



Lidar Sensor Performance in Closed-Loop Flight Testing of the Morpheus Rocket-Propelled Lander to a Lunar-Like Hazard Field

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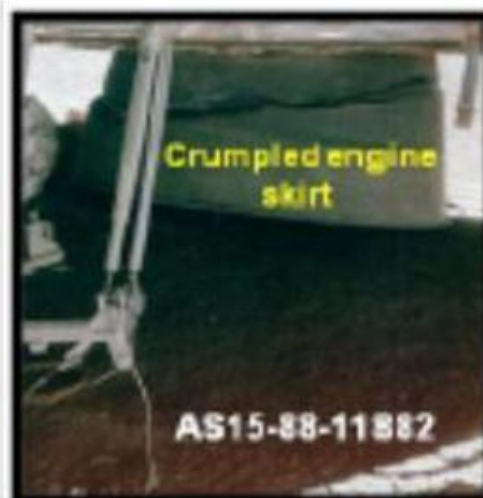


Planetary Landing: the Problem



Autonomous Landing Hazard Avoidance Technology (ALHAT)

- Existing state-of-art
 - Optical photos from orbit (dependent on favorable solar illumination)
 - Laser mapping from orbit
 - Low resolution hazard detection
 - Not real-time
 - Restricts landing to un-challenging lighting & terrain



Apollo 15



Brady, T., and S. Paschall, *The Challenge of Safe Lunar Landing*, Proc. of IEEE Aerospace Conference, Big Sky, MT, March 6 – 13, 2010, pp. 1 – 14.



ALHAT Solution

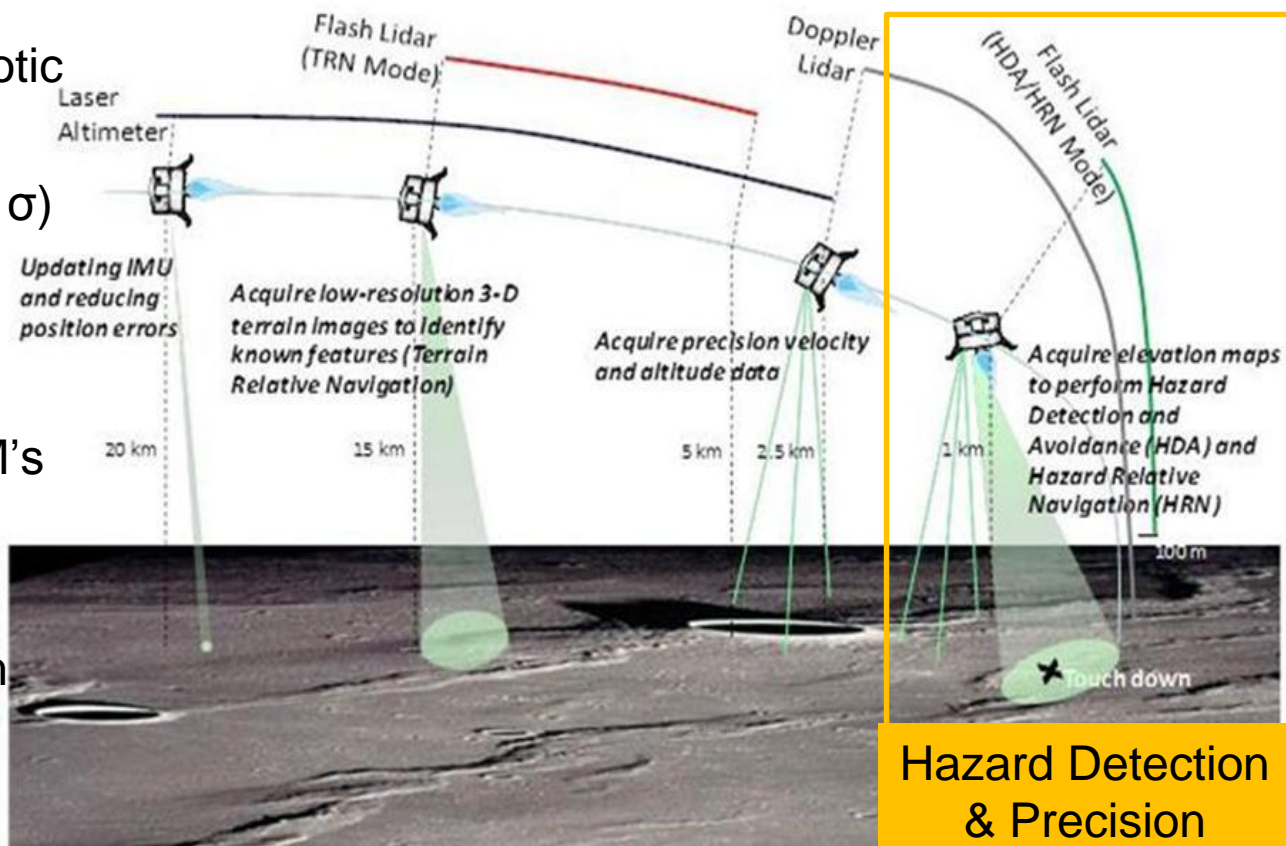
Autonomous Landing Hazard Avoidance Technology (ALHAT)

- GN&C & sensing system

- Crewed or robotic
- Safe
- Precise (30m, 1σ)
- Any ambient lighting (use lidars)
- Real-time DEM's

- System goals

- Detect 30cm hazards @1km
- 1 cm/s velocity precision
- 20 cm range precision



Hazard Detection & Precision Guidance (1km to 100m)



Lidars Installed on Morpheus



Navigation Doppler Lidar (NDL) Chassis



Flash Lidar Electronics Box (LEB)



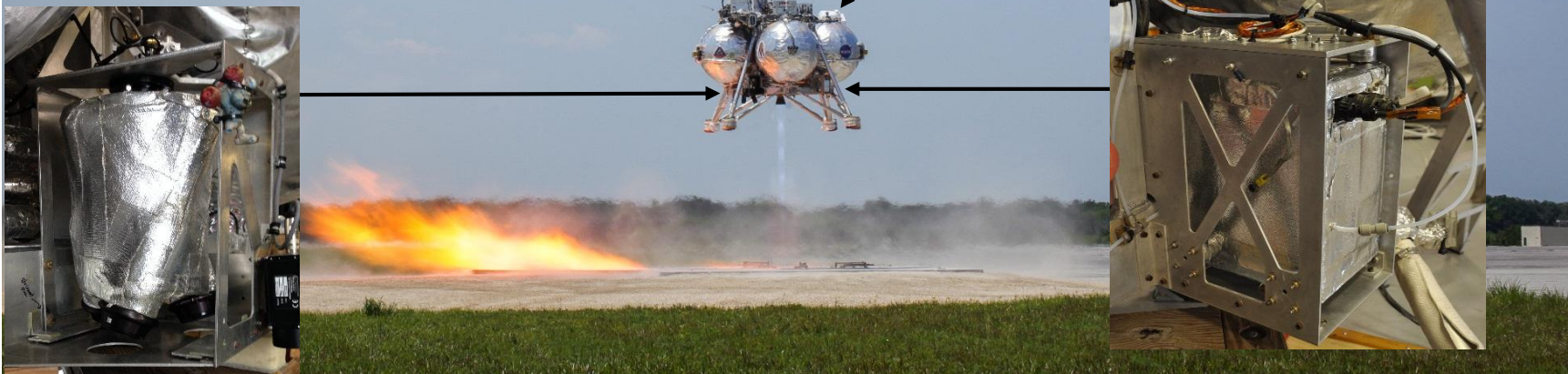
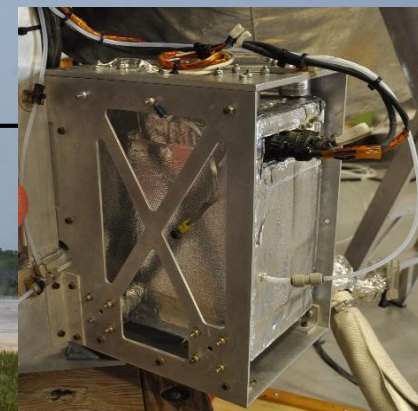
Flash Lidar Sensor Head (FLSH) Mounted to HDS 2-axis Gimbal



NDL Optical Head



Laser Altimeter (LA)



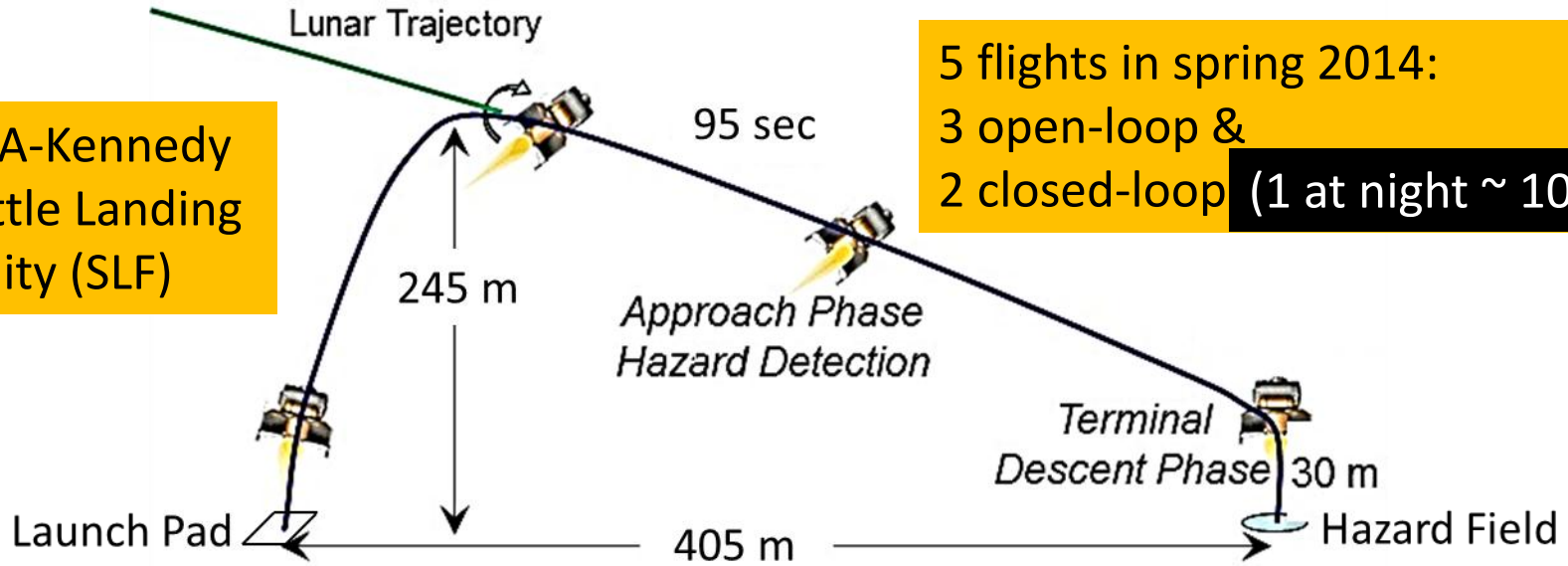


Field Test Plan

Autonomous Landing Hazard Avoidance Technology (ALHAT)

NASA-Kennedy Shuttle Landing Facility (SLF)

5 flights in spring 2014:
3 open-loop &
2 closed-loop (1 at night ~ 10pm)

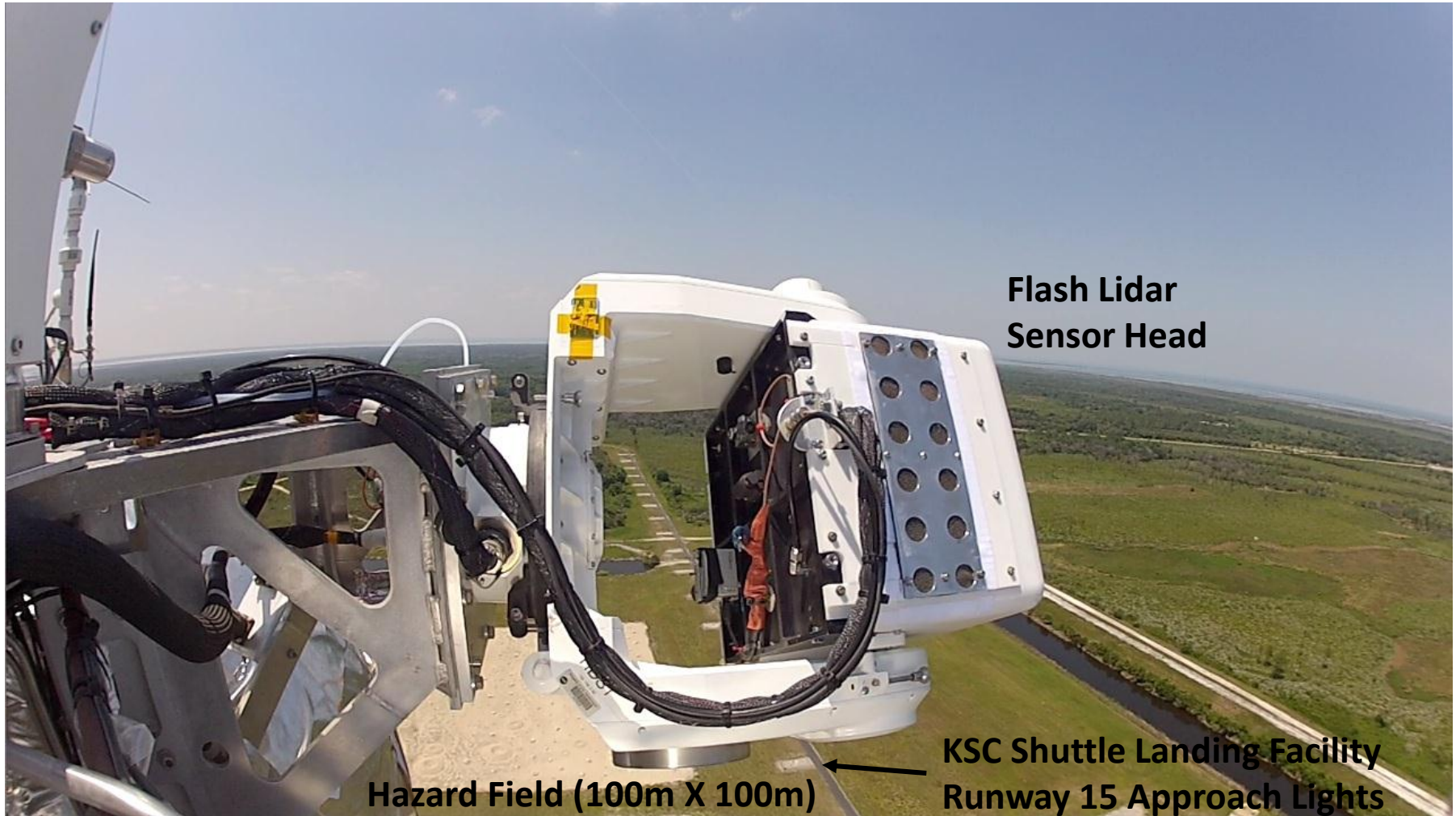




Morpheus on Approach



Autonomous Landing Hazard Avoidance Technology (ALHAT)



**Flash Lidar
Sensor Head**

Hazard Field (100m X 100m)

**KSC Shuttle Landing Facility
Runway 15 Approach Lights**



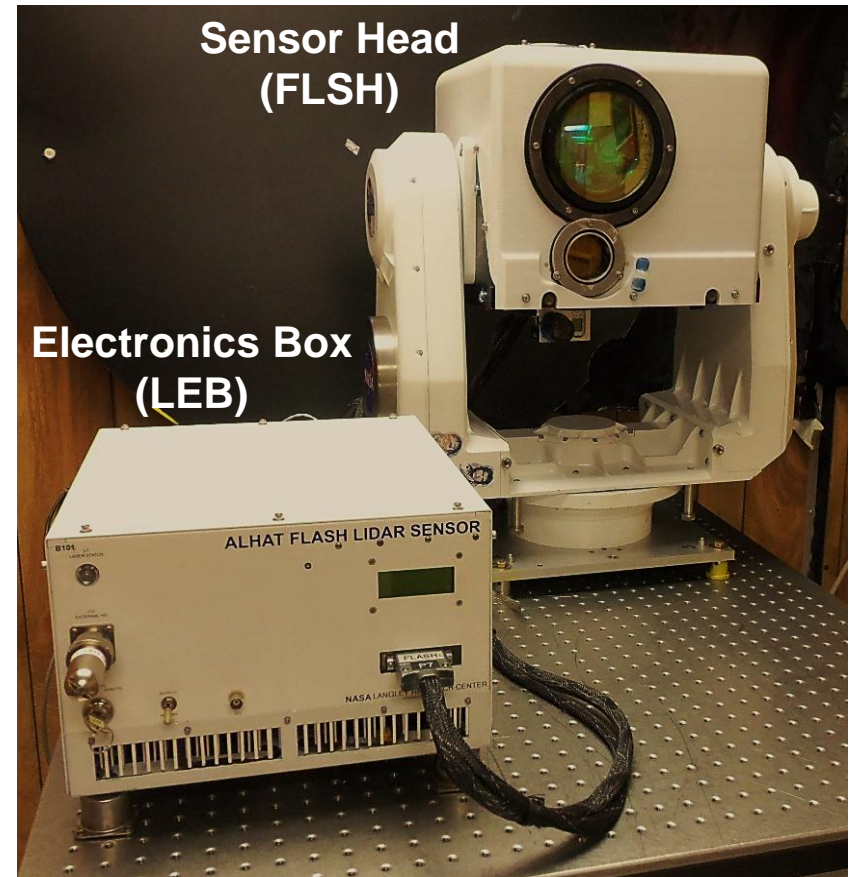
Flash Lidar Specs



Autonomous Landing Hazard Avoidance Technology (ALHAT)

- Max range: 1.35km
- # pixels: $128 \times 128 = 16,384$
- Range precision: 8 cm (1σ)
 - Allows 30cm hazard detection @ 1km
- Size:
 - FLSH: 11x13.5x13.25 inches
 - LEB: 9.5x14.2x13 inches
- Weight:
 - FLSH: *36 lbs
 - LEB: *36 lbs
- Power: *450 Watts

Goal Met



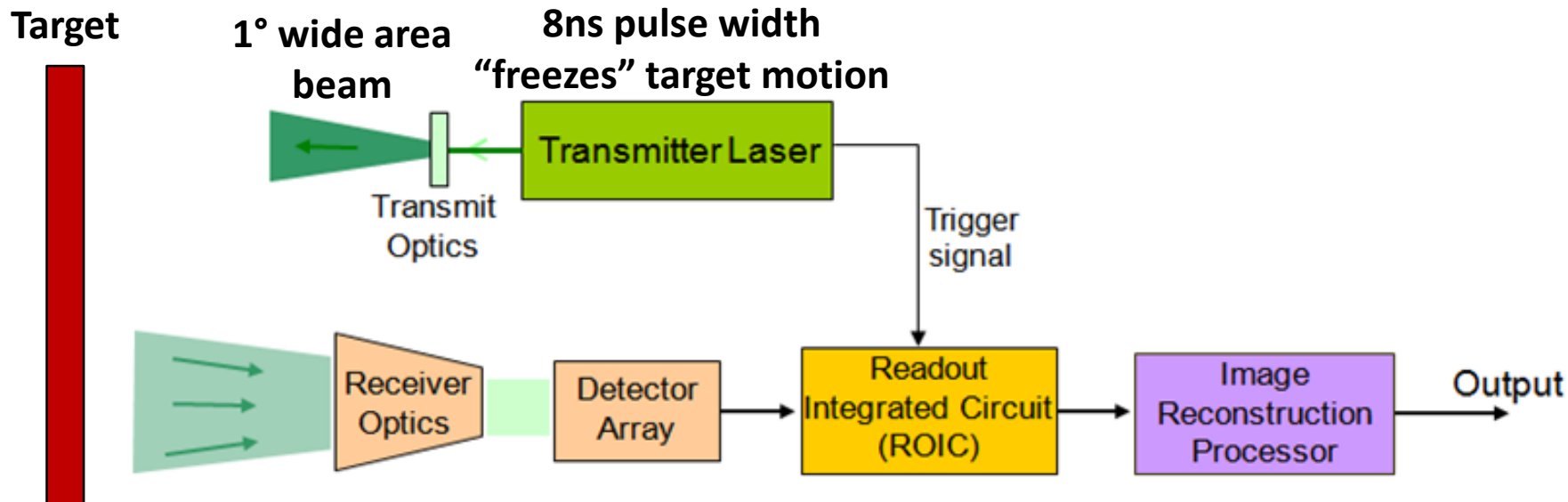
* Dominated by terrestrial cooling system



Flash Lidar Principles of Operation



Autonomous Landing Hazard Avoidance Technology (ALHAT)



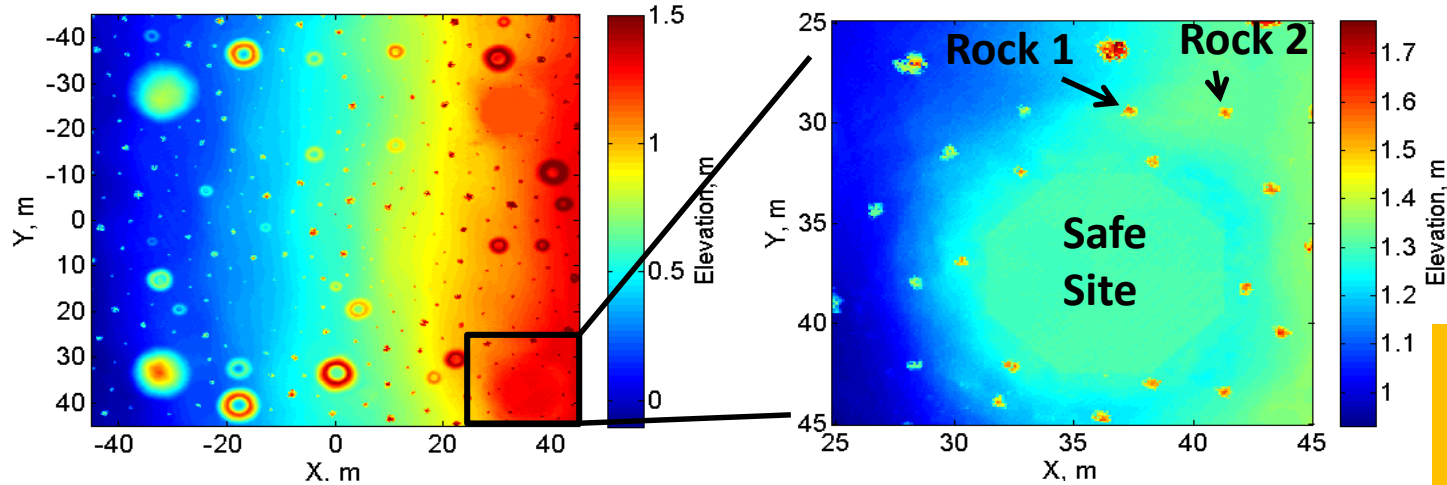
- Round-trip time of flight
 - Range = speed of light x round-trip time of flight / 2
- 3-D images generated in real-time
 - One image per laser shot
 - 128 x 128 pixels (16,384) per image
 - 20 images/sec output



Flash Lidar Flight Data

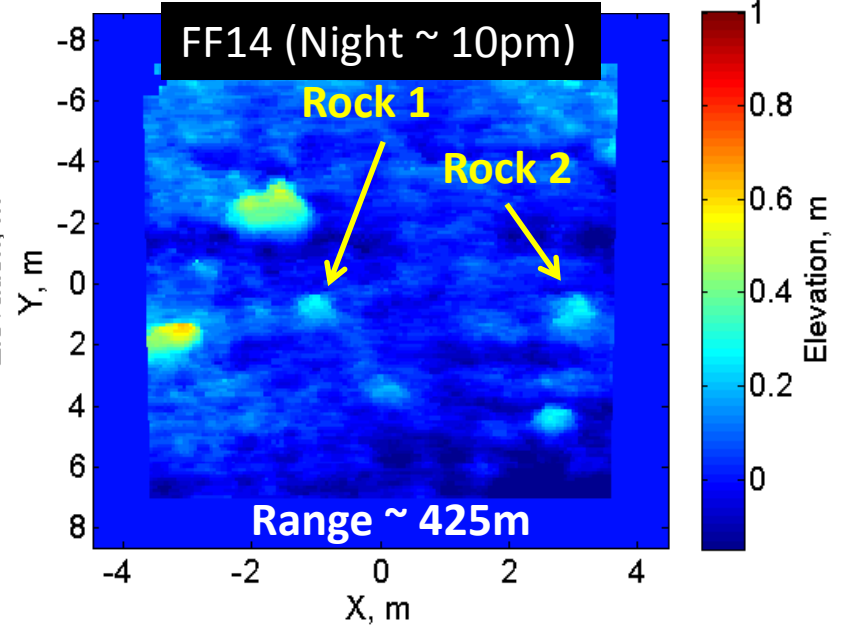
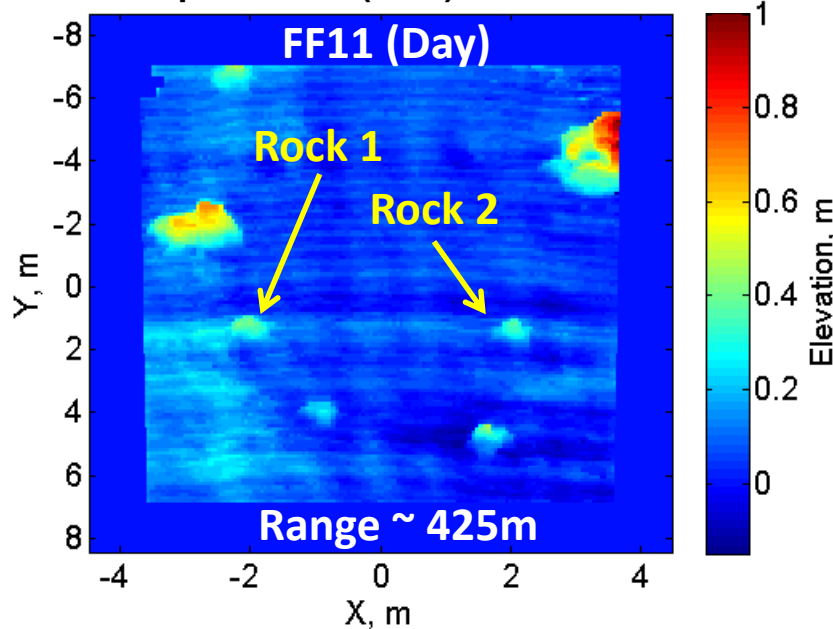


Autonomous Landing Hazard Avoidance Technology (ALHAT)



Mission Elapsed Time (MET) = 45.641564 sec

MET = 46.036214 sec

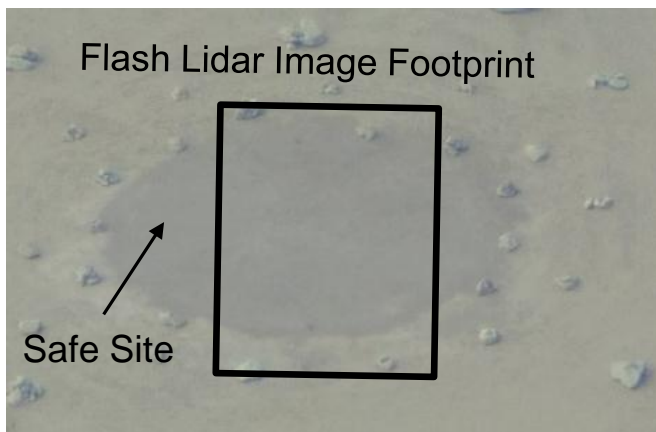
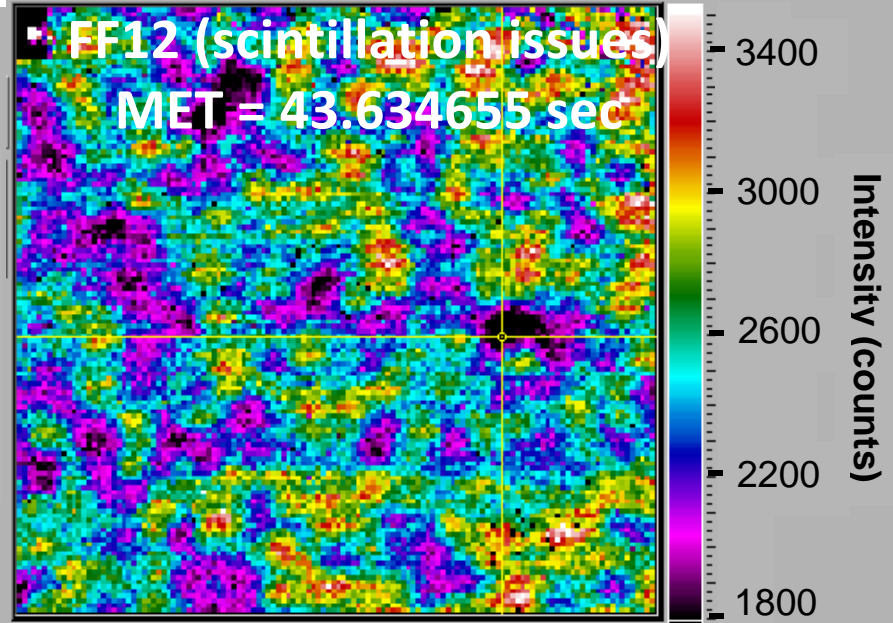
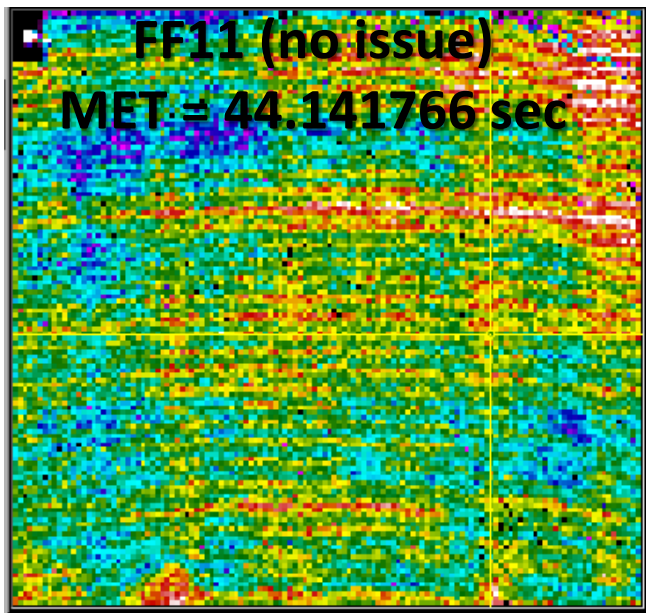




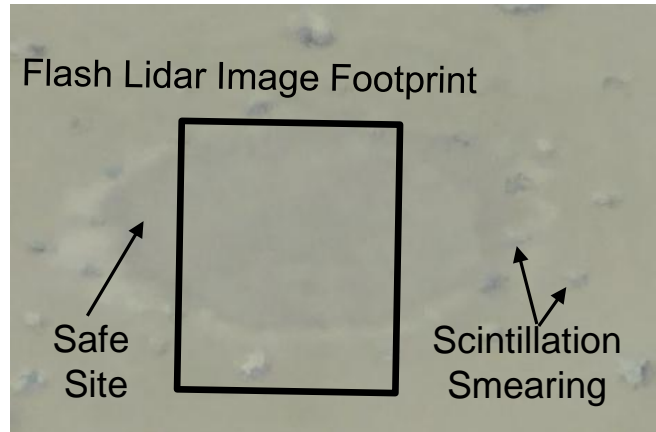
Rocket Plume Heat Effects on Flash Lidar (scintillation)



Autonomous Landing Hazard Avoidance Technology (ALHAT)



Apply wind restrictions for future flights





Navigation Doppler Lidar (NDL) Specs



Autonomous Landing Hazard Avoidance Technology (ALHAT)

- Line-of-sight (LOS) operational range: 2km
- LOS velocity precision: 0.2cm/s
- LOS range precision: 17 cm
- Attitude error: 7 mrad
- Size:
 - Chassis: 17.3 x 15 x 6.3 inches
 - Optical head: 7.9 dia x 9.8H inches
- Weight:
 - Chassis: 37.4 lbs
 - Optical head: 11 lbs
- Power: 95 Watts

Goal Met

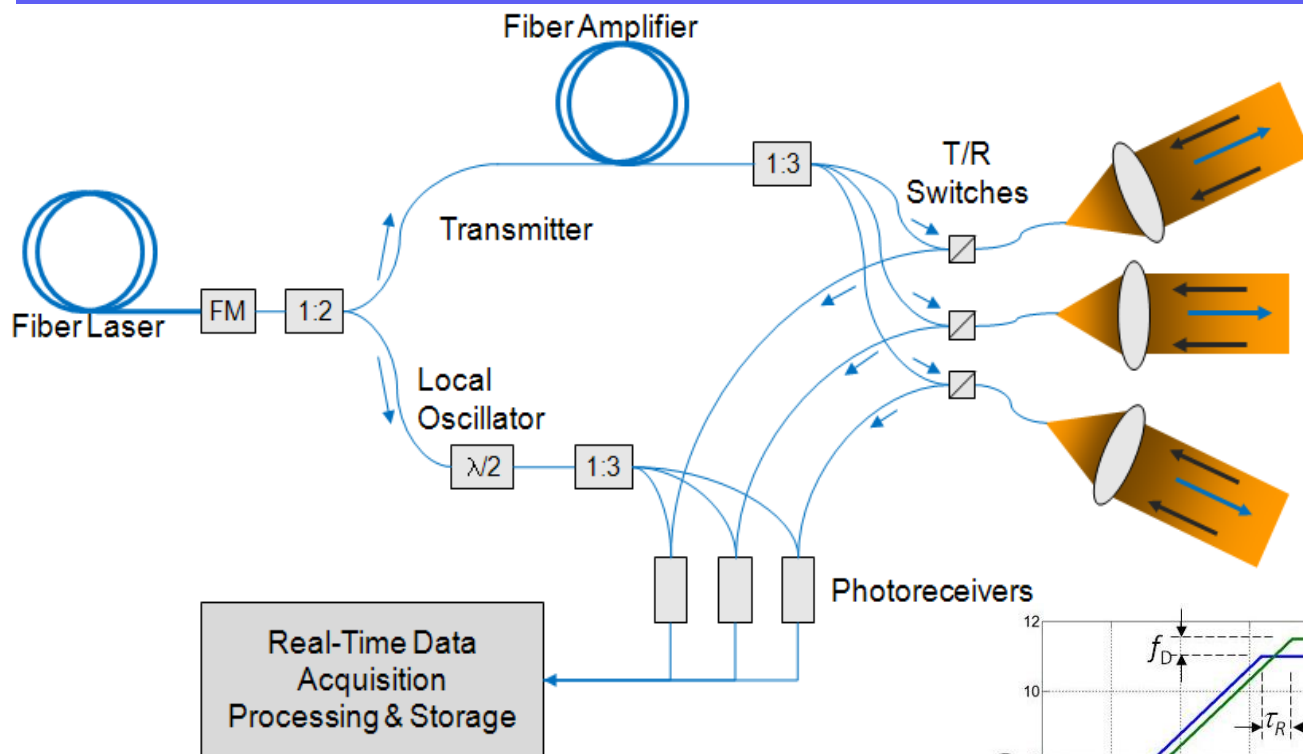




NDL Principles of Operation

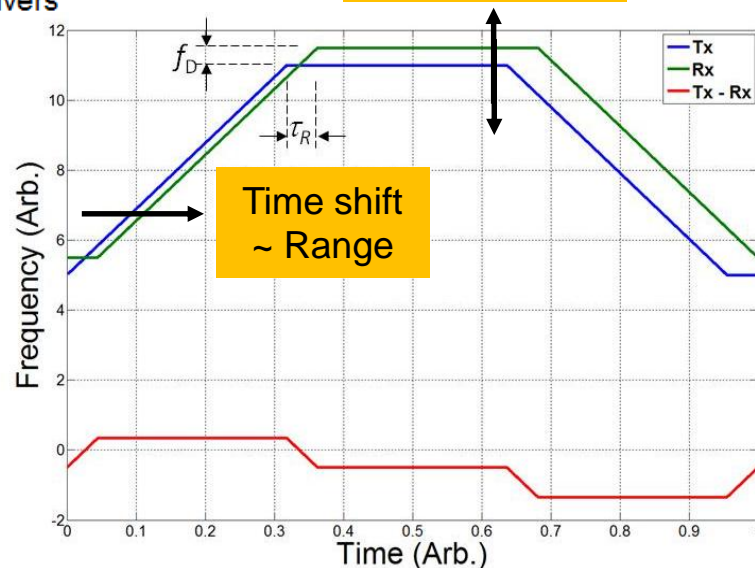


Autonomous Landing Hazard Avoidance Technology (ALHAT)



- Homodyne detection
- Linear frequency modulation to detect range

Frequency shift (Doppler) ~ Velocity



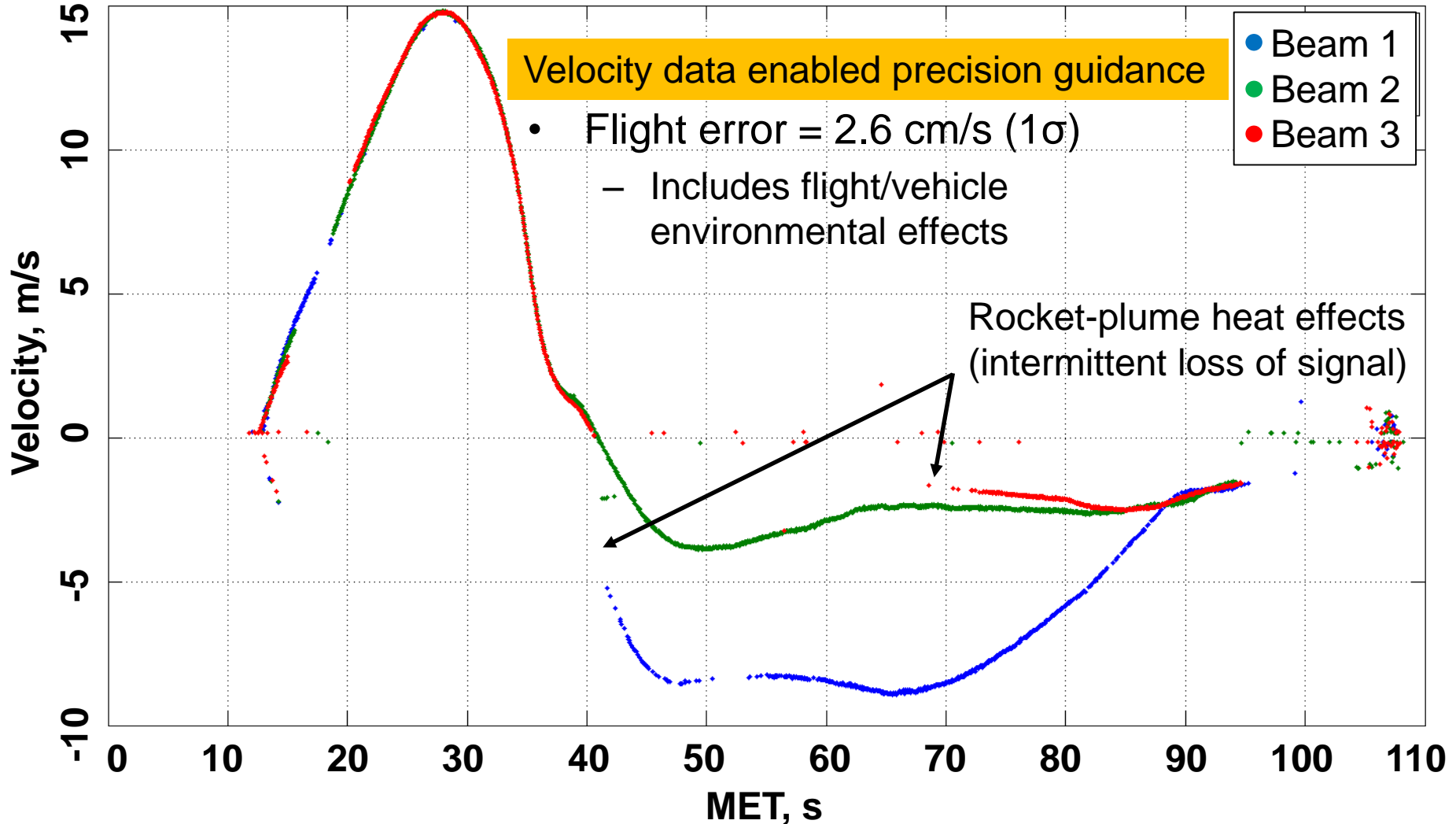
- Line-of-sight (LOS) velocity
- LOS range
- Derived: velocity vector, altitude, attitude



NDL Flight Data (FF11)



Autonomous Landing Hazard Avoidance Technology (ALHAT)





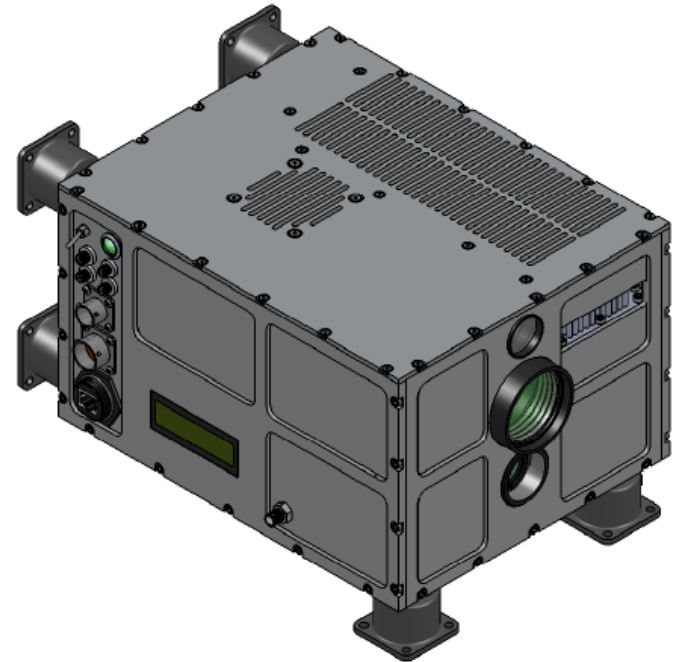
Laser Altimeter Specs



Autonomous Landing Hazard Avoidance Technology (ALHAT)

- Principles of operation similar to flash lidar except with a single pixel (round-trip time-of-flight system)
- LOS range: > 30 km
- Range precision: 5 cm
- Size: 6.5 x 8.75 x 10.5 inches
- Weight: 23.5 lbs
- Power: 170 Watts

**Goal
Met**





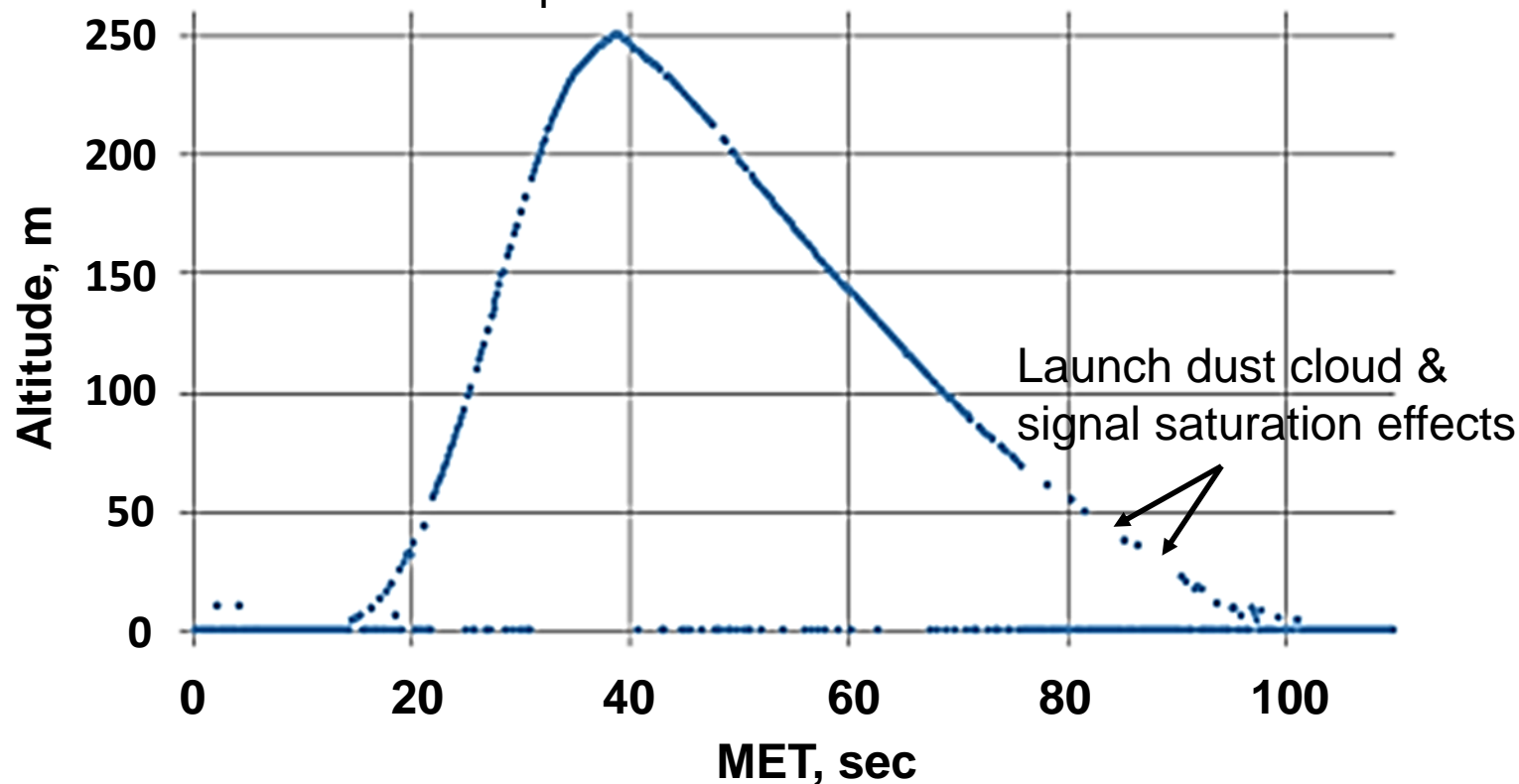
Laser Altimeter Flight Data (FF12)



Autonomous Landing Hazard Avoidance Technology (ALHAT)

Range data enabled precision guidance

- Flight Precision = 20 cm
 - Failure of one bit in counter prevented 5 cm





Concluding Remarks



Autonomous Landing Hazard Avoidance Technology (ALHAT)

- ALHAT-like GN&C & lidar-based sensing system critical for future planetary missions to mitigate hazardous terrain & poor lighting
- 1st hazard detection & avoidance and precision guidance for lander (rocket-propelled, autonomous Morpheus 1.5B) in closed-loop flts to safe-site amongst a lunar-like hazard field of rocks & craters on a lunar trajectory demonstrated during day and night at KSC to TRL 6
 - Flash lidar: detected 30cm hazards via real-time 3-D imaging of large area (1km slant range possible, Morpheus provided 430m slant range)
 - Navigation Doppler Lidar: successful guidance with 2.6 cm/sec velocity error including flight / vehicle environmental effects
 - Laser Altimeter: successful guidance with 20 cm range precision in flight
- Optical effects from rocket-heated air & launch dust cloud impacted safe-site selection & guidance; addressed in late 2014 campaign via wind restrictions, relocated NDL head, and repaired LA laser
- Next step: space design & qualification of sensor package