Simulations of the Hazard Detection System for Approach Trajectories of the Morpheus Lunar Lander

JPL/Caltech: M. Luna, A. Huertas, N. Trawny, C.Y. Villalpando, K.E. Martin, W. Wilson

NASA JSC: C. Restrepo

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Introduction

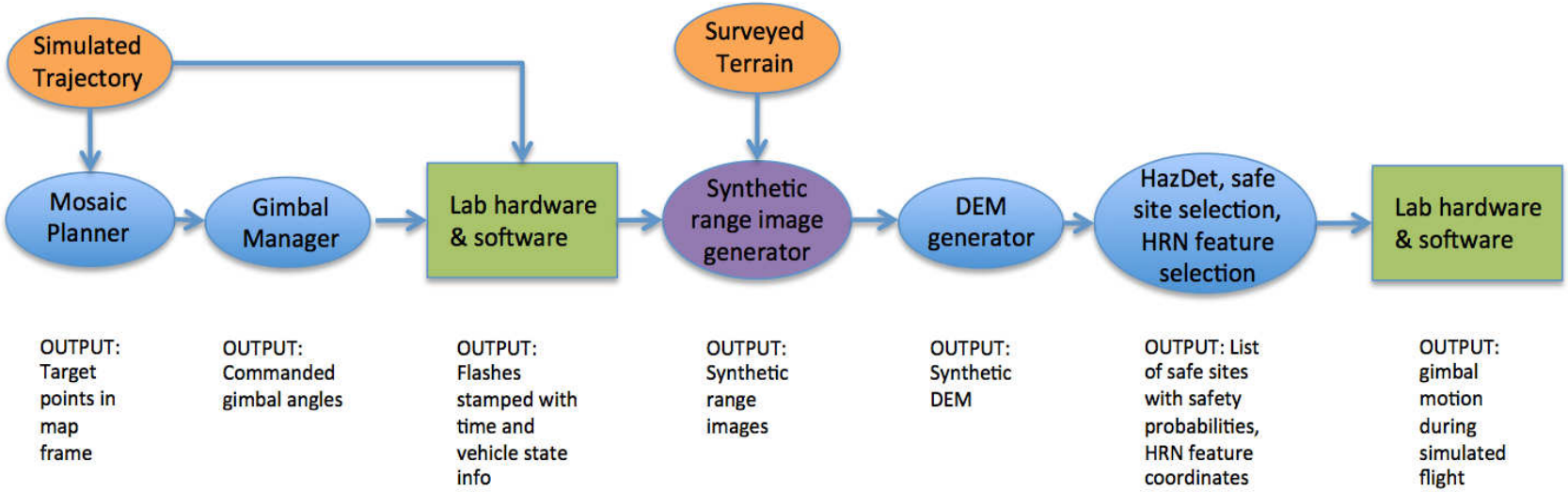
- The ALHAT* system was developed to autonomously land a vehicle on unknown terrain while avoiding hazards
  - Suite of sensors & algorithms to map terrain, identify safe landing sites, navigate host vehicle relative to terrain features
- Hardware:
  - Doppler LIDAR (light detection and ranging) sensor
  - Laser altimeter
  - Hazard Detection System (HDS) (JPL)
    - 2-axis yoke-style gimbal with mounted flash LIDAR sensor
    - Compute Element (CE) box
    - Power Distribution Unit (PDU) and battery box
    - LN-200 Inertial Measurement Unit (IMU)
- ALHAT components mounted on JSC-built Morpheus lunar lander prototype
- Free flights with ALHAT onboard conducted in Spring 2014 at KSC using a lunar-like hazard field
- 2 separate simulations conducted to test HDS functionality
  - Hardware-in-the-loop test w/ actual fight software & lab-based hardware
  - Monte Carlo timing simulation

*Autonomous Landing and Hazard Avoidance Technology

HDS Concept of Operations

- Prior to lift-off HDS is powered on and initialized
- After lift-off, at desired altitude, Morpheus commands PREPARE
  - Configures system for hazard detection algorithms
  - Commands LIDAR to start lasing
- At desired time, Morpheus commands OPERATE
  - Plans mosaic
  - Gimbal executes mosaic
  - DEM is constructed from LIDAR range images
  - Hazard Detection algorithm runs to find safe sites
  - Feature selected for Hazard Relative Navigation (HRN) feature tracking
  - HRN measurements provided to improve navigation to safest site
- At desired slant range prior to landing, SHUTDOWN is commanded
  - HDS software stopped and hardware powered off

Hardware-in-the-loop Simulation Process



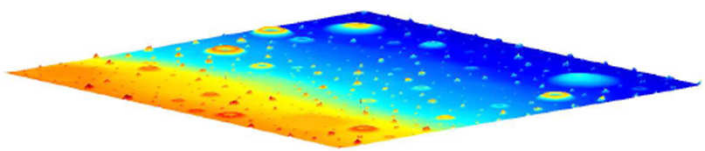
Hardware-in-the-loop Simulation

- Purpose: To predict HDS hardware and software behavior & safe landing performance given a simulated Morpheus trajectory (at JPL HDS lab)
- Process:
  - Navigation state from simulated trajectory passed to *Mosaic Planner* (MP)
  - MP plans mosaic using Boustrophedon pattern (scanning left-to-right and right-to-left in alternating rows) assuming 50% crosstrack overlap and 20% downtrack overlap between LIDAR flashes
  - MP sends mosaic points to *Gimbal Manager* (GM)
  - GM computes gimbal angles given mosaic points and simulated trajectory (vehicle position + attitude)
  - Gimbal executes mosaic motion w/ flash LIDAR mass simulator (1st pass)
  - Smaller LIDAR on optic bench provides blank range images so *Annotator* can stamp each range image w/ vehicle navigation state
  - Synthetic range images are generated from LIDAR survey of hazard field (ground truth) and replace small LIDAR range images
  - Synthetic range images are run through hazard detection algorithm
    - DEM generation, safe site selection, HRN feature selection
  - HRN feature coordinates converted to gimbal angles
  - Gimbal executes for entire flight (mosaic + HRN feature tracking + SHUTDOWN) (2nd pass)

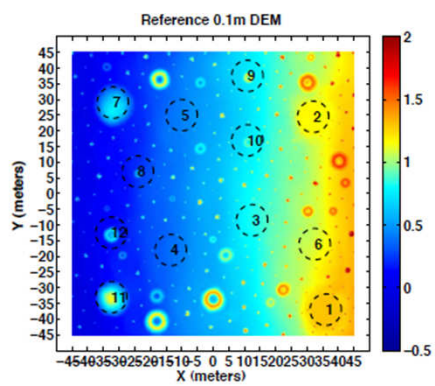
Terrain Model

- HDS performance predictions depend on DEM quality and hence range sensor
- Synthetic range-image generator uses high-fidelity LIDAR sensor model
- Ground truth DEM (0.1m/pixel resolution) constructed from high-density (10-million point) LIDAR survey of 100x100m hazard field at KSC
  - Hazard field derived from size-frequency distributions of craters and rocks from actual lunar terrain
- HDS has no knowledge of terrain
- Zones 1 and 2 in ground truth DEM have 10m concrete pads
- Goal to land on concrete pad, so rocks adjusted to maximize chances of safest site on concrete pad
- Therefore, simulations expected to show safest location on visible concrete pad

(a) Panoramic view



(b) Ground-truth DEM

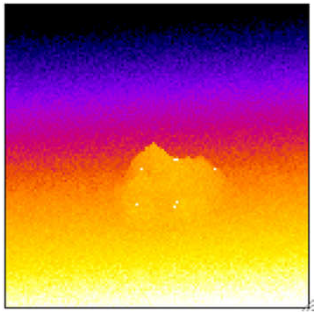


(c) Location of experimental 10 m-diameter zones

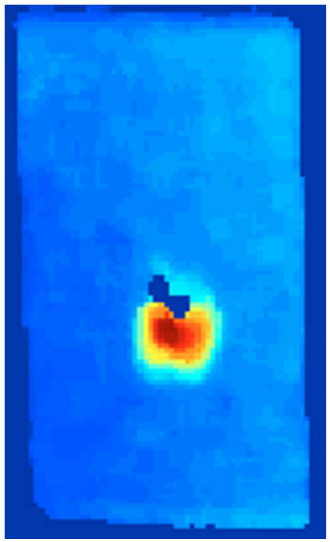
Flash LIDAR model

- HDS uses a flash LIDAR
  - 1 µm wavelength laser at 70 mJ
  - 12.1 cm receiver aperture diameter
  - Range images generated at 20 Hz using time-of-flight of transmitted/reflected laser pulse
  - 128x128 pixel range image converted to 3D image of surface
- NASA LaRC built a high-fidelity flash LIDAR model for early ALHAT simulations
  - Based on sensor imaging equation: $\boldsymbol{s(x,y,t) = p(x,y,t) \otimes o(x,y,t) + n(t)}$
  - p = point-spread function (temporal pulse), o = object function (terrain map), n = random noise
  - Accounts for various noise sources: background thermal noise, dark current electronic noise, Johnson noise, shot noise

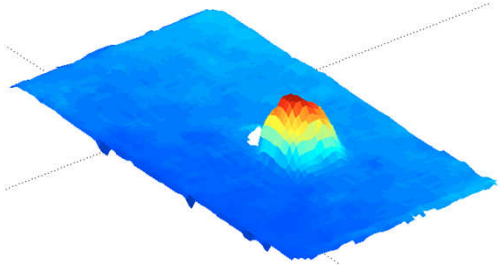
Parameter	Value
Focal Plane Assembly rows (pixels)	128
Focal Plane Assembly columns (pixels)	128
Receiver IFOV (mrad)	1.364e-4
Receiver optical efficiency R_{eff} (%)	0.8
Receiver aperture diameter D_r (m)	0.125
Range precision (m)	0.12
Laser wavelength (m)	1.06e-6
Transmitter laser energy per pulse E (J)	7.0e-2
Transmitter beam divergence (rad)	0.0256
Detector Gain M (dB)	40
Quantum efficiency QE (%)	0.7



Range image of rock on reference hazard field



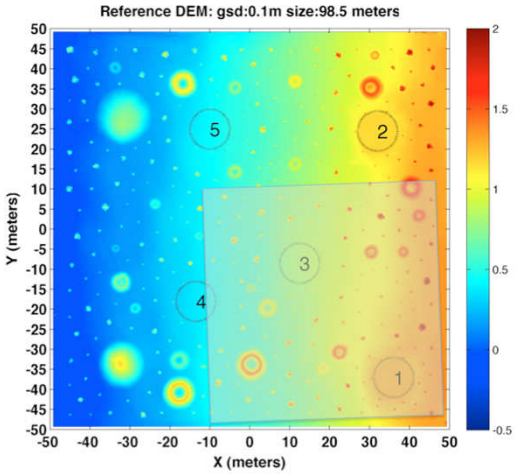
Flash DEM built from range image (13x7m from 400m away, 30 deg FPA)



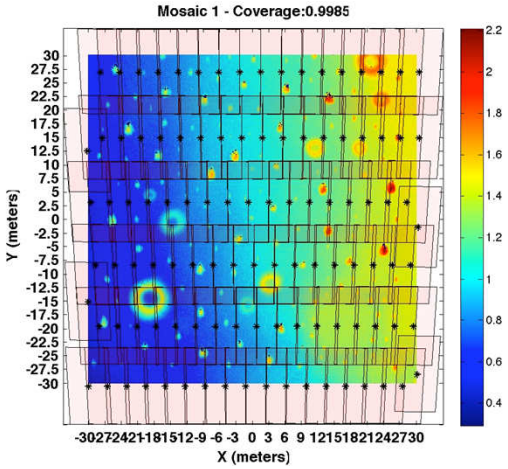
3D view of flash DEM

DEM Generator

- DEM generator assembles LIDAR range images into a single DEM
- Incoming range images are annotated with navigation state of LIDAR sensor (position and attitude) w.r.t. initial intended landing point (ILP)
- Range images first converted to 3D point cloud
- Each incoming point cloud is aligned to accumulating DEM to compensate for LIDAR and navigation noise
  - Avoids discontinuous seams and/or smeared features
  - DEM is accumulated at desired map resolution (0.1 m/pixel)
- Simulated range images incorporate LIDAR range precision of 12 cm
- Top right: ground truth DEM
- Bottom right: 50/20% overlap (CT/DT) between flashes in simulated 60x60m DEM



60x60m portion of reference (ground truth) DEM used in simulation



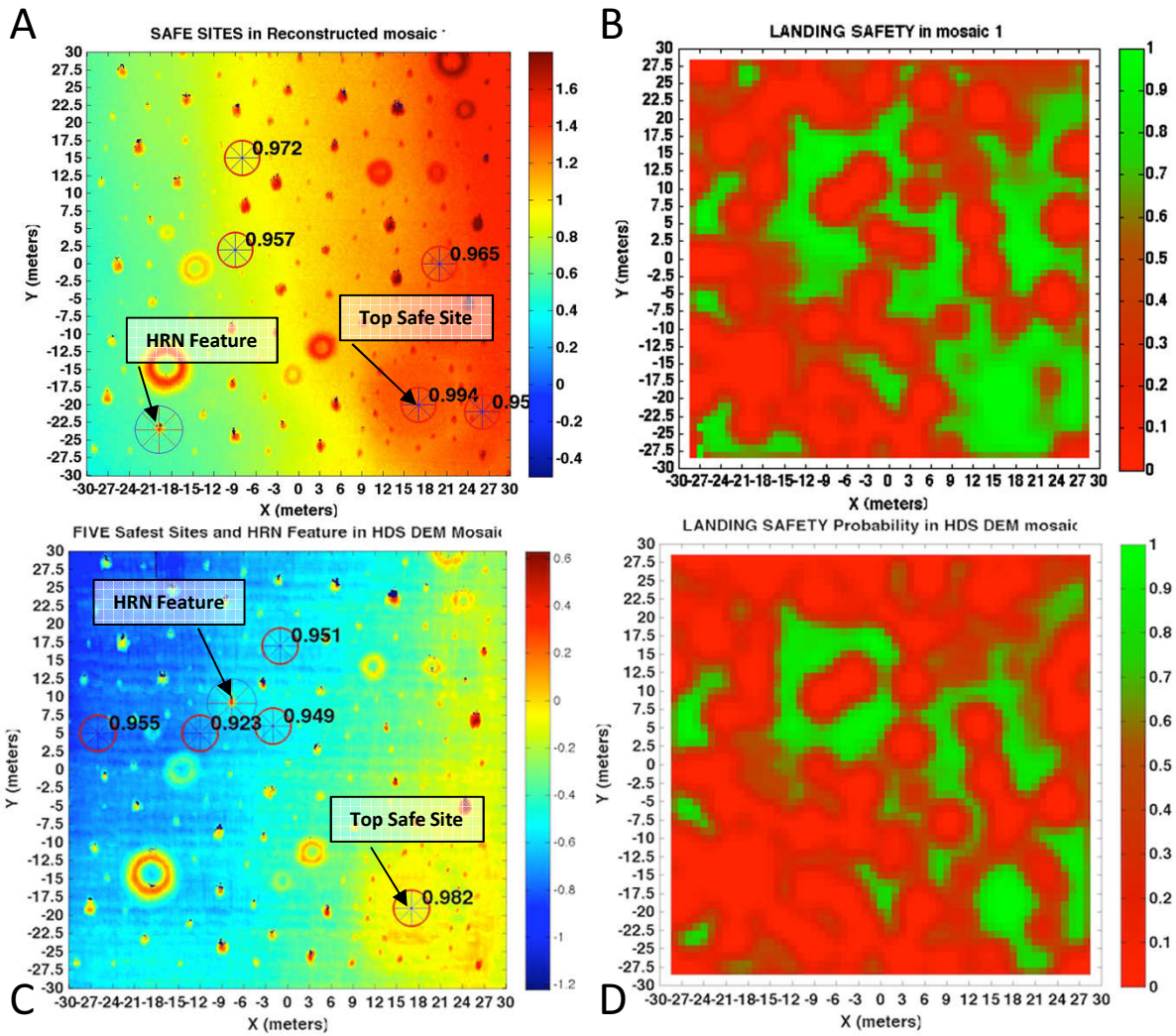
Flash footprints during mosaic for 60x60m map

Hazard Detection, Safe Site Selection, HRN Feature Selection

- HDS uses a probabilistic hazard analysis algorithm
  - Integrates vehicle geometry and navigation uncertainty to identify "safety probability" of each pixel in DEM
- Each pixel in DEM evaluated for safety given vehicle size (4m diameter) and mechanical tolerances (max. lander deck tilt + distance from underside to terrain) for a range of vehicle orientations
- Safety map computed with top 5 regional maxima (safe sites)
  - Terrain slopes and roughness in DEM are analyzed at 1m increments
  - Roughness map convolved with 1m, 1-σ Gaussian filter to model navigation uncertainty
- Two goals:
  - Safest site should be on concrete pad
  - All safe sites should be on truly (known) safe regions

Simulated vs. Actual DEM and Safety Maps

- **A**: Simulated 0.1m resolution DEM
  - Top safe site (0.994) on concrete pad1
  - HRN feature (blue wheel)
- **B**: Simulated 1m resolution safety map
- **C**: FF #11 actual DEM (60x60m)
  - Top safe site (0.982) on concrete pad1
  - Different HRN feature (blue wheel)
- **D**: FF #11 actual 1m resolution safety map
- Simulation vs. Flight:
  - Ground truth DEM model slightly different from actual KSC terrain (rock placement)
  - Environmental conditions (not modeled) affect LIDAR sensor performance
- Hazard Relative Navigation (HRN) phase
  - Selected HRN feature in FF #11 differs from feature selected in simulation due to LIDAR noise differences

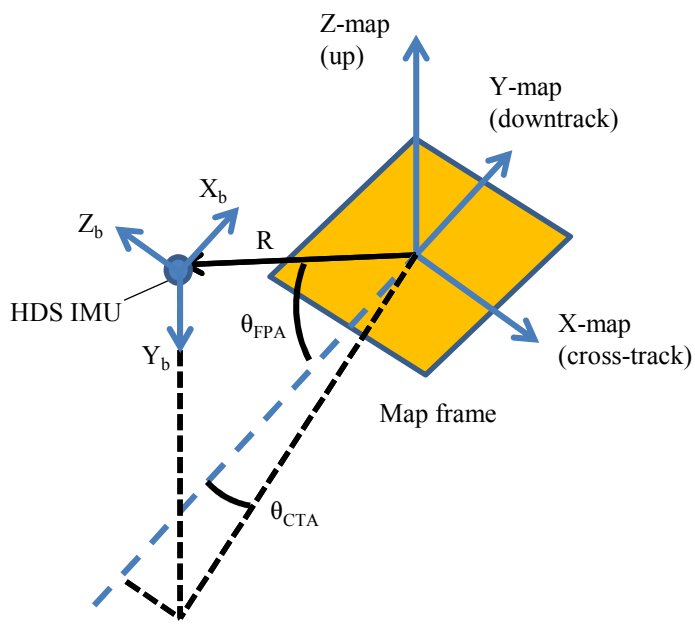


Timing Simulations

- Purpose: To predict total duration of the OPERATE command (up to reporting of safe sites to host vehicle) in comparison to allocated duration (Morpheus requirement)
  - Originally planned 90x90m map, but vehicle placed a timing requirement on HDS, leading to need for timing simulation
- Commands:
  - PREPARE:
    - Computes ESEF-to-map frame transform
    - Enables *Annotator* so it can tag incoming range images w/ vehicle navigation state
    - Starts LIDAR flashing
    - Pre-points gimbal at a "reconnoiter" point in lower left corner of map
  - OPERATE
    - Reconnoiter: If vehicle w/in desired range, HDS computes average elevation of terrain from single range image (elevation used by *Mosaic Planner*)
    - Mosaic Planning: Using DEM parameters and navigation state, computes mosaic plan
    - Mosaic Execution: Gimbal physically points to mosaic points under vehicle dynamics
    - DEM generation: Range images accumulated into a DEM
    - DEM finalization: Once gimbal motion complete, final DEM computed at desired resolution
    - Hazard Detection: DEM analyzed for top 5 safe sites
    - HRN Feature Selection: High-contrast feature selected for later gimbal tracking
    - HRN measurement updates:
      - Gimbal points LIDAR boresight at selected feature
      - Range images analyzed at 1 Hz to find navigation error to feature
      - HRN measurements passed to host vehicle for use in ALHAT navigation filter

OPERATE Command Timing Constraint

- Host vehicle has a constraint on OPERATE command duration (from command startup to safe sites reporting)
- OPERATE duration is a function of:
  - HDS IMU navigation state (geometric parameters)
    - Position
    - Attitude
- HDS map frame: defined at PREPARE command
  - Origin is centered at the initial landing point on hazard field
  - X-map is cross-track
  - Y-map is down-track
  - Z-map is up
- HDS IMU frame:
  - X_b is forward
  - Y_b is down
  - Z_b is left
- HDS IMU navigation state:
  - Position: Slant range, Flight Path Angle, Cross-track Angle
  - Attitude: HDS roll (about X_b), pitch (about Y_b), yaw (about Z_b)



Timing Prediction Methods

- 3 OPERATE timing prediction methods used
  - Coarse "Approximate Partials" method
  - Coarse "Curve Fit Partials" method
  - Robust Monte Carlo simulation method
- Coarse methods used to determine suitable map size for free flights
- Monte Carlo method used to refine coarse estimates prior to actual free flights

Approximate Partials Method

- OPERATE duration & uncertainty estimated using:
  - Timing data from Nov 2012 helicopter flights and Nov 2013 JPL FSW Tilera processor timing studies
  - Predictions of *Mosaic Planner* planned points vs. geometric parameters (position & attitude)
- Uncertainty
  - Uncertainty in each OPERATE component activity was estimated
  - Only uncertainty in <u>mosaic planning</u> and <u>DEM generation</u> durations required explicit calculation (all other activities estimated from timing study data)
    - Estimate uncertainty in # mosaic points, # flashes, DEM generation interval (sec/flash)
    - Total uncertainty in # mosaic points computed using partial derivatives of number of mosaic points w.r.t. various geometric parameters via central difference method

Approx. Partials Method Predictions

Case	Map Size (m)	Slant Range (m)	Flight Path Angle (deg)	# Mosaic Points	# Flashes	OPERATE dur (sec)	OPERATE unc (sec)	OPERATE min dur (sec)	OPERATE max dur (sec)
1	30x30	450	30	120	27.0	2.484	0.487	1.997	2.971
2	30x30	475	30	115	26.0	2.413	0.406	2.007	2.819
3	30x30	500	30	105	23.0	2.203	0.375	1.828	2.578
4	45x45	450	30	271	60.0	6.152	0.796	5.355	6.948
5	45x45	475	30	257	56.0	5.828	0.838	4.990	6.667
6	45x45	500	30	250	55.0	5.746	0.583	5.163	6.329
7	60x60	450	30	500	109.0	11.220	1.661	9.560	12.881
8	60x60	475	30	430	94.0	9.930	1.226	8.703	11.156
9	60x60	500	30	375	82.0	8.898	1.129	7.769	10.027
10	75x75	450	30	730	159.0	18.381	2.005	16.377	20.386
11	75x75	475	30	688	150.0	17.501	2.141	15.360	19.642
12	75x75	500	30	564	123.0	14.861	1.515	13.346	16.377
13	90x90	450	30	1021	223.0	27.201	2.842	24.359	30.043
14	90x90	475	30	959	209.0	25.742	2.302	23.439	28.044
15	90x90	500	30	904	197.0	24.490	2.479	22.011	26.968

- Conditions studied:
  - Maps from 30x30m to 90x90m
  - Slant ranges of 450, 475, 500m @ 30 deg flight path angle
- Predicted # mosaic points, # flashes, OPERATE nominal, min and max durations
- Allocated maximum OPERATE-to-safe sites duration requirement = 13.5 sec
- 75x75m and 90x90m map cases exceed requirement (red cells) → 60x60m largest feasible map size

Curve Fit Partials Method

- Same as Approx. Fit Partials method except that partials of # mosaic points vs. geometric parameters computed via taking derivatives of curve fits
  - Only affects OPERATE uncertainty calculations
  - Difference in uncertainties between Approx. vs Curve Fit Partials method is insignificant (< 1 sec)
- Confirms 60x60m is largest feasible map size

Case	Map Size (m)	Slant Range (m)	Flight Path Angle (deg)	# Mosaic Points	# Flashes	OPERATE dur (sec)	OPERATE unc (sec)	OPERATE min dur (sec)	OPERATE max dur (sec)	Uncertainty Diff (Curve Fit – Approx.) (sec)
1	30x30	450	30	120	27.0	2.484	0.420	2.064	2.904	-0.068
2	30x30	475	30	115	26.0	2.413	0.401	2.012	2.814	-0.005
3	30x30	500	30	105	23.0	2.203	0.374	1.829	2.577	-0.002
4	45x45	450	30	271	60.0	6.152	0.835	5.317	6.987	0.038
5	45x45	475	30	257	56.0	5.828	0.663	5.166	6.491	-0.176
6	45x45	500	30	250	55.0	5.746	0.623	5.123	6.369	0.040
7	60x60	450	30	500	109.0	11.220	1.425	9.796	12.645	-0.236
8	60x60	475	30	430	94.0	9.930	1.221	8.708	11.151	-0.005
9	60x60	500	30	375	82.0	8.898	1.201	7.696	10.099	0.073
10	75x75	450	30	730	159.0	18.381	2.143	16.238	20.525	0.139
11	75x75	475	30	688	150.0	17.501	1.698	15.803	19.200	-0.443
12	75x75	500	30	564	123.0	14.861	1.544	13.317	16.406	0.029
13	90x90	450	30	1021	223.0	27.201	2.346	24.856	29.547	-0.496
14	90x90	475	30	959	209.0	25.742	2.355	23.387	28.096	0.052
15	90x90	500	30	904	197.0	24.490	1.848	22.642	26.338	-0.631

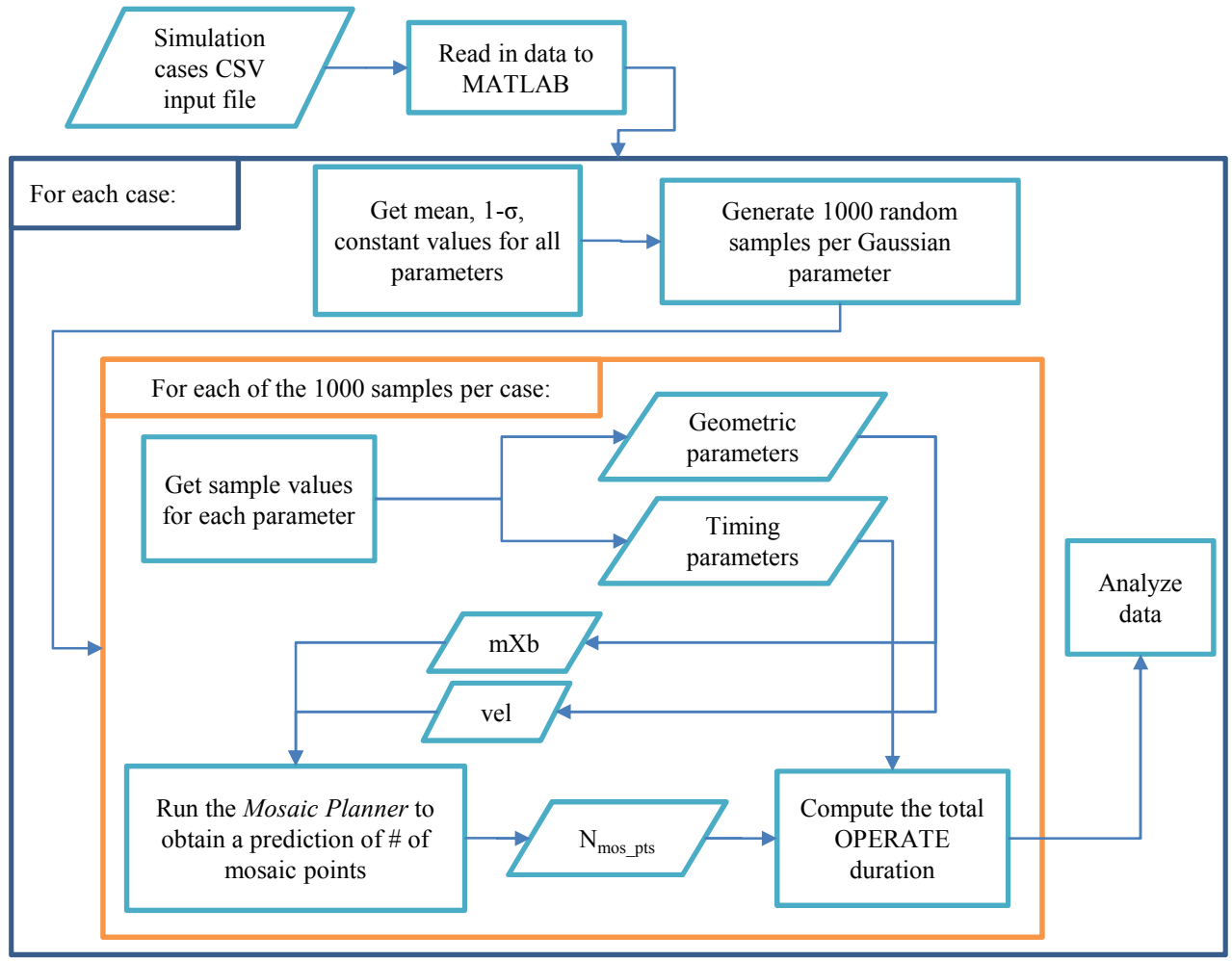
Monte Carlo Timing Method

- Purpose: To obtain more accurate estimates of OPERATE-to-safe sites duration under expected variation in vehicle navigation state and timing parameters
- Method: geometric and timing parameters used in coarse timing methods are treated as random variables with normal (Gaussian) distribution
  - Each variable sampled 1000 times w/ defined mean and 1-sigma
  - All geometric parameters are independent of map size
  - Most timing parameters are a function of map size
- Notice addition of velocity
  - Mosaic Planner can take instantaneous velocity at time of mosaic planning and propagate it forward during mosaic
  - Without velocity propagation, vehicle assumed farther away, leading to additional mosaic rows and increased time

Parameter	Comment
Geometric Parameters	
Slant Range	3 values (450, 475, 500m) mean per DEM size
Flight Path Angle	3 values (25, 30, 35deg) mean for some cases, otherwise ~30deg mean
Cross-track Angle	Mean/1-sigma constant for all DEM sizes
Roll Angle (about HDS x-axis)	Mean/1-sigma constant for all DEM sizes
Pitch Angle (about HDS y-axis)	Mean/1-sigma constant for all DEM sizes
Yaw Angle (about HDS z-axis)	Mean/1-sigma constant for all DEM sizes
Velocity Magnitude	Mean/1-sigma constant for all DEM sizes
Timing Parameters	
OPERATE startup duration	Constant 2 ms for all map sizes
Primary slew to reconnoiter trackpoint duration	Constant 0 sec assumed since the PREPARE command pre-points the gimbal/LIDAR
Range check duration	Constant 1 ms for all map sizes
Reconnoiter duration	Constant 0.058 sec for all map sizes
k_{ppf} (points per flash)	Mean/1-sigma constant for all DEM sizes (capped at 100 Hz/20 Hz = 5 points per flash)
Mosaic Planning Interval (sec/mos pt)	Mean/1-sigma constant for all DEM sizes
DEM Accum Interval (sec/flash)	Mean/1-sigma a function of DEM size
DEM Finalization duration	Mean/1-sigma a function of DEM size
Hazard detection duration	Mean/1-sigma a function of DEM size
Feature Selection duration	Mean/1-sigma a function of DEM size
1st HRN update duration	Mean/1-sigma constant for all DEM sizes

Monte Carlo simulation process

- Build CSV file of simulation cases (varying in map size, slant range, FPA) and read into MATLAB
- Generate 1000 samples per parameter per case
- For each sample per case:
  - Compute position & attitude state (mXb) and velocity
  - Pass to *Mosaic Planner* to predict # of mosaic points
  - If # mosaic points within maximum allowed (1200), compute OPERATE-to-safe sites duration



Set 1: Monte Carlo validation runs

Case #	DEM size	Slant Range mean (m)	Flight Path Angle mean (deg)	# Failed Mosaic Plans	Mean # Mosaic Points	Min # Mosaic Points	Max # Mosaic Points	OPERATE mean dur (sec)	OPERATE min dur (sec)	OPERATE max dur (sec)
7	60	450	25	0	511	436	590	10.312	7.852	13.807
8	60	450	30	0	567	515	668	11.379	9.266	15.948
9	60	450	35	0	635	603	770	12.617	10.368	16.844
10	60	475	25	0	436	409	538	8.906	7.424	11.937
11	60	475	30	0	506	486	615	10.208	8.538	12.470
12	60	475	35	0	586	485	631	11.716	9.073	14.458
13	60	500	25	0	401	386	444	8.231	6.907	10.600
14	60	500	30	0	472	388	521	9.588	7.188	11.554
15	60	500	35	0	509	452	591	10.236	8.183	13.496
16	75	450	30	0	954.091	796	1170	21.449	15.873	28.277
17	75	475	30	0	831.48	733	951	18.839	15.098	24.927
18	75	500	30	0	724.598	620	908	16.572	13.987	22.567
19	90	450	25	923	1177.221	1020	1200	28.28	23.62	33.067
20	90	450	30	1000	0	0	0	0	0	0
21	90	475	30	983	1129.941	1071	1200	27.477	23.541	34.09
22	90	500	30	160	1114.682	980	1200	26.889	21.574	34.965

- 1st set of runs: Done to validate coarse timing results
  - Expanded to include 50x50m and 55x55m maps
  - Mean and 1-sigma values for geometric parameters were educated guesses
  - Confirms that 75x75m and 90x90m maps infeasible
    - For 90x90m cases, high percentage of runs failed (see # Failed Mosaic Plans column)
  - New result: in some cases 60x60m map OPERATE duration exceeds allocation of 13.5 sec
    - Low slant range and high flight path angle

Set 2: Monte Carlo run for FF10

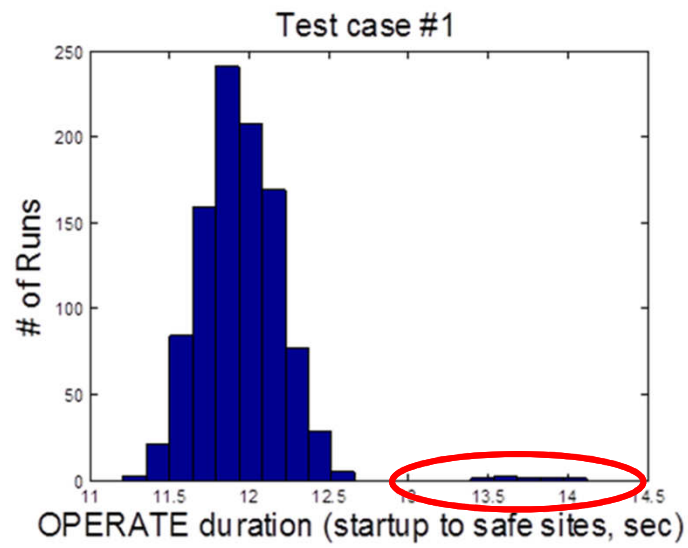
Case #	DEM size	Slant Range mean (m)	Flight Path Angle mean (deg)	# Failed Mosaic Plans	Mean # Mosaic Points	Min # Mosaic Points	Max # Mosaic Points	OPERATE mean dur (sec)	OPERATE min dur (sec)	OPERATE max dur (sec)
1	60	462.762	30.960	0	530	527	538	11.995	11.333	12.721
2	55	462.762	30.960	0	482	479	487	10.789	10.059	11.424
3	50	462.762	30.960	0	364	361	366	7.734	7.171	8.228

- Mean and 1-sigmas of geometric parameters were refined based on Monte Carlo simulations of Morpheus trajectory (provided by JSC)
- Focused Monte Carlo runs done for 50x50m, 55x55m, and 60x60m maps
- No cases exceeded max duration of 13.5 sec

Set 3: Monte Carlo run for FF11 - 14

Case #	DEM size	Slant Range mean (m)	Flight Path Angle mean (deg)	# Failed Mosaic Plans	Mean # Mosaic Points	Min # Mosaic Points	Max # Mosaic Points	OPERATE mean dur (sec)	OPERATE min dur (sec)	OPERATE max dur (sec)
1	60	462.530	31.191	0	532	528	631	11.947	11.205	14.120
2	55	462.530	31.191	0	483	479	492	10.756	10.189	11.658
3	50	462.530	31.191	0	367	361	442	7.774	7.205	9.319

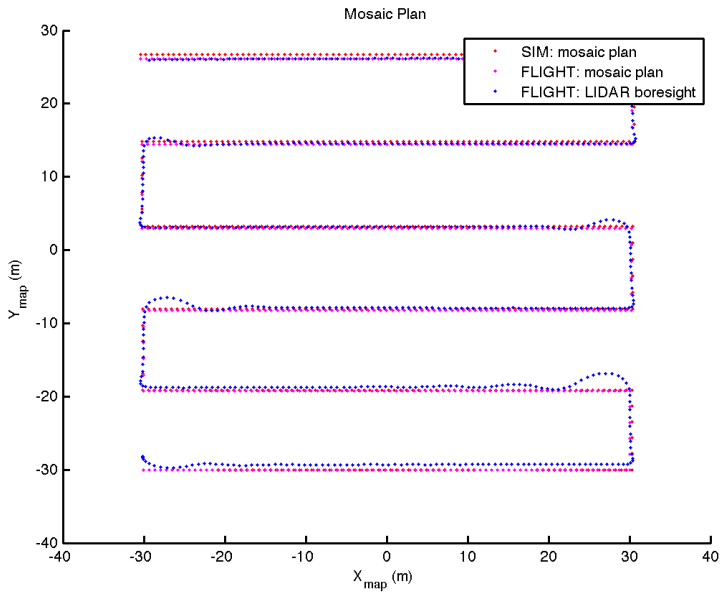
- After FF10 performance assessed, max OPERATE duration allocation was **increased to 14.1 sec**
- Monte Carlo simulations re-run for the new OPERATE command timing with new Morpheus trajectory and its position/attitude/velocity dispersions
- Only 1 out of 1000 runs in case 1 (60x60m map) exceeded allocation (red cell), and only by 20 ms



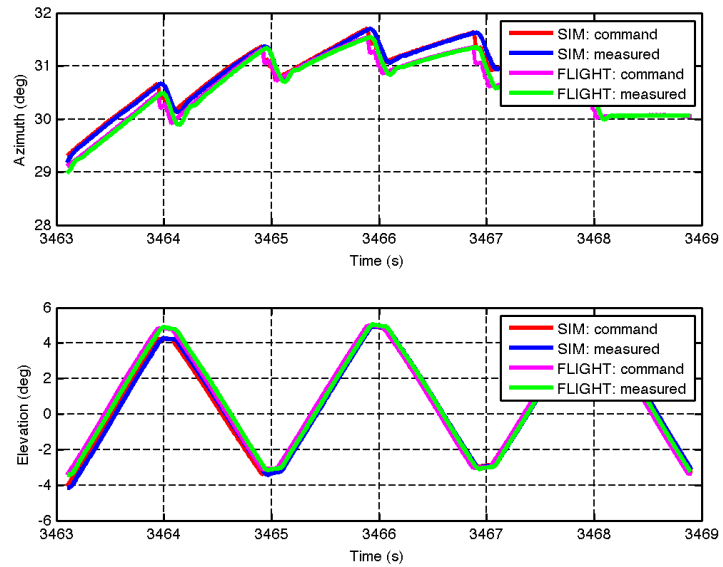
Free Flight Tests

- 5 Morpheus free flights w/ ALHAT hardware onboard in Spring 2014
- Goal: top safe site should be within 2m of concrete pad center
- FF10, 11 were “Open Loop”
  - VTB-Nav: Morpheus IMU + GPS provides Nav state
  - Vehicle lands at pre-determined concrete pad1 site (overrides ALHAT-provided safe sites list)
- FF12 was “Advanced Open Loop”
  - Landing site allowed to be ALHAT-provided
  - Still flying vehicle on VTB-Nav
- FF13, 14 were “Closed Loop”
  - ALHAT-Nav: ALHAT sensors (Doppler LIDAR, laser altimeter, HDS LIDAR) provide measurements to estimate Nav state
- In all cases, both VTB-Nav and ALHAT-Nav states computed and compared
- In Closed Loop flights, ALHAT-Nav switches to VTB-Nav when error tolerance exceeded

Hardware-in-the-loop Results



FF11 Mosaic Plan (Sim vs. Flight)



FF11 Gimbal Angles (Sim vs. Flight)

- Left: FF11 Mosaic Plan (Sim vs. Flight)
  - Simulation predicted 530 mosaic points, Flight result agreed
  - Simulation and flight mosaic plans agreed
  - Some overshoot from row-to-row in flight
- Right: FF11 Gimbal Angles (Sim vs. Flight)
  - Lab gimbal executed mosaic only 0.1 sec faster
  - Simulation gimbal angles (Azimuth & Elevation) very similar to flight

Monte Carlo Timing Simulation Results (1/2)

Parameter	FF10	FF11*	FF12*	FF13*	FF14*
Maximum OPERATE Duration Requirement (sec)	13.5	14.1	14.1	14.1	14.1
Monte Carlo Total OPERATE Min Duration (sec)	11.333	11.205	11.205	11.205	11.205
Monte Carlo Total OPERATE Mean Duration (sec)	11.995	11.947	11.947	11.947	11.947
Monte Carlo Total OPERATE Max Duration (sec)	12.721	14.120	14.120	14.120	14.120
Actual Flight Total OPERATE Duration (sec)	**12.230**	**11.498**	**12.856**	**11.332**	**11.391**

*The OPERATE command start was shifted 0.6 sec earlier than in FF #10 in these free flights

- Total OPERATE-to-safe sites durations within MC prediction and max allocation for all flights
  - Allocation was 13.5 sec for FF10, 14.1 sec for FF11-14
  - In FF12, total OPERATE duration > 1sec larger than in FF11
    - Majority of time diff due to flight DEM generation duration
    - DEM generation interval (sec/flash) was underestimated in MC simulations
    - Future MC simulations should revise estimation of DEM generation duration

Monte Carlo Timing Simulation Results (2/2)

- Some OPERATE component activity flight durations not within MC bounds
  - Reconnoiter bias duration & mosaic planning duration: Small differences from MC bounds corrected using actual flight data
  - DEM Finalization flight durations all above max MC predict except in FF11
    - JPL Tilera timing studies had assumed lower slant range than flown, predicted fewer mosaic flashes, so underestimated DEM Finalization duration
  - HazDet + Safe Site selection flight duration in FF13 slightly below lower MC bound
  - HRN Feature Selection flight durations all above upper MC bound, however, NOT critical to flight operations
  - FF12 1st HRN update duration below lower MC bound
  - Of all small differences above, max difference was 0.24 sec (Hazdet + Safe Sites duration)

Flight vs. Monte Carlo timing prediction Performance Table

OPERATE Activity	FF10	FF11	FF12	FF13	FF14
Open Loop (OL) or Closed Loop (CL)	OL	OL	OL	CL	CL
Total OPERATE-to-safe sites	Y	Y	Y	Y	Y
Startup + In-range check	Y	Y	Y	Y	Y
Reconnoiter Point Tracking	**N (o)**	Y (r)	Y	Y	Y
Reconnoiter Elevation Bias Computation	**N (o)**	Y	**N (o)**	Y	Y
Mosaic Planning	**N (u)**	Y (r)	Y	Y	Y
Gimbal Mosaic Execution	Y	Y	Y	Y	Y
DEM generation (in parallel to mosaic execution)	Y	Y	Y	Y	Y
Finalize DEM	**N (o)**	Y	**N (o)**	**N (o)**	**N (o)**
Hazard Detection + Safe Site Selection	Y	Y	Y	**N (u)**	Y
HRN Feature Selection	**N (o)**	**N (o)**	**N (o)**	**N (o)**	**N (o)**
1st HRN update	Y	Y	**N (u)**	Y	Y

Monte Carlo (MC) Timing Performance Table.
u = flight value below min MC bound,
o = flight value above max MC bound,
r = MC estimate revised based on prior flight data

Conclusion

- Hardware-in-the-loop gimbal simulations and all OPERATE timing analyses (including Monte Carlo timing simulations) provided excellent predictions of:
  - # mosaic points
  - Gimbal performance
  - OPERATE-to-safe sites duration
- Provided JPL team confidence that free flight command profile would execute within timing requirement
  - Avoiding scenario where host vehicle would bypass HDS safe site list and land at pre-designated abort landing site