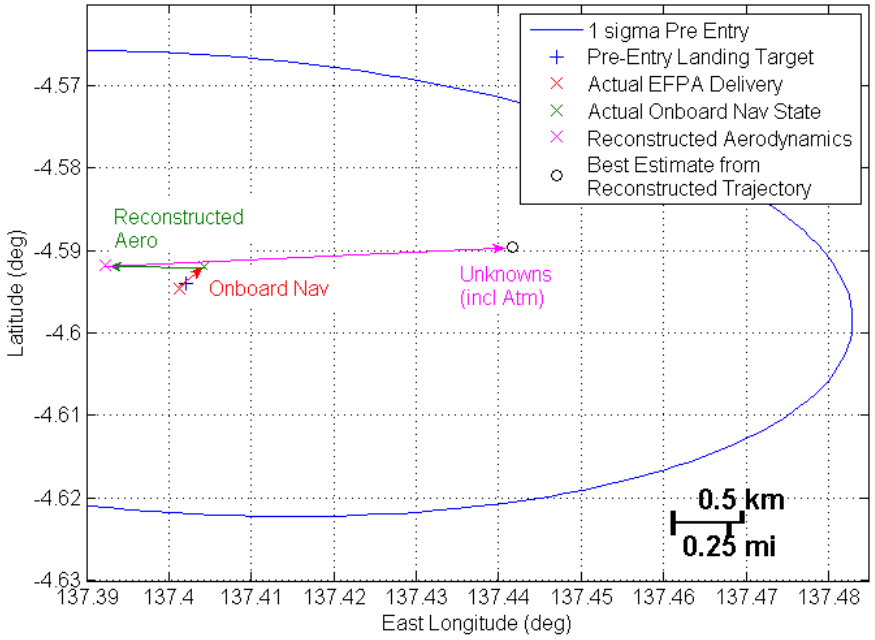
Source Data	Guidance Prediction, Relative (km)	Delta (km)	Downrange at Deploy, Relative (km)	Delta (km)	Downrange at Landing, Relative (km)	Delta (km)
Monte Carlo of Pre Entry Trajectory	0.0	--	0.0	--	0.0	--
+ Actual EFPA Delivery	0.0	0.0	0.0	0.0	0.0	0.0
+ Actual Onboard Nav State	-0.1	-0.1	-0.1	-0.1	-0.1	-0.2
+ Reconstructed Aerodynamics	0.5	0.5	0.7	0.8	0.6	0.7
Best Estimate from Reconstructed Trajectory	-0.6	-1.0	-2.4	-3.1	-2.3	-2.9

Negative values are downrange past the target

Parachute Deploy



Touchdown



Summary & Forward Work

- Curiosity landed successfully only 2.2 km away from the expected target given the onboard navigation state
  - Better than the average Apollo capsule splashdown miss distance
  - A late bank reversal and a suspected tail wind contributed to this slight miss
- Refinement of the guidance gains and alternative parachute deploy triggers to reduce the ellipse size will be studied for future Mars landing missions