Pinpoint Landing Technology Assessment

MSR Technology Workshop

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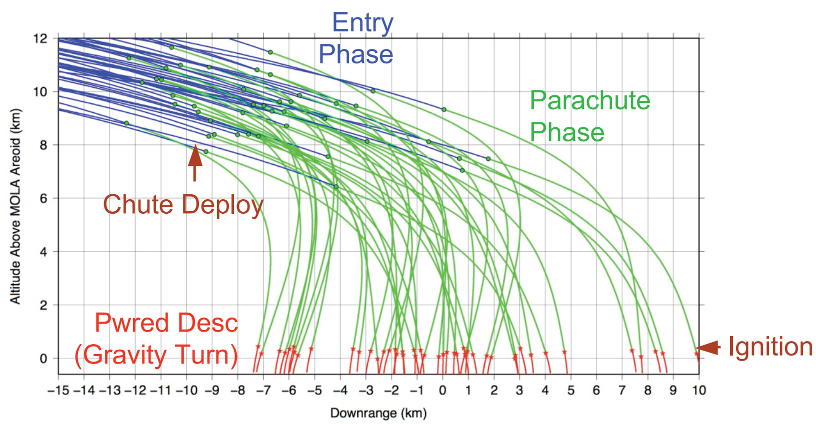
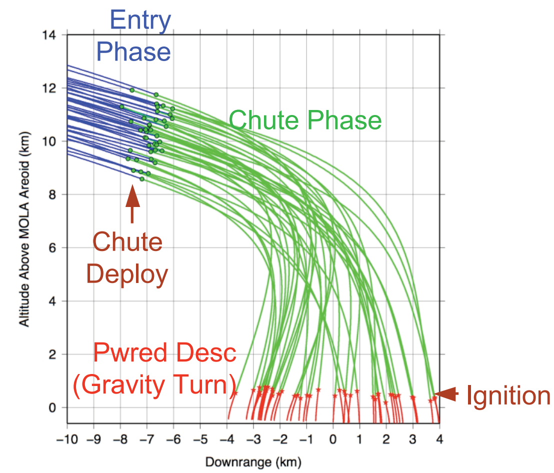
Introduction

- Better approach nav (and "quieter" s/c) improved landing precision from ~150km semimajor axis (Mars Pathfinder) to ~40km (MER)
  - MSL baseline (performance ~equivalent to MER): ~1km 3-sigma knowledge uncertainty at entry, DSN radiometrics only
- Hypersonic entry guidance (based on Apollo's, bank-only control) improves MSL landing precision to ~10km by "flying out" uncertainties in atm modeling and aero coefficients
- **Further reduction (to 2 – 3km? 100m?) requires multiple improvements**
  - **Approach navigation**
  - **Attitude knowledge** (assumed no tech devel needed)
  - **Entry guidance "endgame" (chute deployment strategy)**
  - **Onboard navigation with multiple data types**
  - **Terrain-relative navigation**
  - **Powered descent guidance**
- **Major challenge: propellant mass penalty!**
  - **Reducing this requires minimizing delivery error at powered descent ignition (which includes wind drift)**

Technology Options

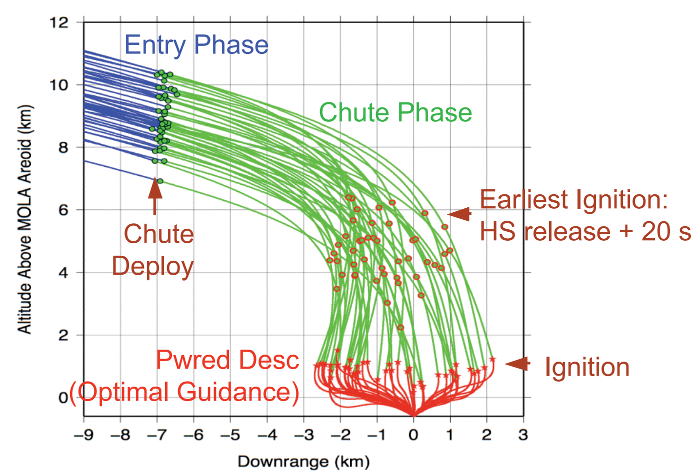


MSL (Doppler, range, DDOR):
~**10km** from target



Improved chute deploy strategy +
improved entry att. knowledge =>
~3 - 4km from target

Improved chute deploy strategy + improved
apch nav (not shown here) + improved entry
att. knowledge (not shown here) + terrain-
relative nav + powered desc guidance =>
≤~100m from target

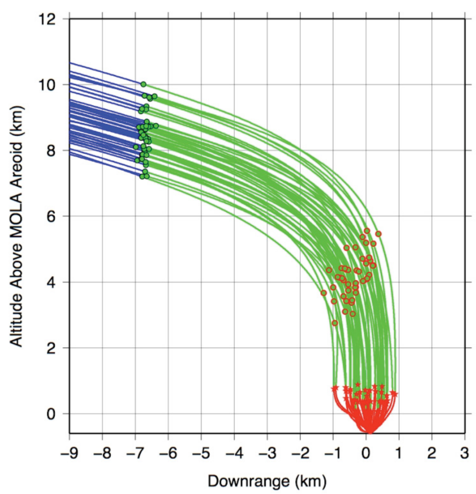


Approach Navigation

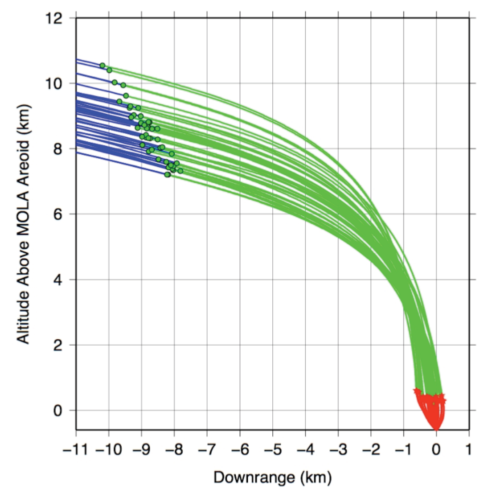
- **Recent history**
  - MSL baseline: DSN Doppler, ranging, DDOR
  - Small OPNAV camera successfully demonstrated on MRO
  - Use of UHF for landed ops (MER, PHX) and EDL comm (PHX)
  - MTP tasks: S/C-S/C Nav (LMA): EKF to TRL4, Orbiting Beacon Navigation for Pinpoint Landing (JPL, UT Austin): IMU+UHF Doppler processed in Electra to TRL5
- **Development options:**
  - **S/C-S/C radiometrics (onboard or ground-based)**
    - UHF link works out to ~100000 - 200000 km,
    - X-band works out to ~6M km - not demonstrated to date
    - Strength: Performance ≥ OPNAV with ~no impact on s/c configuration
    - Weakness: Need long-term commitment to orbiter network, receivers
  - **OPNAV (onboard or ground-based)**
    - Strength: Carry it with you (no dependence on any other assets)
    - Weakness: Need increased knowledge of Phobos / Deimos ephimerides, surface landmarks; impacts s/c configuration (e.g. difficult to implement on a spinner)
  - **Differential S/C-S/C** (DSN tracks both lander and orbiter or previously landed asset at Mars)
  - **Use of the MSR rover as a radio "beacon"?**

Entry Guidance "Endgame"

- Recent history
  - "Smart Chute" developed but not used on MSL
- Development options: Any strategy that can produce propellant savings
  - "SuperSmart Chute" - use knowledge in entry phase and prediction of chute phase trajectory to better choose chute deploy point



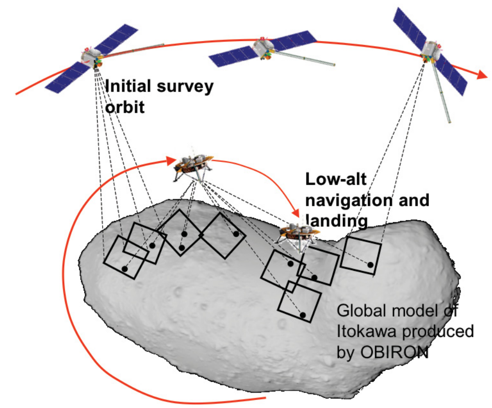
Smart Chute



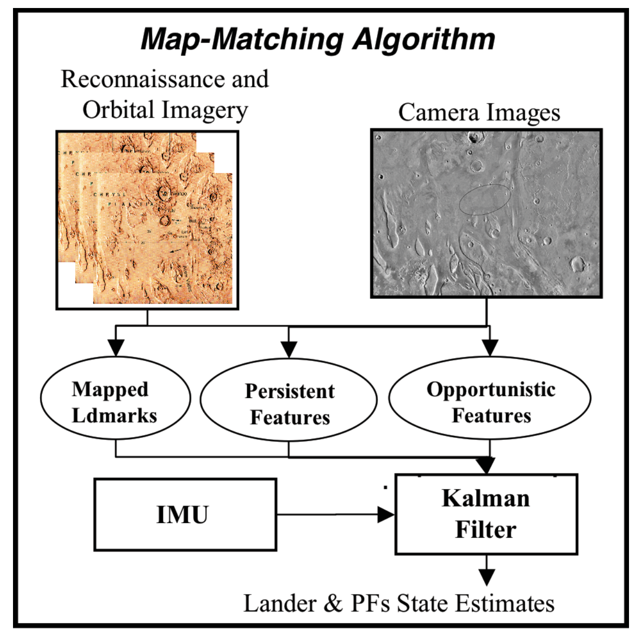
SuperSmart Chute

Terrain-Relative Navigation

- Recent history
  - ALHAT: Field testing / high-fidelity simulation of lidar and passive imaging approaches for lunar ldg (JSC, JPL, LaRC, Draper)
  - Mars Technology Program "Coupled Vision and Inertial Navigation for Pin-Point Landing" task (U. Minn and JPL)
  - ST9: passive imaging on 41.068 sounding rocket test flight 4/06 (JPL, Wallops, LaRC)
  - MER: DIMES used to estimate horizontal vel at touchdown, used for onboard decision to fire TIRS thrusters
  - OBIRON algorithm (JPL) used for ground-based postflight nav reconstruction (NEAR, Hayabusa) and map-tie error reduction on Mars
- Suggested tech development
  - Evaluate various approaches in light of MSR criteria (performance, computational load, development cost)



OBIRON at Itokawa

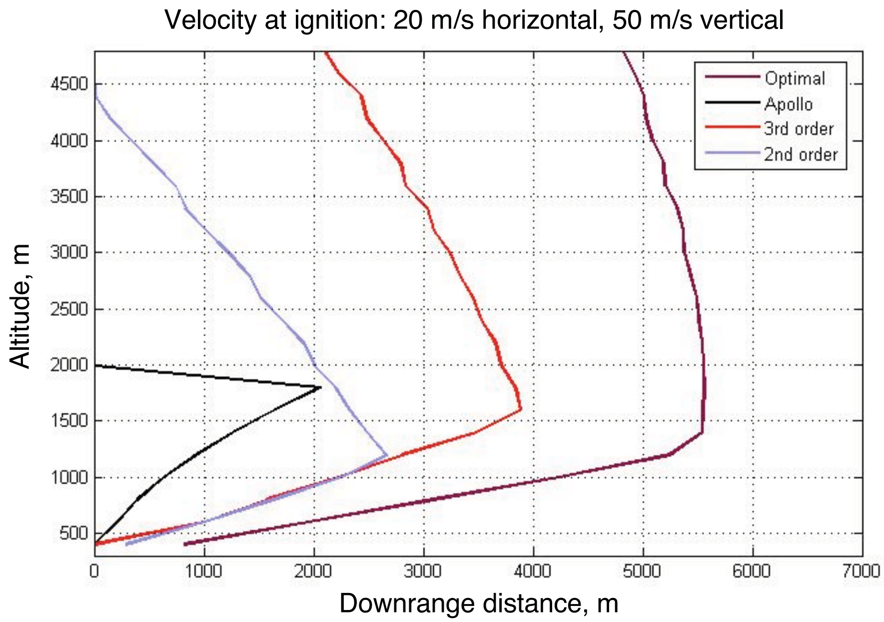


Onboard Navigation

- Recent History
  - MSL, PHX: IMU + radar only
  - Mars Technology Program “Coupled Vision and Inertial Navigation for Pin-Point Landing” task (U. Minn and JPL) - IMU + imaging in EKF at TRL4
  - Onboard navigation algorithm for ALHAT (UT Austin / JSC)
  - MTP “Orbiting Beacon Navigation for Pinpoint Landing” task (JPL, UT Austin): IMU+UHF Doppler processed in Electra to TRL5
  - MTP “Adaptive On-Board Navigation for Pinpoint Landing” task (UT Austin, JPL): IMU-only adaptive filtering
- Development needed
  - Capability to estimate position, velocity, and attitude onboard **using all available data types** (IMU + radar + imaging or other terrain-relative navigation)

Powered Descent Guidance

- Recent History
  - MER: Solid rockets + airbags (no help here..)
  - MSL: Doesn't target to preselected landing site
  - Apollo lunar landing guidance: Fuel consumption prohibitively high for Mars Pinpoint Landing
- Development needed: Near-ΔV-optimal performance needed to minimize ΔV "penalty" of Pinpoint Landing



Spacecraft:
Wetmass = 1308 kg Fuel = 214 kg Max. Thrust = 3000 N Num. of thrusters = 6 Cant angle = 25 deg Throttle = 0.15 -> 0.95 Isp = 225 sec
Constraints:
1. No subsurface flight 2. Boundary conditions 3. Glide-slope 4. Angular Velocity 5. Thrust Direction

Challenges and Decision Criteria For MSR

- Performance = ability to reduce amount of propellant required to meet 100-m Pinpoint Landing requirement
- Computational loading in onboard computer
- Development cost (including V&V, testing programs)

Challenges and decision criteria are the same

Rough Schedule

- Year 1
  - Algorithm development / downselect from available options
  - Definition of requirements and plan for field testing / V&V
- Year 2
  - Development of algorithms / FSW for flightlike simulations and / or field testing
  - Development of flightlike simulation testbed and field test H/W
- Year 3
  - Algorithms validated at TRL6 via mix of flightlike simulations and field testing

End-to-end PPL System Validation Strategy

System / Subsystem Field Tests

- data collection for analysis
- open-loop real-time FSW execution
- sensor characterization

Key challenge: "Test as you fly - Fly as you test"

- Sensor Data & Model Validation
- Scenes & Maps

HWIL / Simulation Testbed

- end-to-end system tests
- exercises closed-loop system (incl. guidance & control)

Key challenge: Flight-like timing

TRL6 : System /subsystem model or prototype demonstration in a relevant environment (ground or space)

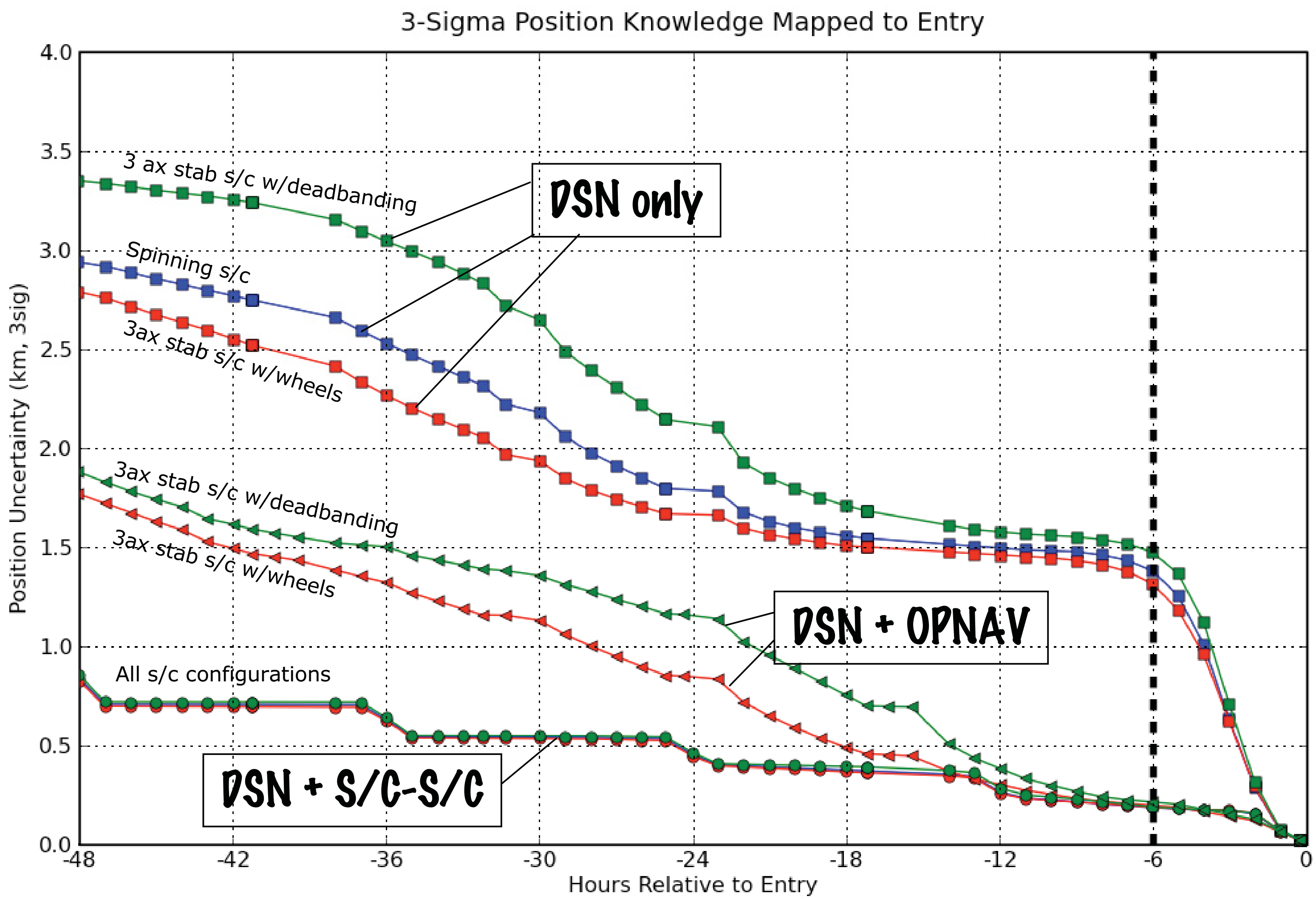
Conclusions

- Multiple technology developments are needed for Pinpoint Landing
- Issues / questions:
  - How much can be leveraged from ALHAT and other experience?
  - What should the test program look like? (Close the loop w/powered descent guidance?)
- 800-lb gorilla issue
  - How much propellant cost is “too much” (and could result in deletion of Pinpoint Landing from the MSR baseline)?

Backup

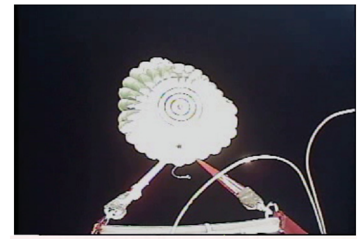
Approach Navigation Performance Comparisons

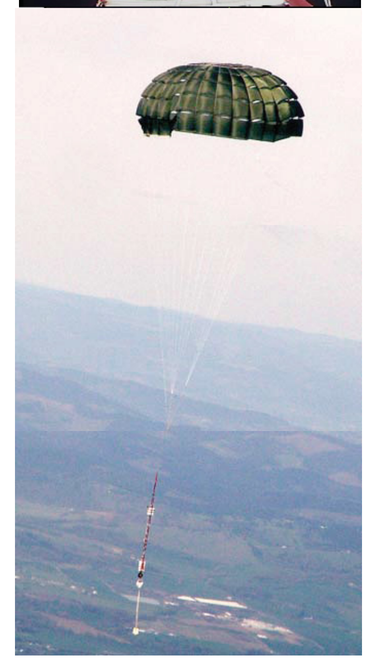
Credit: Dolan Highsmith, JPL



Steerable Parachute

- Recent history
  - Affordable Guided Airdrop System (AGAS) tests for military use (Vertigo)
  - MTP Mars Guided Parachute Design and Flight Test task (Boeing, Irvin, Vertigo): Beagle chute + AGAS control system drop-tested at Mars-relevant density (L/D=0.25 - .45)
  - Preliminary design studies in 2004 (Pioneer, Vertigo)
- Technology needed
  - Subsonic chute capable of directional control without turning
    - Strength: **Could significantly reduce propellant penalty of Pinpoint Landing)**
    - Weakness: Cost of development and testing program (~$10s of M), additional complexity of 2-chute operation





Rough Schedule (1/2)

(detail developed for PPL Tech Devel Program cancelled in FY05)

	End of Year 1	To TRL6 (End of Year 3)	To Flight
PPL Mission Design	• Initial PPL operating envelope, end-to-end error budget & sensitivity analysis • Approach navigation requirements definition and trades	• PPL Reference Mission Design • Refinement of PPL operating envelope & error budget • Reference Approach Navigation implementation	• Adaptation of Reference Mission Design & Approach Navigation to 2011 Testbed Lander
PPL System Design	• Key PPL system & testbed requirements • Refinement of PPL Validation Plan • Initial Avionics & GNC architecture	• PPL Reference System Design (incl. requirements & i/f) • Test & Validation PPL Reference System to TRL6	• Adaptation of PPL System Design to 2011 Testbed Lander • PPL System V&V plan & execution
Algorithm - Terrain Rel. Nav.	• Algorithm performance studies and downselect from available options • Mars map building requirements and approach	• Selected algorithm validated at TRL 6 • Landmark map construction validated with Mars data and test data and at TRL 6	• Landmark recognition flight like code delivered to FSW • Algorithm SW performance evaluation with flight camera simulator and EM camera
Algorithm - Powered Descent GNC	• Preliminary powered descent integrated GN&C architecture and interface • Preliminary powered descent guidance design formulation & prototype matlab based optimal guidance planner • 6-DOF estimator architecture, interface & requirements definition	• Guidance and estimator algorithms validated at TRL6 • Integrated GN&C capability demonstration	• GN&C powered descent flight software delivery • GN&C performance validation in FSW testbed/DSENDS, and system I&T

Rough Schedule (2/2)

(detail developed for PPL Tech Devel Program cancelled in FY05)

<table>
<tr><th></th><th>End of Year 1</th><th>To TRL6 (end of Year 3)</th><th>To Flight</th></tr>
<tr><td>Descent Camera</td><td>• Refinement of descent camera requirements
• Completion of make/buy decision and implementation approach</td><td>• Design, build, test and deliver 3 EM descent cameras
• Descent camera simulator</td><td>• Build, test and deliver 2 FM descent cameras for 2011 testbed lander</td></tr>
<tr><td>System Validation Testing</td><td>Terrain Relative Navigation System (open-loop field tests):
• First development test to demonstrate end-to-end terrain relative navigation (landmark recognition, map building, real-time)
• Design of COTS Sensor Field Test (SFT) avionics consistent with I&T avionics and most field tests

End-to-end System (Closed-loop ITL):
• Definition of simulation requirements & level of inheritance</td><td>Terrain Relative Navigation System (open-loop field tests):
• Terrain relative navigation system (landmark recognition, navigation filter, sensors) tested numerous times in relevant environment (TRL6)

End-to-end System (Closed-loop ITL):
• Verification and Validation of the end-to-end Pinpoint Landing system in a relevant test environment (TRL6)
• PPL Flight Software functional and requirement testing</td><td>Terrain Relative Navigation System (open-loop field tests):
• Terrain relative navigation system (landmark recognition, navigation filter, sensors) tested numerous times in flight-like environment as part of system
End-to-end System (Closed-loop ITL):
• System Verification and Validation in a closed-loop, hardware in-the-loop environment
• PPL Flight Software functional and requirement testing</td></tr>
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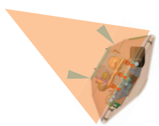
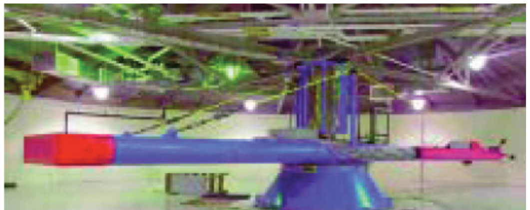
End-to-end PPL System Validation Strategy - Trade Space

System / Subsystem Tests

Hypersonic Entry Phase





Centrifuge / Rate Table Test

Objective: IMU Characterization

Rocket Sled

Objective: IMU Characterization

Increasing Complexity & Cost →

Parachute Phase

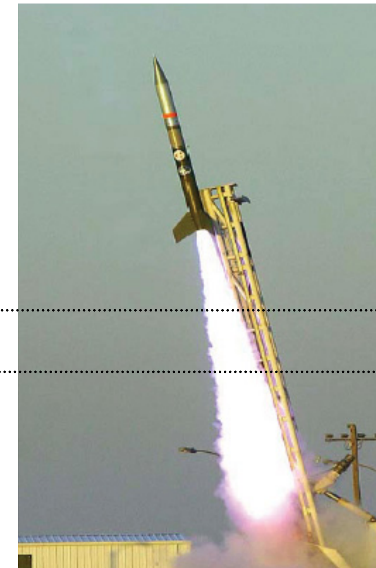
Powered Descent Phase

Helicopter Test

Objective: - Terrain Rel. Navigation
- Terrain data collection (lateral dynamics)

Drop Test

Objective: - Terrain Rel. Navigation
- terrain data collection (vertical dynamics)



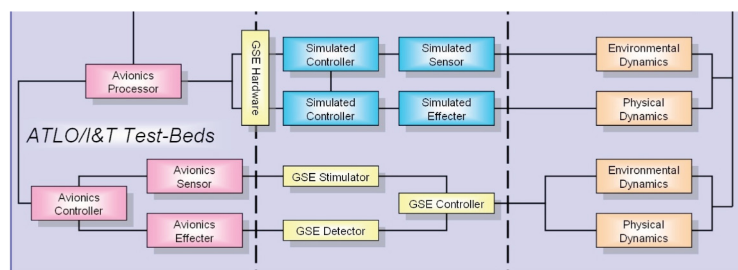
Suborbital Test

Objective: End-to-end Navigation & Sensor Characterization

- Sensor Data & Model Validation
- Scenes & Maps

HWIL Testbed / POST /DSENDS

– end-to-end system tests
– exercises closed-loop system (incl. guidance & control)



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Tech Demos of Interest

- S/C-S/C radiometrics:
  - Ground-based processing of open-loop data MRO, ODY, and Mars Express will record from PHX and MSL on approach (PHX dataset will be available in May ‘08)
  - Collection of two-way Doppler by MRO or ODY on MSL approach (requires pointing by orbiter) with ground-based processing
- Terrain-relative nav:
  - ST9
  - AIM-54 Phoenix missile test
  - MSL reconstruction with MARDI images (or PHX with single descent camera image?)
- Radiometric + IMU reconstruction (+ images)? MER, PHX, MSL
- Differential S/C - S/C radio demo: ground-based processing using data from MRO and ODY, MRO and MSL on apch, and / or ODY and MER on apch

More S/C - S/C Nav Demo Options

- Demonstrate processing of S/C-S/C data onboard MRO (need to upload new s/w to Electra onboard MRO)
- Full-up UHF S/C-S/C nav demo onboard MSL during approach
  - Requires MSL flight s/w changes
  - MRO points to MSL (MSL unable to point to MRO)
  - Can’t do open-loop recording and two-way Doppler collection at same time (open-loop isn’t a credible “backup” if coherent Doppler fails)