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

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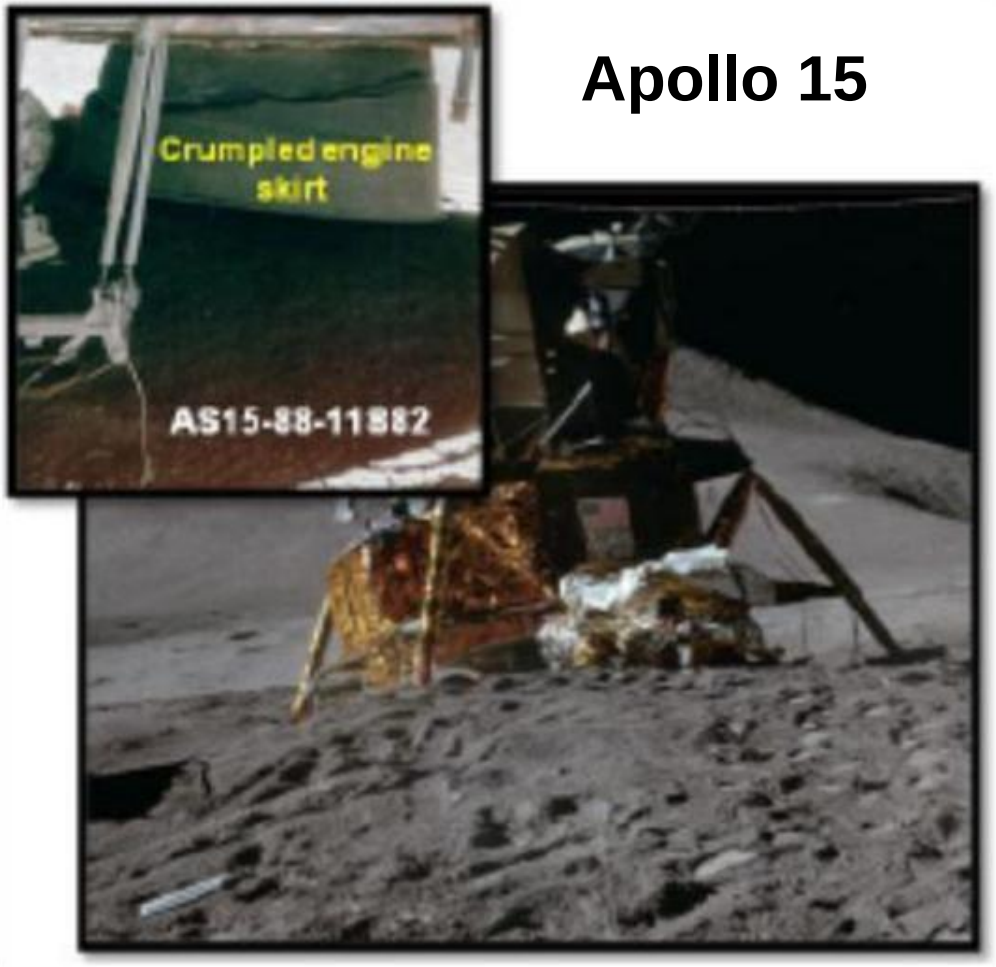
Planetary Landing: the Problem

- 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

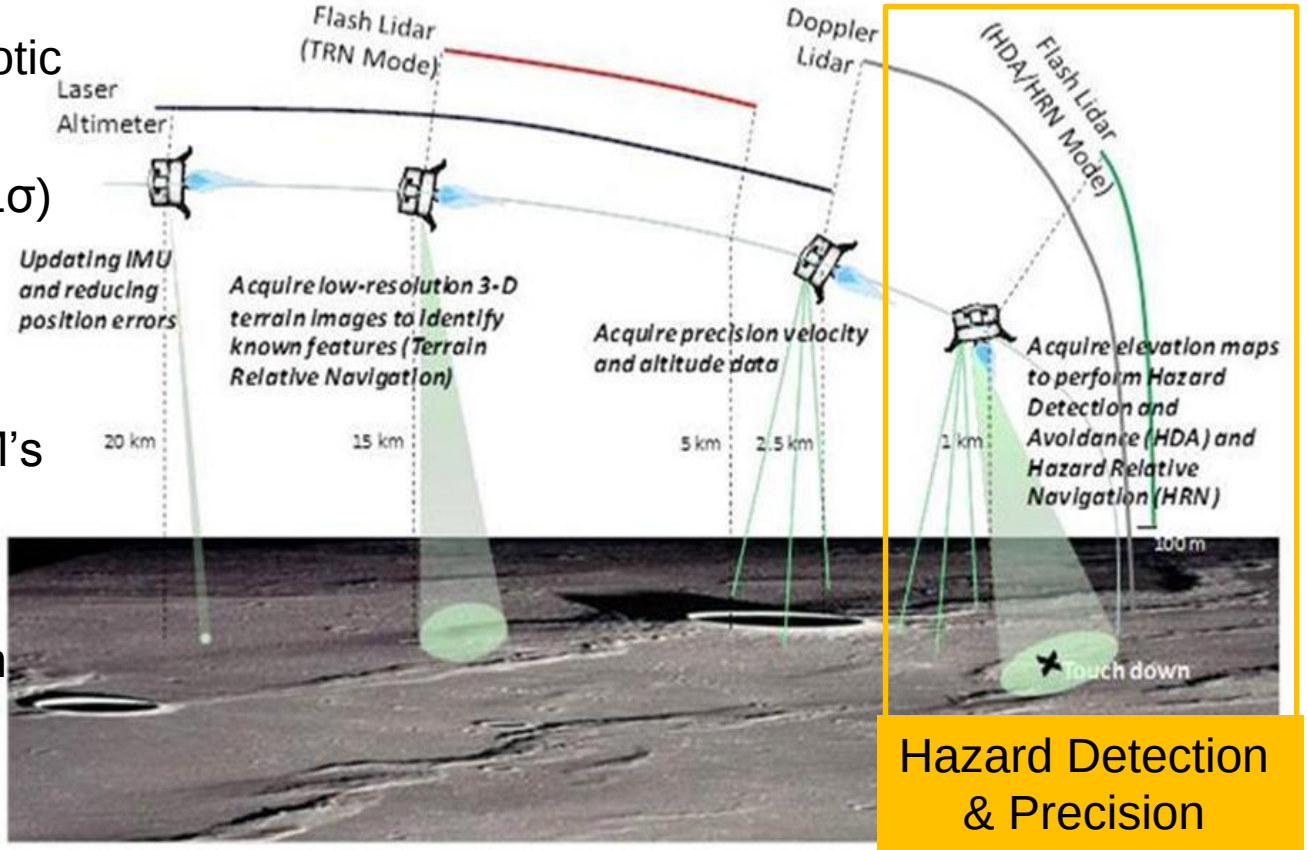
Apollo 15



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

- 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

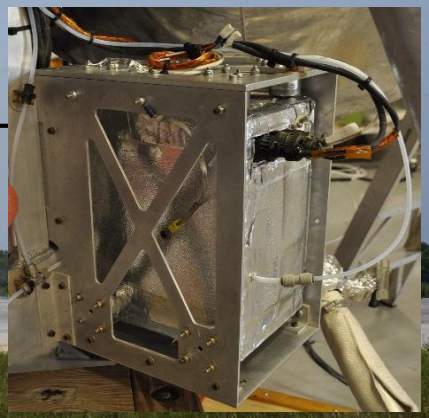
Navigation Doppler Lidar (NDL) Chassis

Flash Lidar Electronics Box (LEB)

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

NDL Optical Head

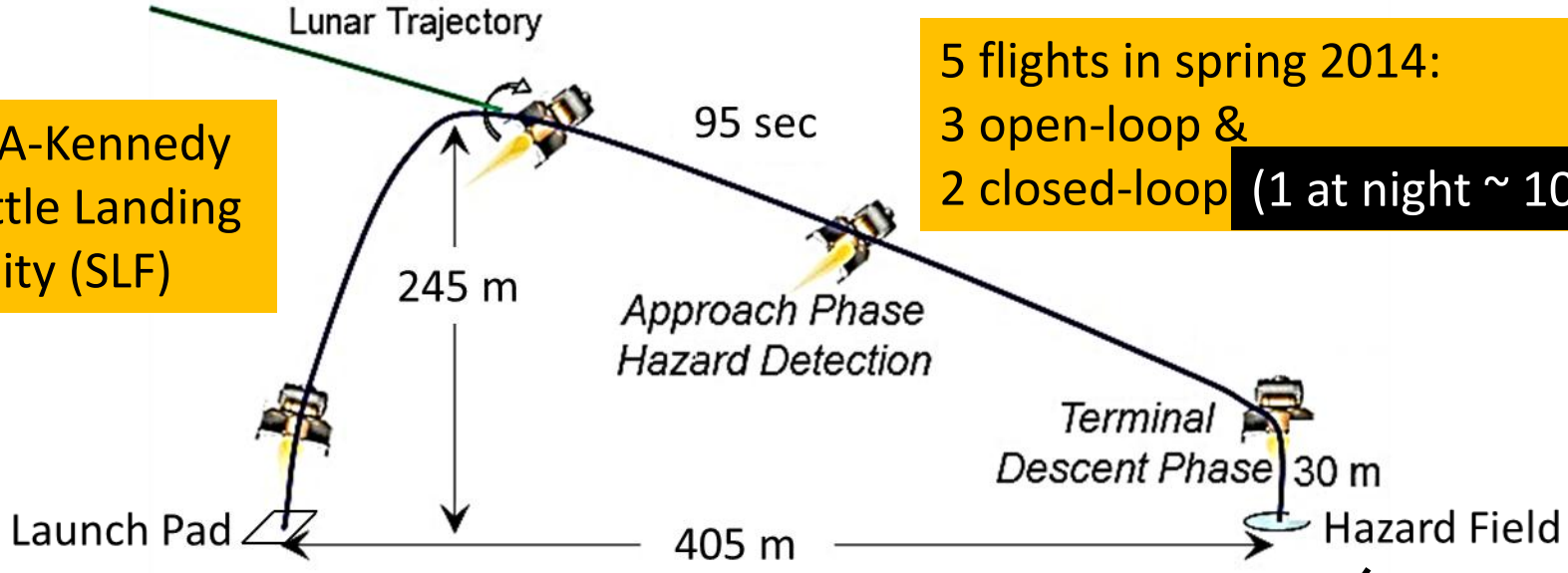
Laser Altimeter (LA)



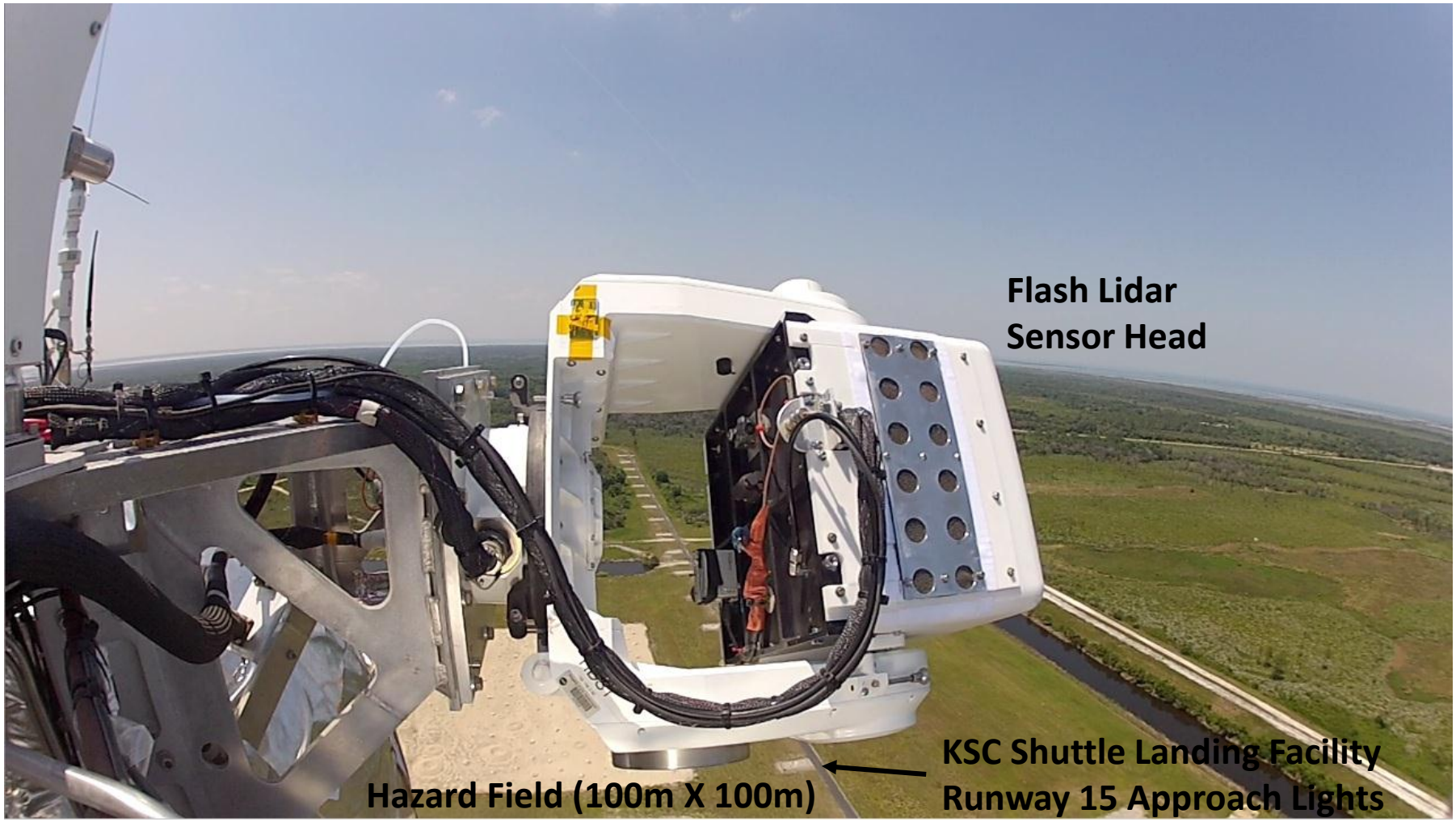
Field Test Plan

NASA-Kennedy Shuttle Landing Facility (SLF)

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



Morpheus on Approach

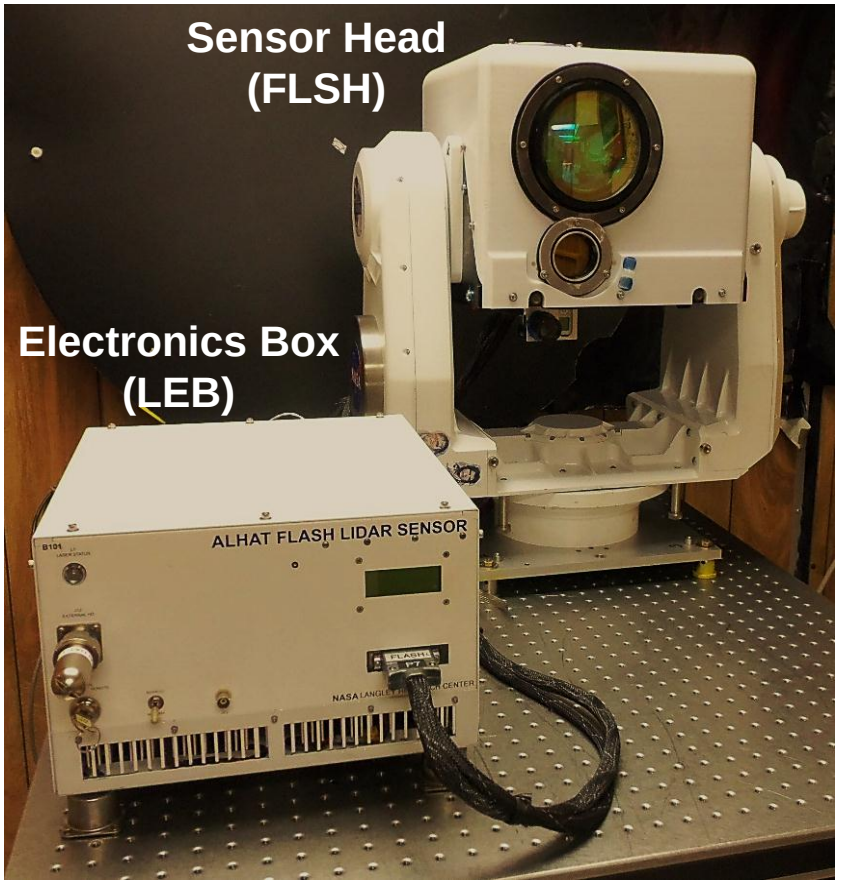


Flash Lidar Specs

- Max range: 1.35km
- # pixels: 128 x 128 = 16,384
- Range precision: 8 cm (1σ)
  - Allows 30cm hazard detection@1km

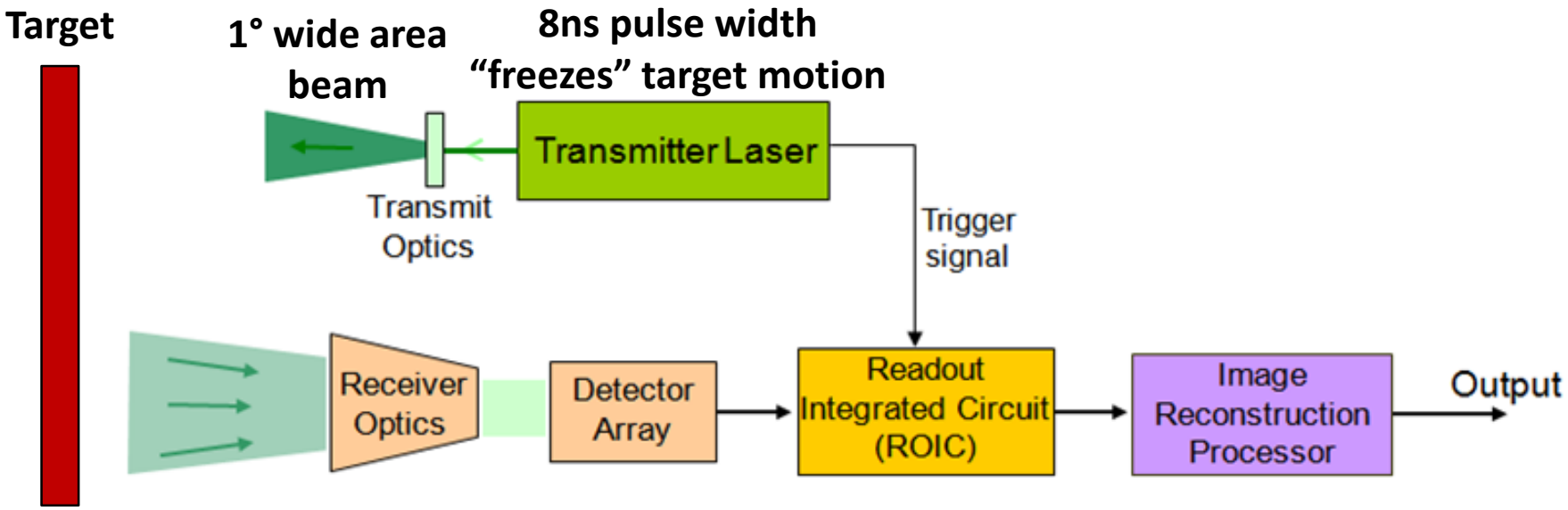
Goal Met

- Size:
  - FLSH: 11x13.5x13.25 inches
  - LEB: 9.5x14.2x13 inches
- Weight:
  - FLSH: *36 lbs
  - LEB: *36 lbs
- Power: *450 Watts



* Dominated by terrestrial cooling system

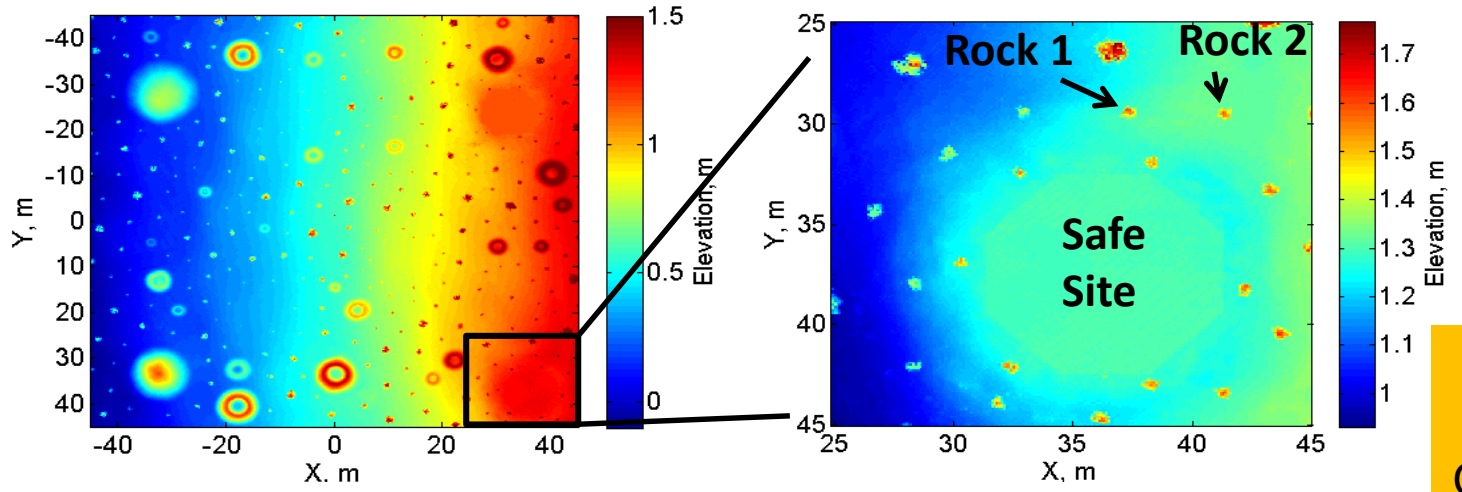
Flash Lidar Principles of Operation



- 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)

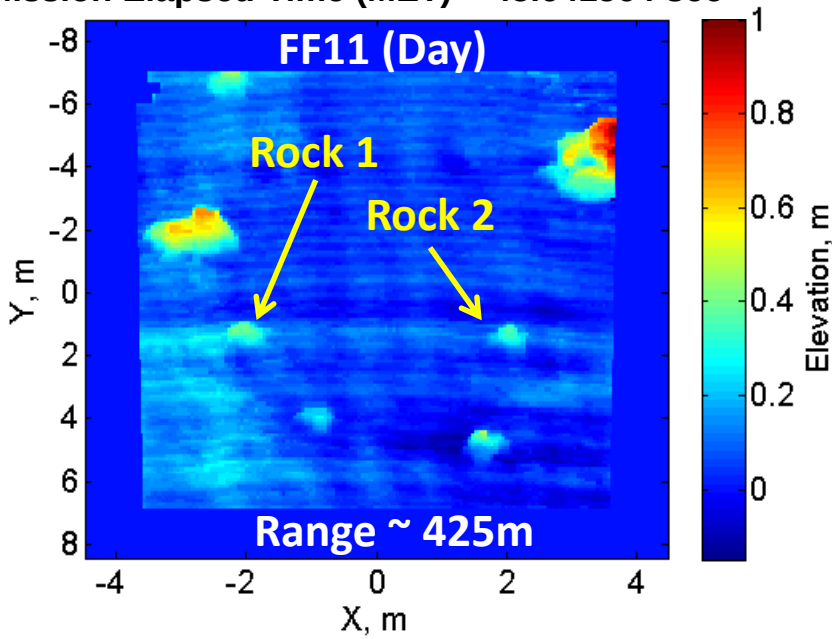


Rock 1 (30cm)

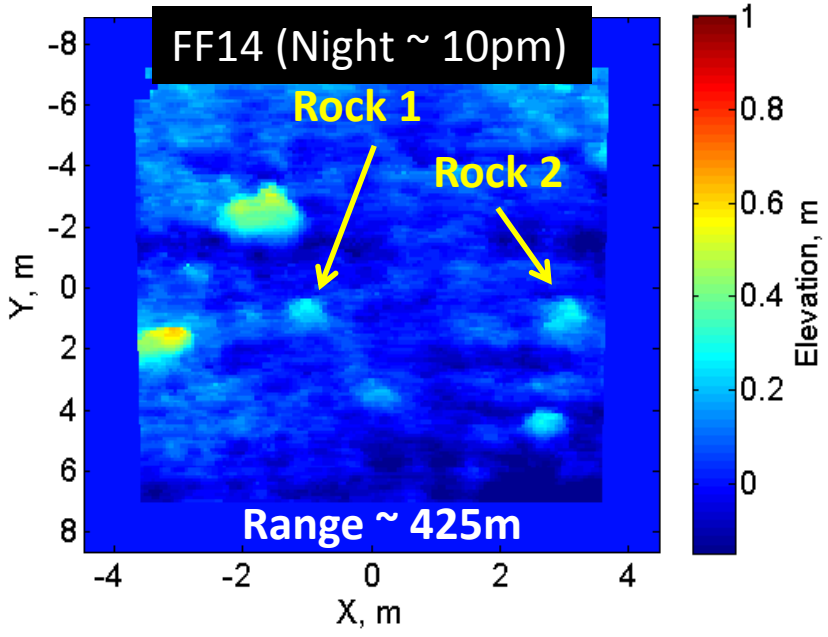
Rock 2 (28cm)

Hazard Detection Goals Met

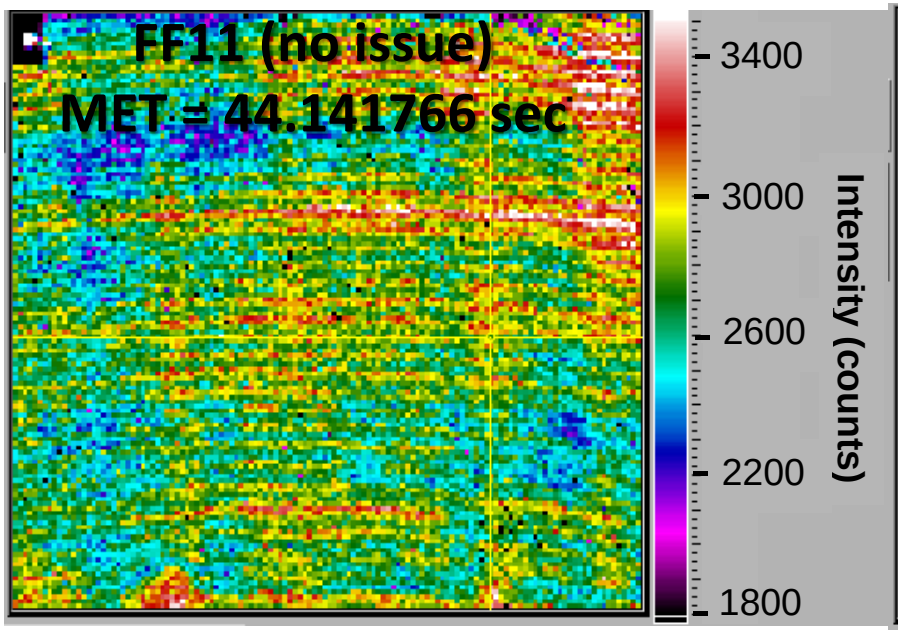
Mission Elapsed Time (MET) = 45.641564 sec

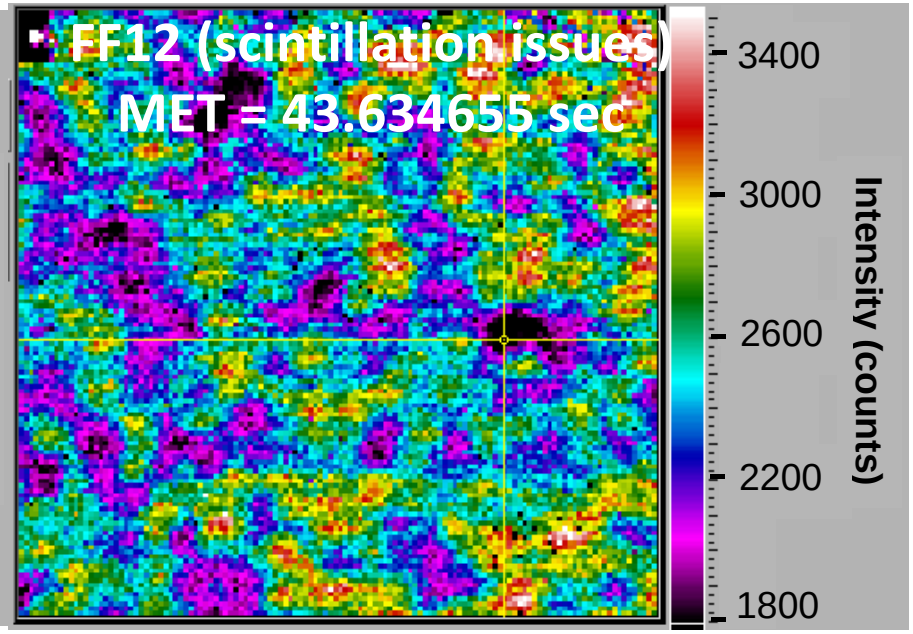


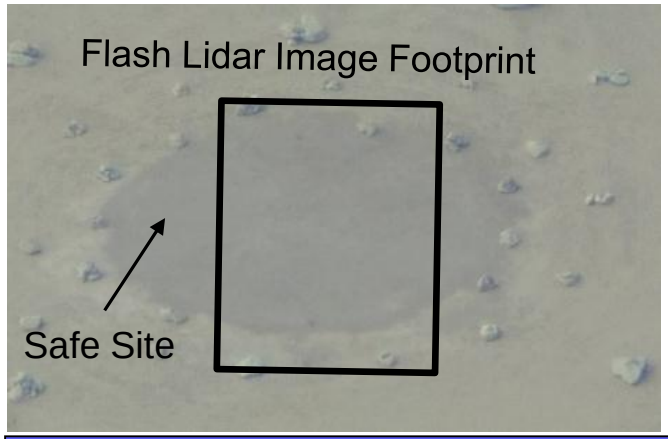
MET = 46.036214 sec



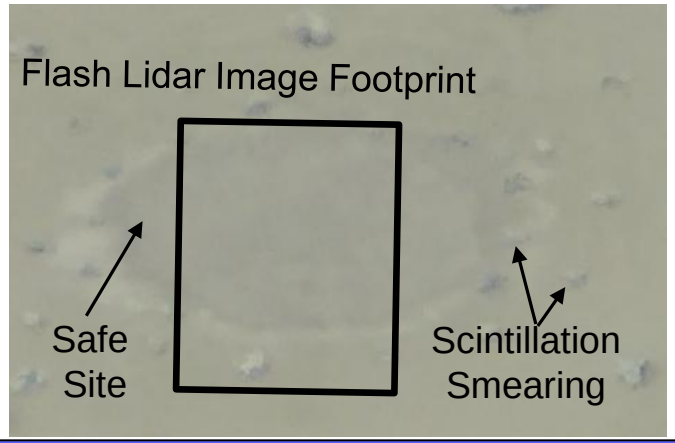
Rocket Plume Heat Effects on Flash Lidar (scintillation)







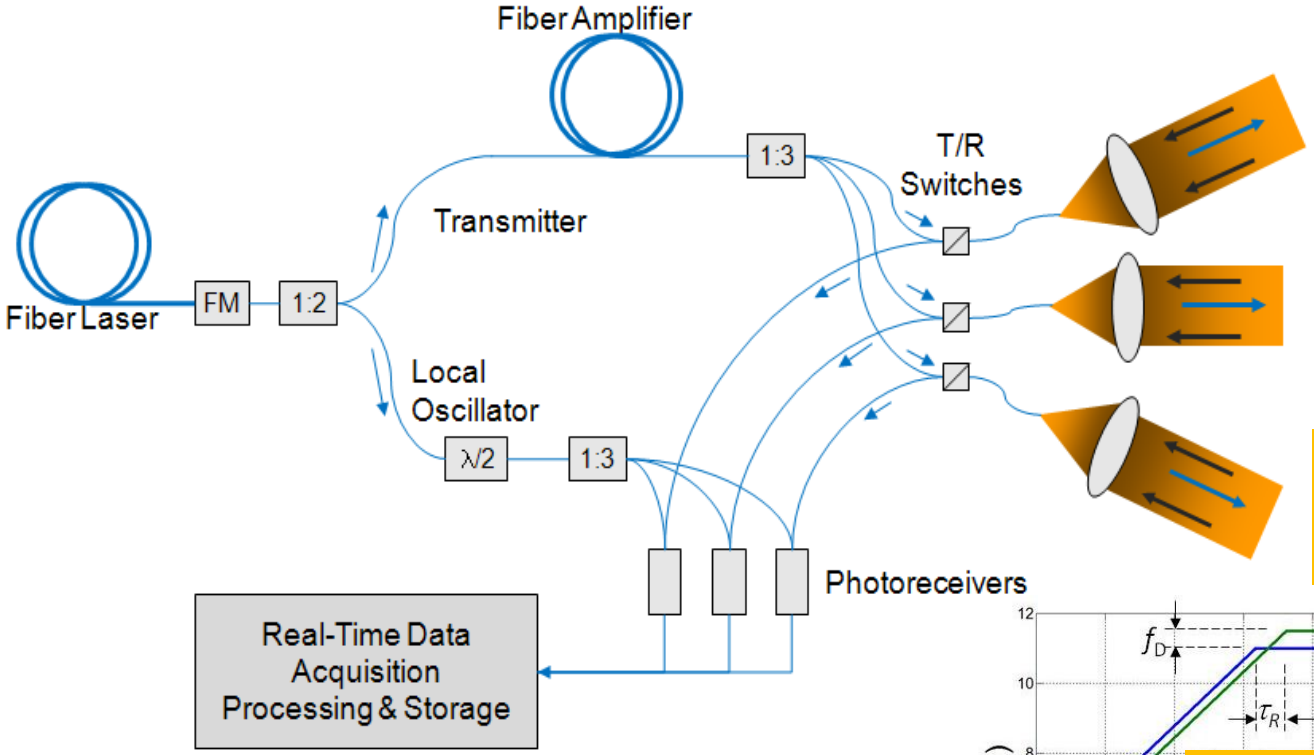
Apply wind restrictions for future flights



Navigation Doppler Lidar (NDL) Specs

- Line-of-sight (LOS) operational range: 2km
- LOS velocity precision: 0.2cm/s **Goal Met**
- 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

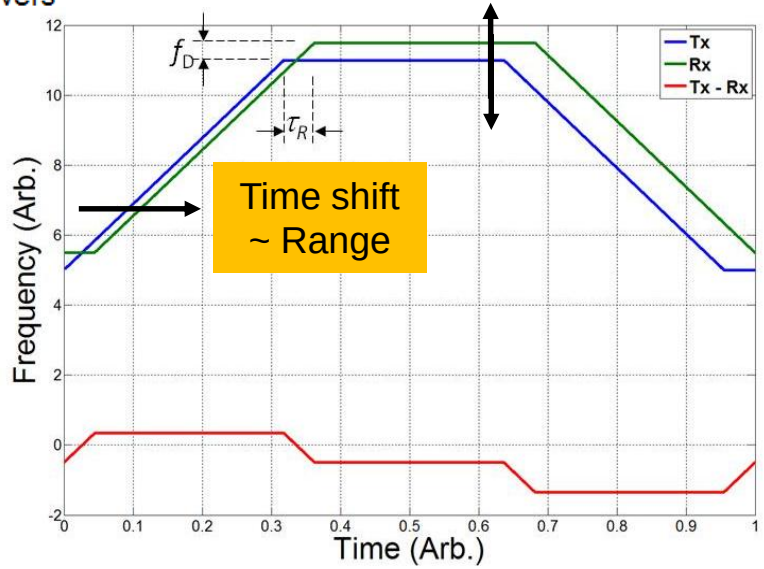
NDL Principles of Operation



- Homodyne detection
- Linear frequency modulation to detect range

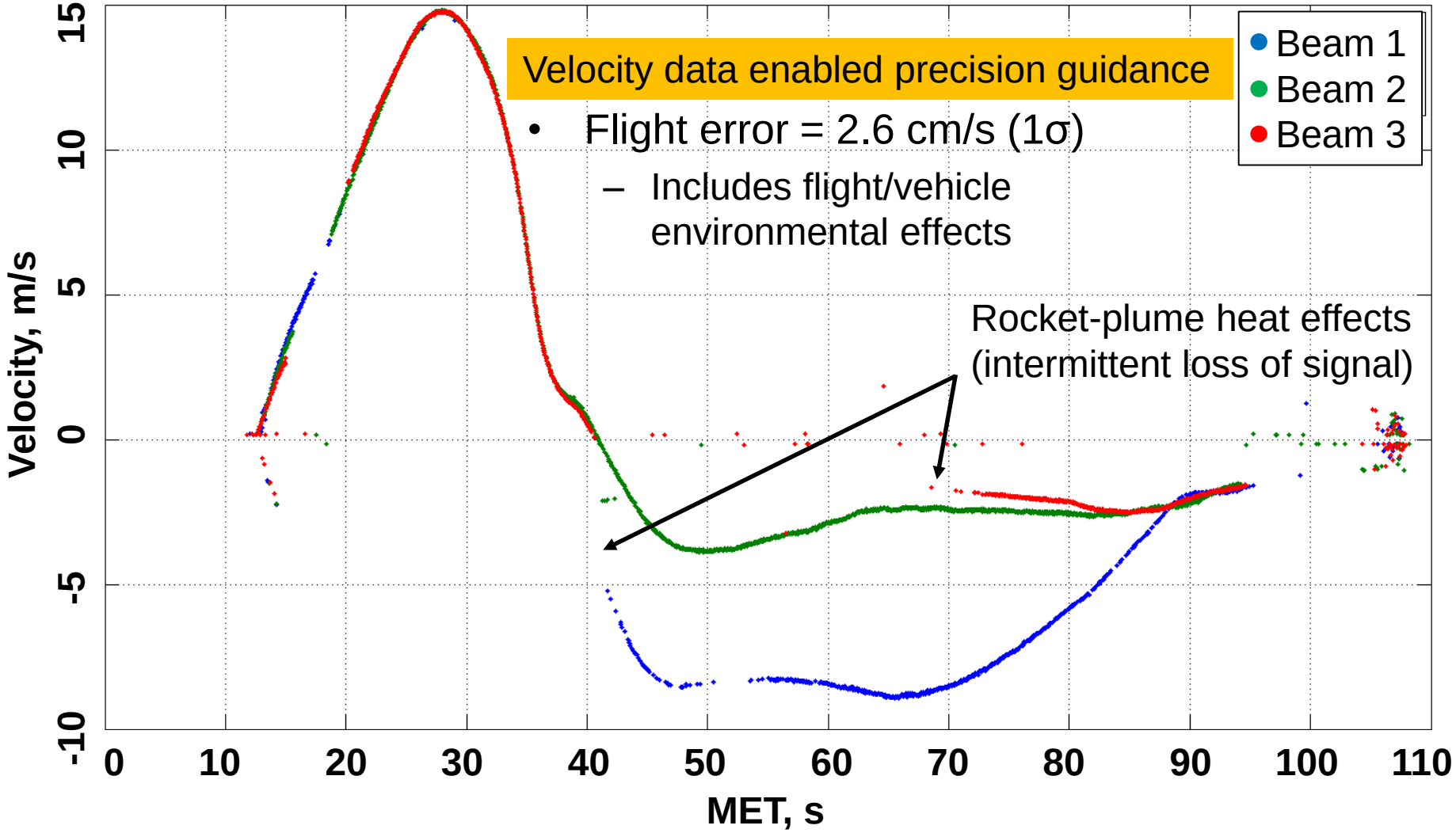
Frequency shift (Doppler) ~ Velocity

Time shift ~ Range



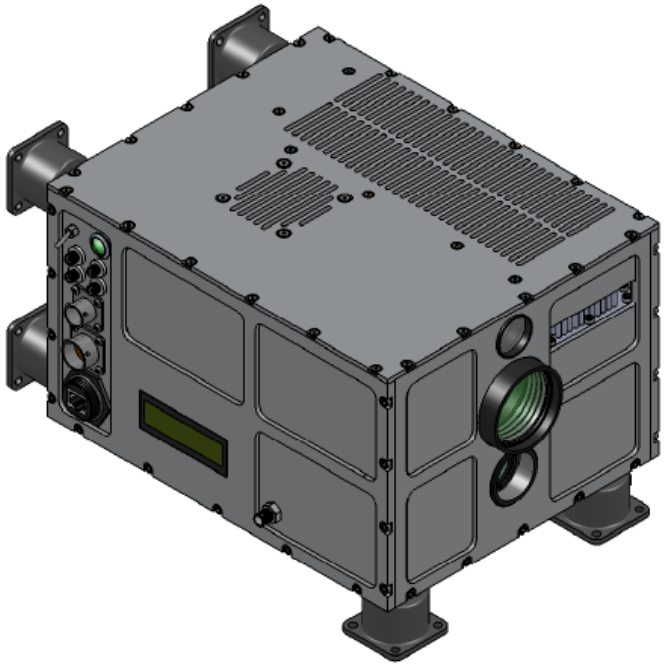
- Line-of-sight (LOS) velocity
- LOS range
- Derived: velocity vector, altitude, attitude

NDL Flight Data (FF11)



Laser Altimeter Specs

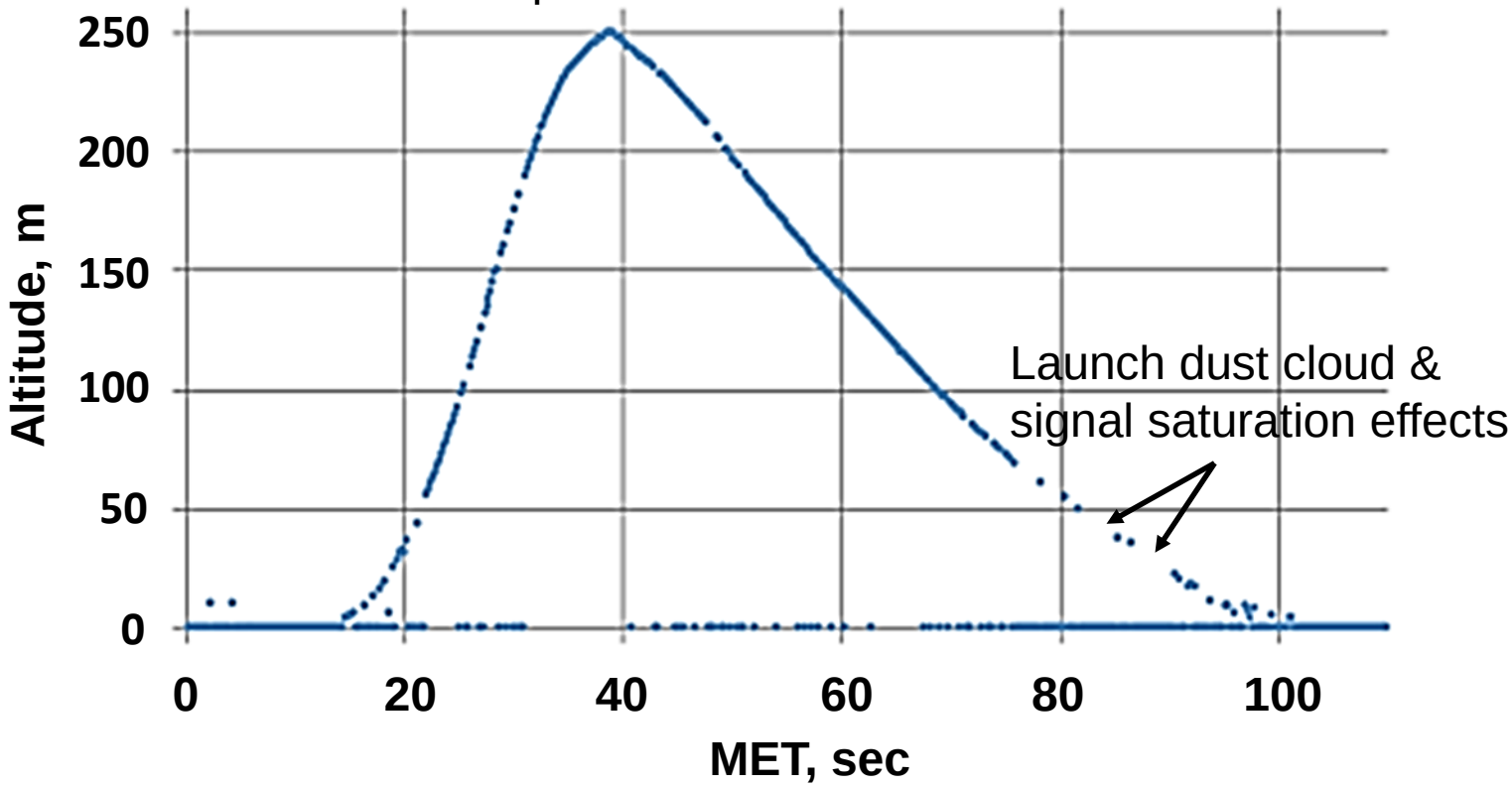
- Principles of operation similar to flash lidar except with a single pixel (round-trip time-of-flight system)
- LOS range: > 30 km
- Range precision: 5 cm **Goal Met**
- Size: 6.5 x 8.75 x 10.5 inches
- Weight: 23.5 lbs
- Power: 170 Watts



Laser Altimeter Flight Data (FF12)

Range data enabled precision guidance

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



Concluding Remarks

- 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