Mapping **A**rchitecture **C**oncept for **U**niversal **L**anding **A**utomation

MACULA

Spring Final Review

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AGENDA

Project Purpose and Objectives

Design Description

Test Overview

Test Results

Systems Engineering

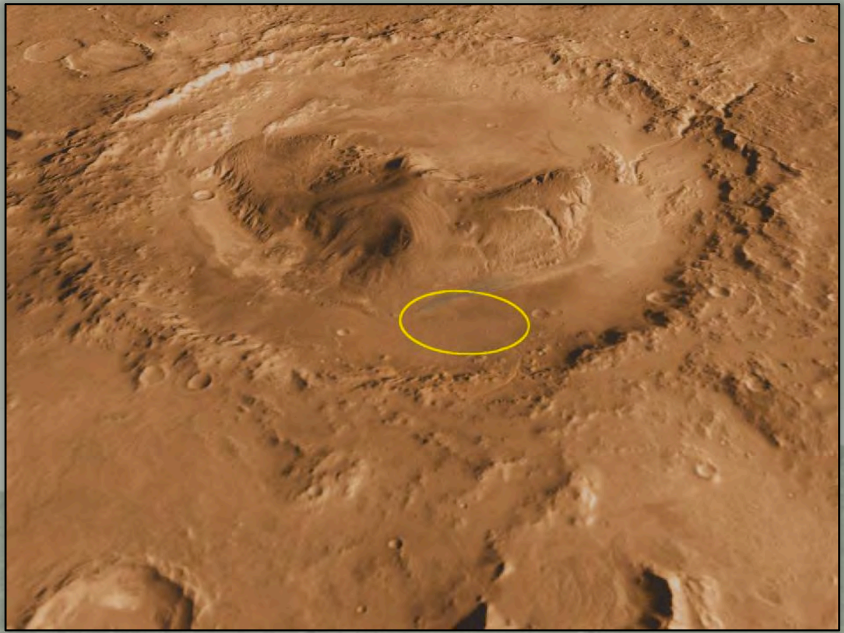
Project Management

PROJECT PURPOSE AND OBJECTIVES

MOTIVATION: MARS EDL

Martian surface topography is well mapped, allowing for the selection of safe landing areas

Due to uncertainty in orbital insertion and EDL trajectory, safe landing areas must be large



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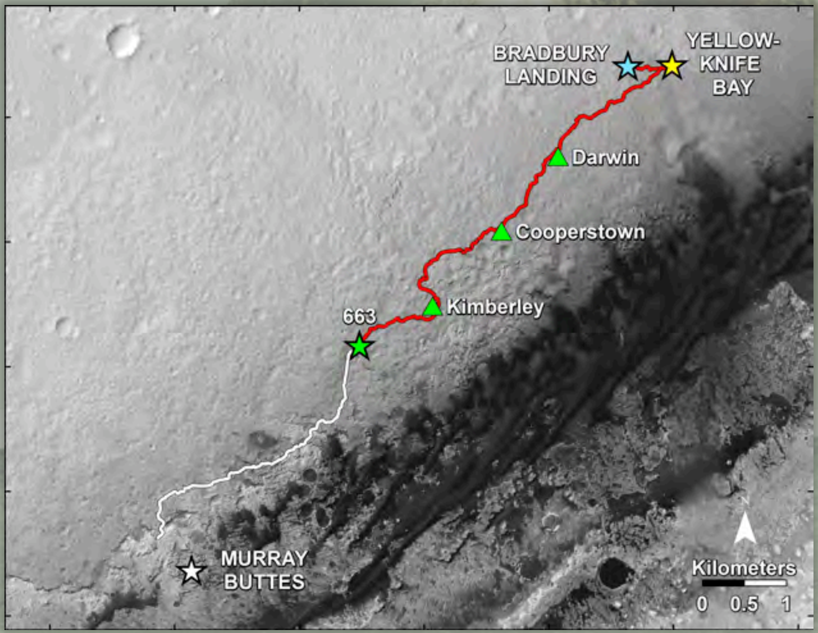

https://www.nasa.gov/sites/default/files/pia18391_sol663map-small.jpg

MOTIVATION: OTHER TARGETS

Other bodies, like Europa or asteroids, are not well mapped

Unknown surface topography poses significant risk for a lander

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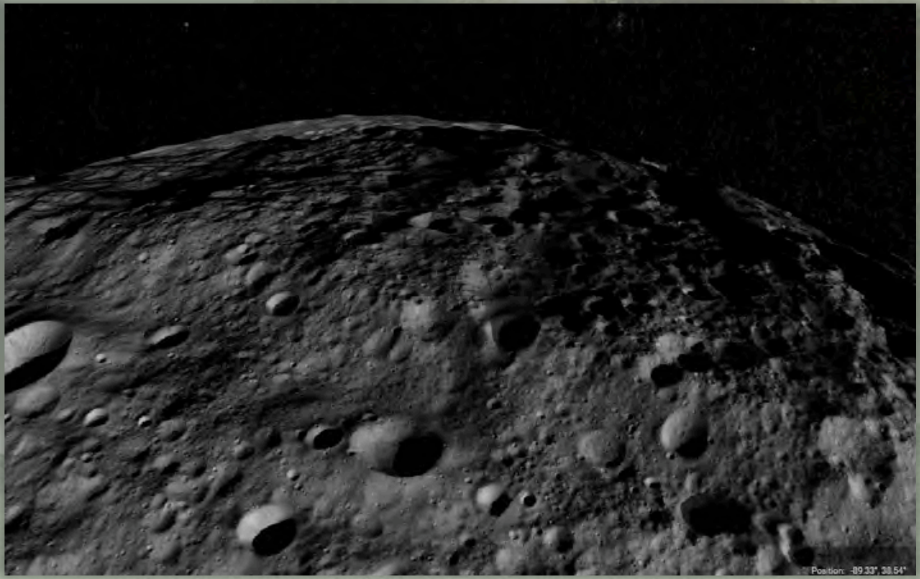
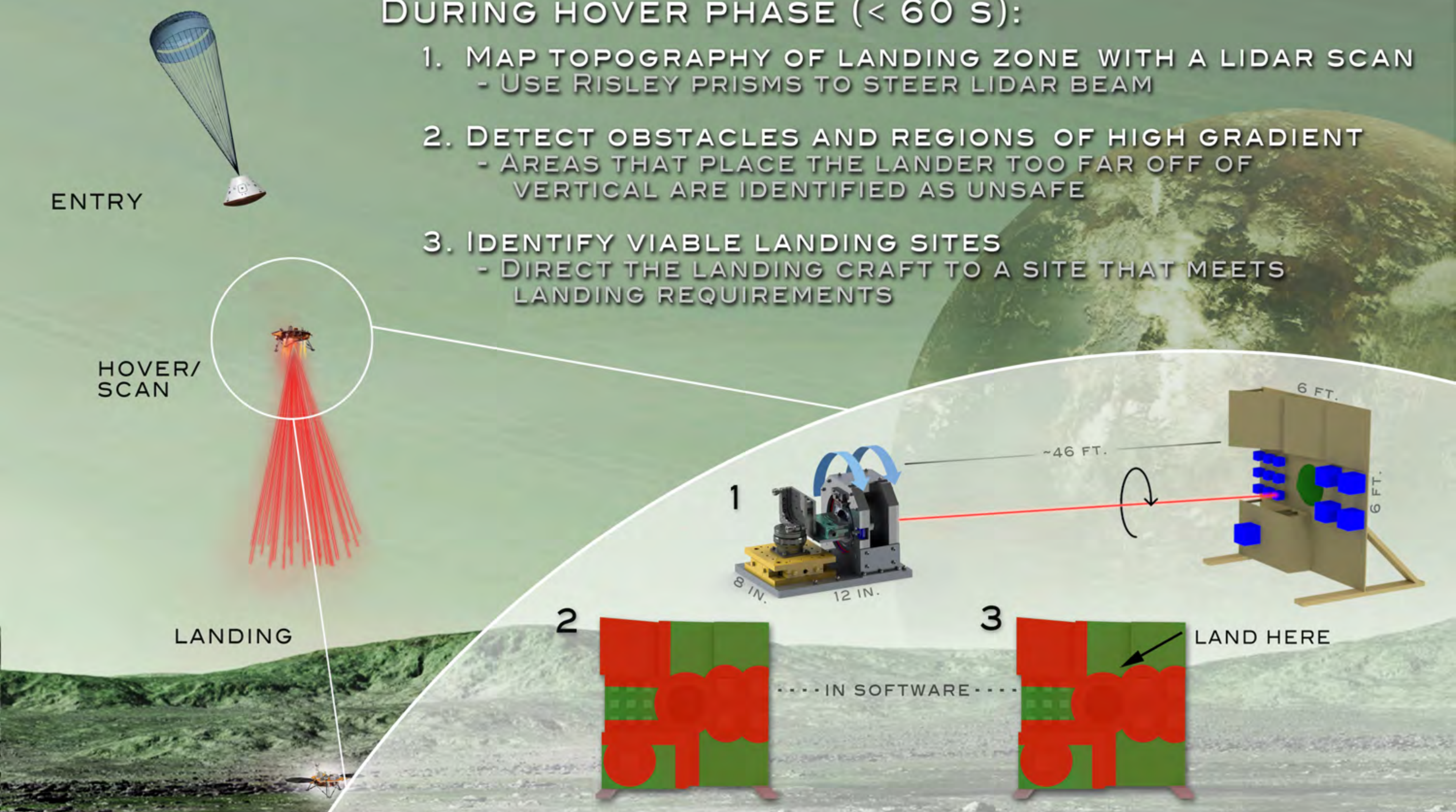


https://www.nasa.gov/sites/default/files/thumbnails/image/vesta_trek.jpg

Concept of Operations

During hover phase (< 60 s):

1. Map topography of landing zone with a lidar scan
   - Use Risley prisms to steer lidar beam
2. Detect obstacles and regions of high gradient
   - Areas that place the lander too far off of vertical are identified as unsafe
3. Identify viable landing sites
   - Direct the landing craft to a site that meets landing requirements



OBJECTIVES & SUCCESS LEVELS

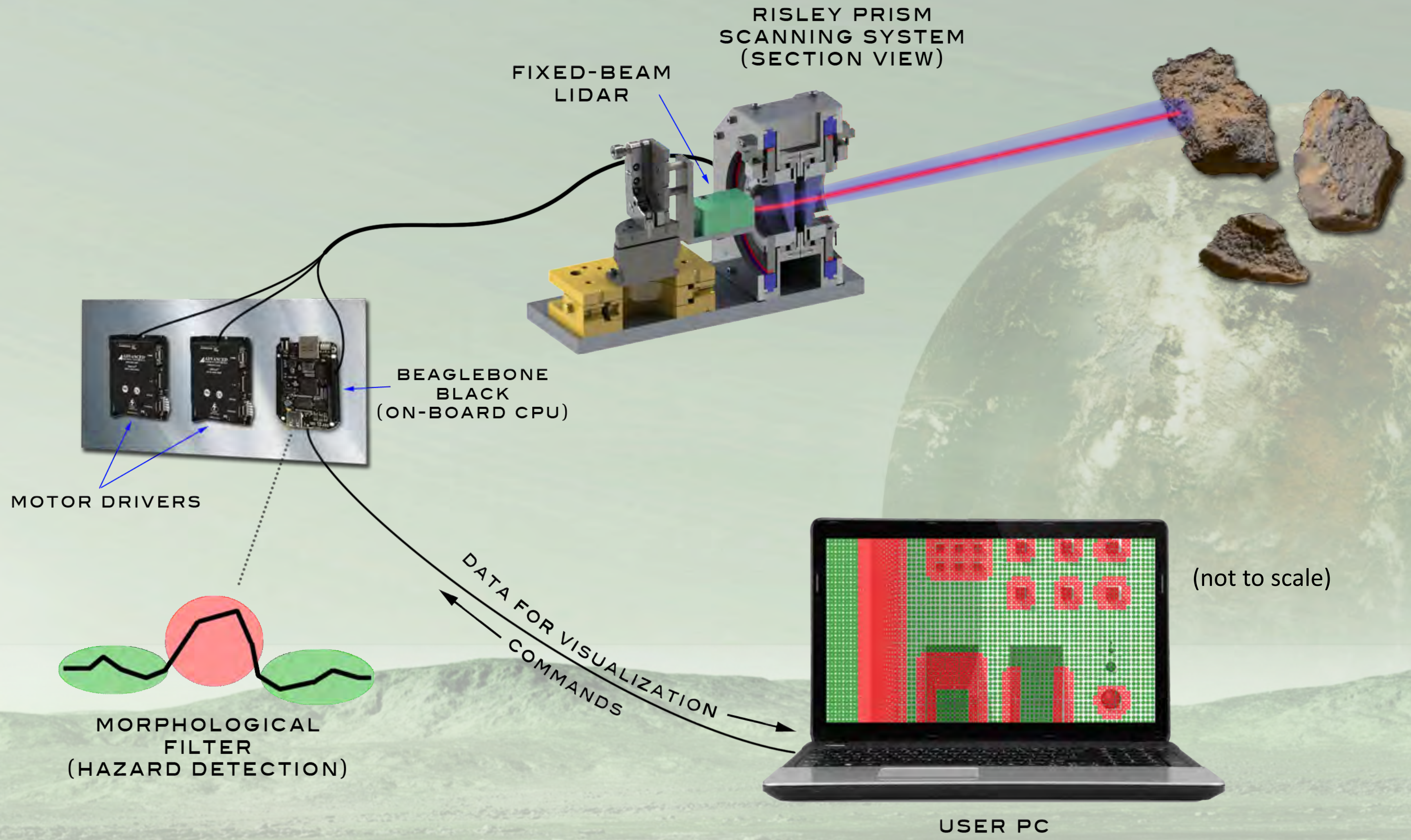
Design, **manufacture**, and **test** a **proof-of-concept** light detection and ranging (lidar) **scanning system** for a landing spacecraft

Success Levels:

1. Lidar sensor and scanning mechanism, mounted on a stationary platform, shall **record correlated range and attitude measurements**
2. System shall scan a known test scene and **project measurements into a 3D point cloud**
3. System shall scan a landing zone mockup and **analyze the 3D point cloud for hazards**
4. System shall **select a safe landing zone**

Design Description

Baseline Design Summary

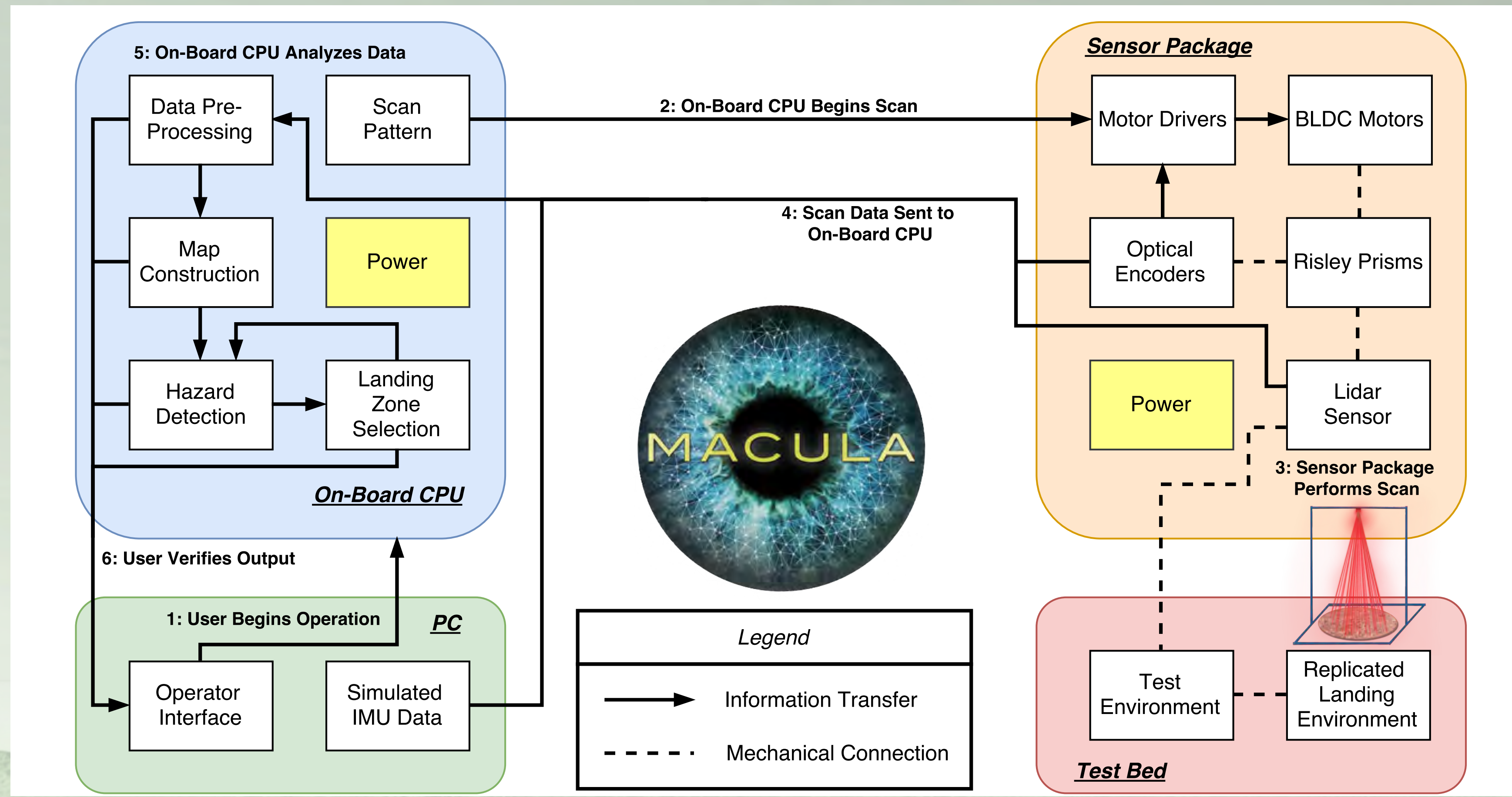


(not to scale)

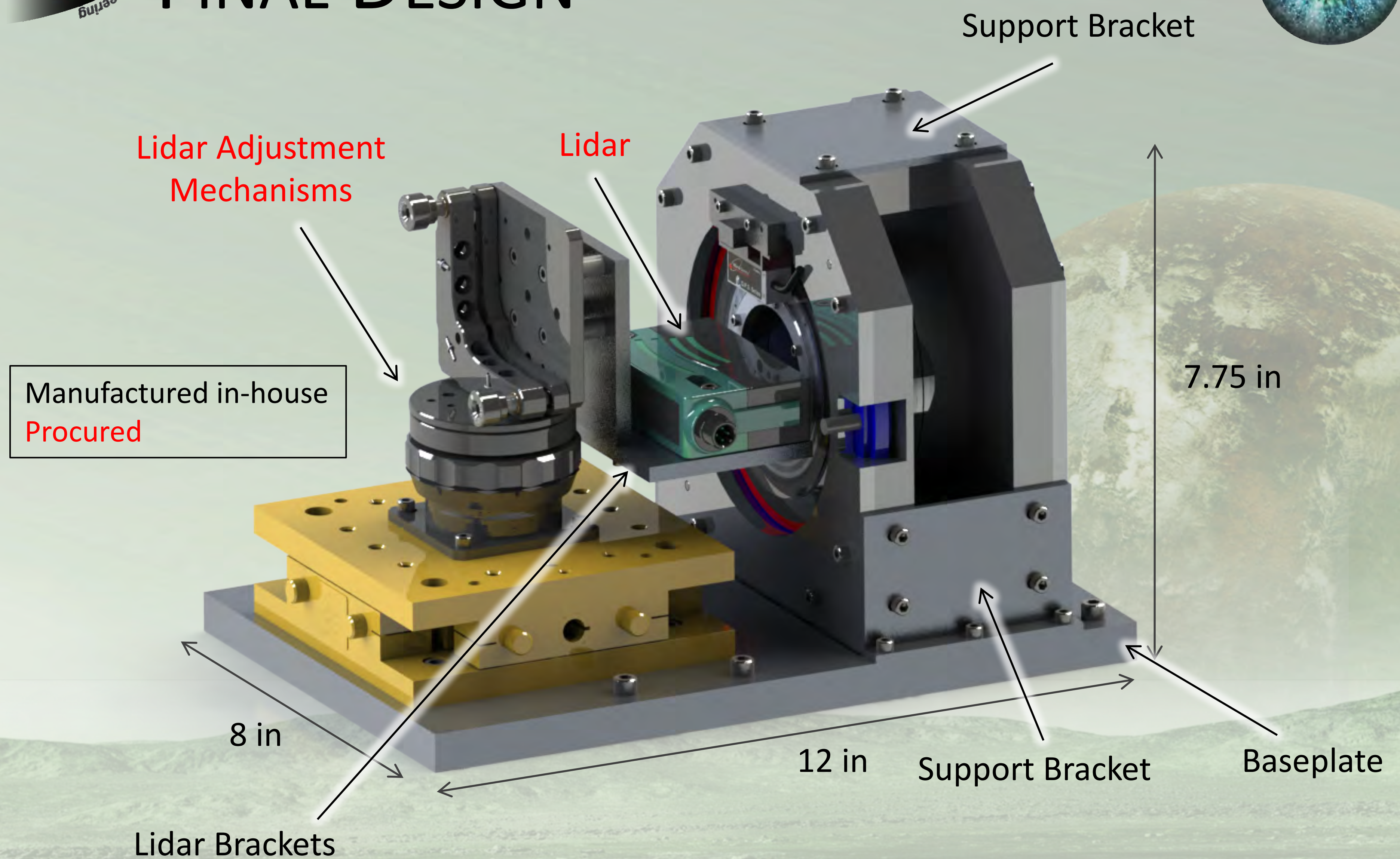
Changes Since TRR

Modification	Rationale
Test range reduced from 14.1 m to 8 m	Lidar return reliability
Ghost mitigation	Noise in lidar data
Ferrite bead	Noise from motor EMI
Electronics shielding	Noise from motor EMI
PCB Rev B	Encoder level shifting issue
Motor cable strain relief	Improper lead attachment
Encoder mounting block	Correct error in mounting plan

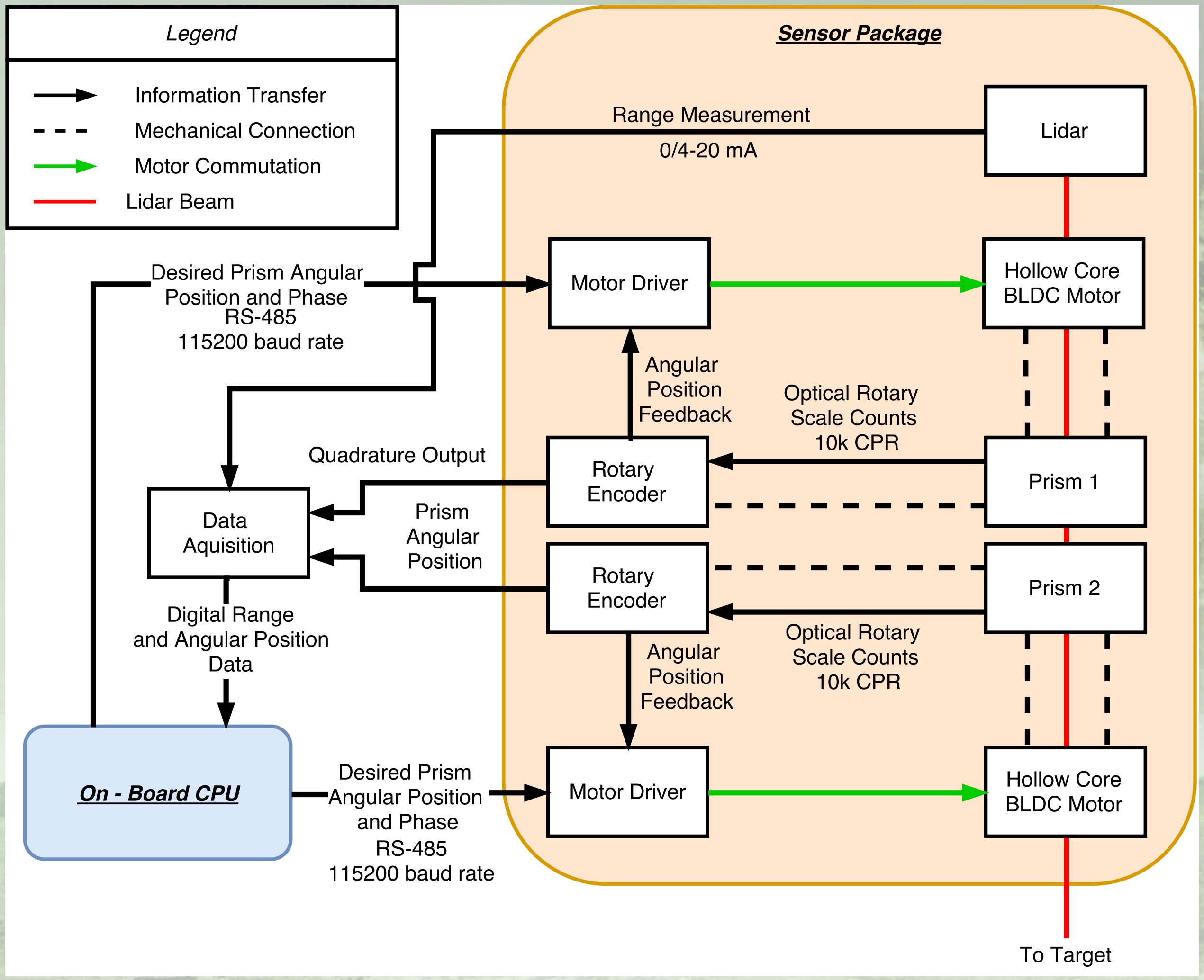
Functional Block Diagram



FINAL DESIGN

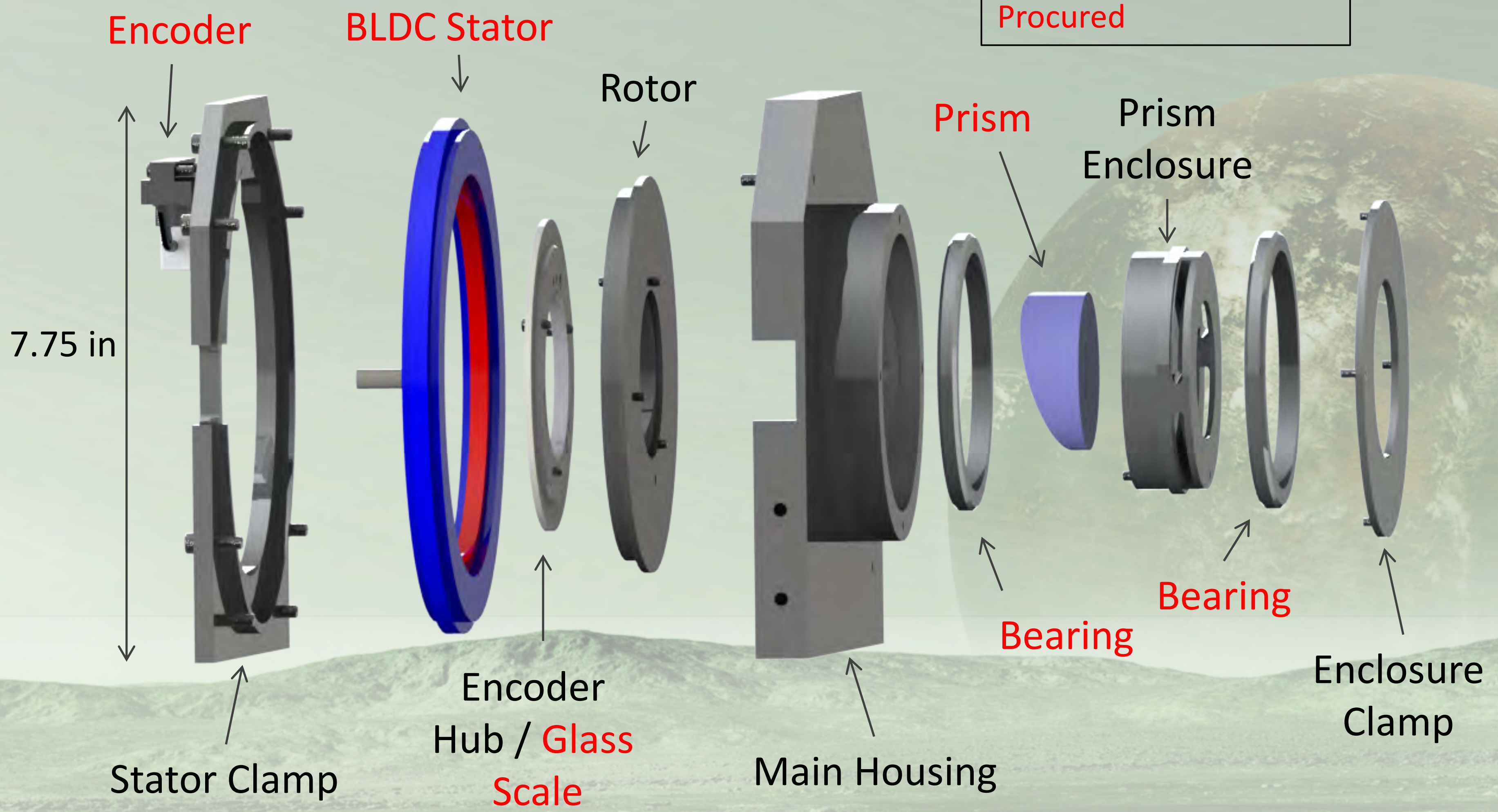


Scanning System Functional Block Diagram

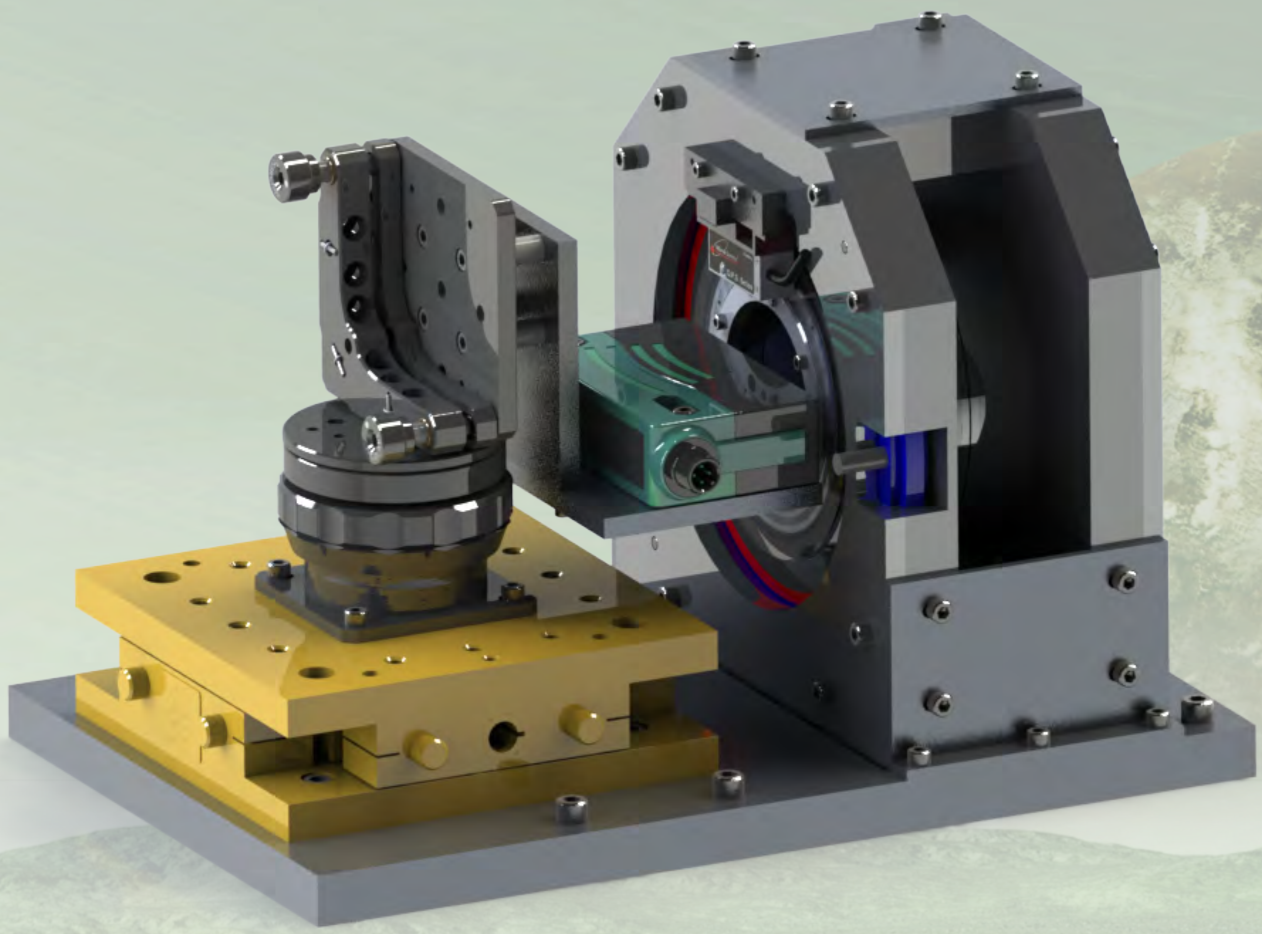


Scanning System

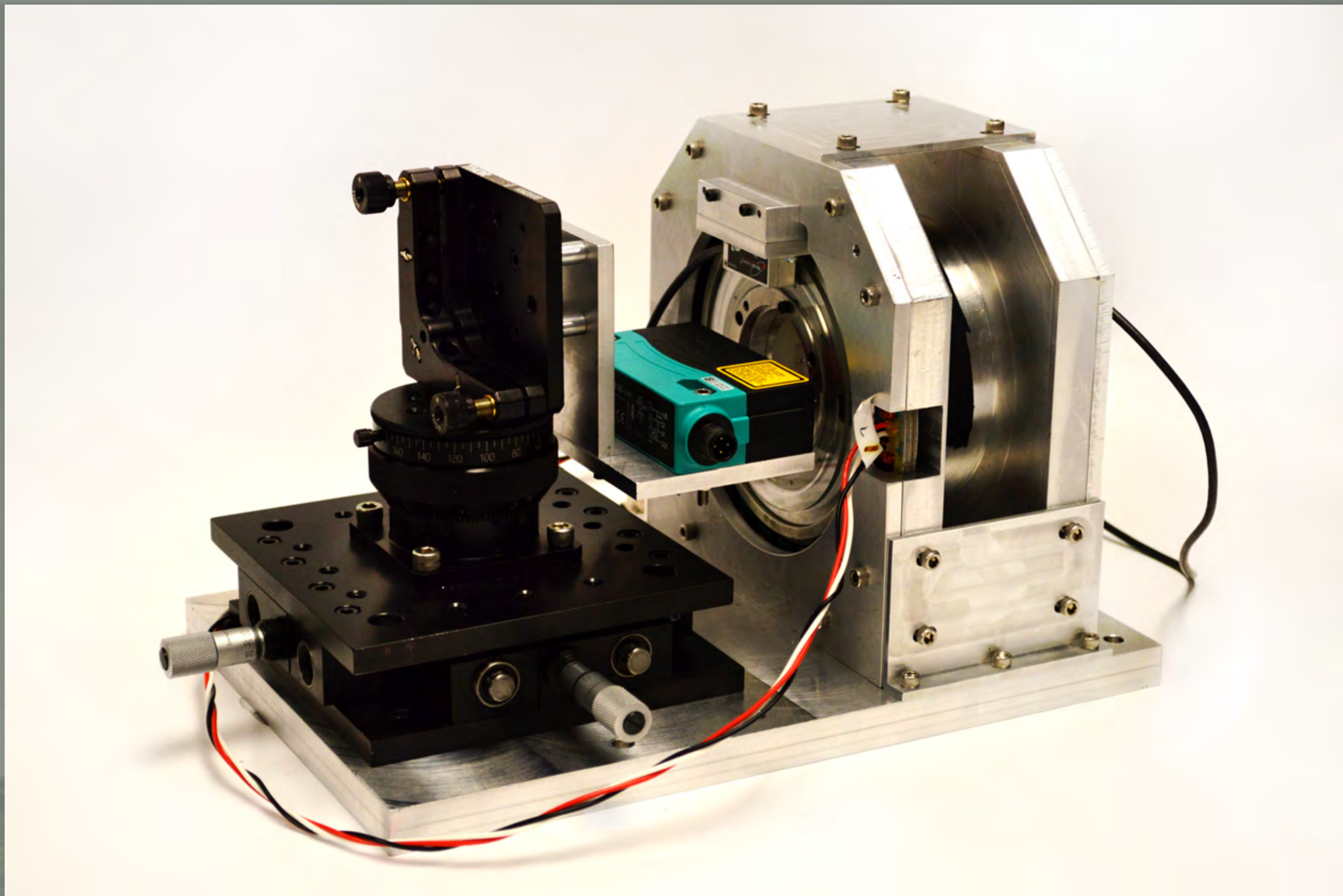
Manufactured in-house
Procured



Assembled System



Assembled System

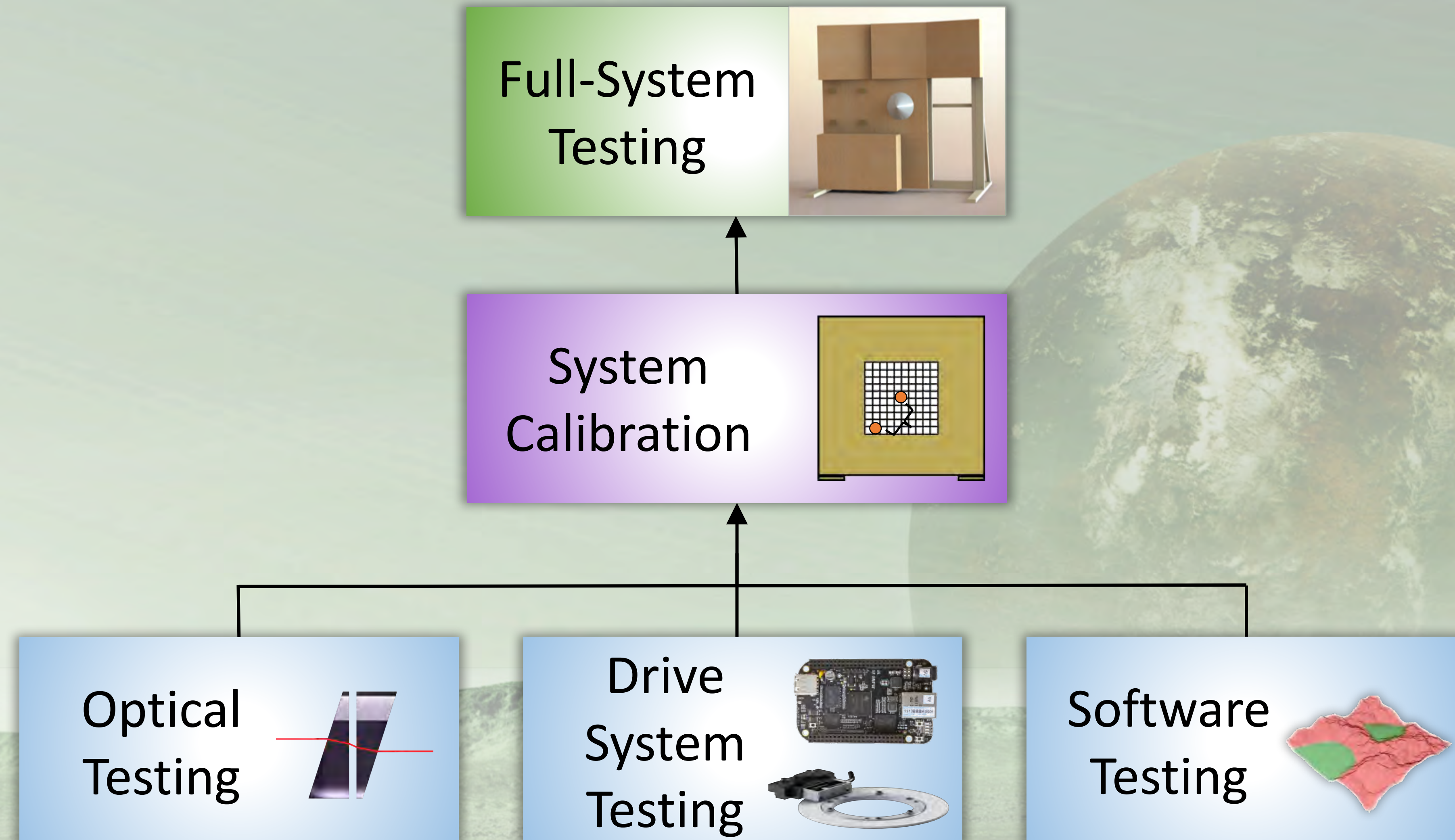


Critical Project Elements

1. Optics
   - Why: concerned about measurements through prisms
   - Result: resolved – measurements taken through prisms
2. Risley Prism Control
   - Why: precise pointing knowledge is required for scan
   - Result: partially resolved – motors cannot be driven sufficiently fast
3. Embedded System
   - Why: communications and timing required for precise scan
   - Result: partially resolved – encoders cannot be read sufficiently fast
4. Manufacturing
   - Why: quantity of work
   - Result: resolved – all manufacturing completed on time

TEST OVERVIEW

TEST HIERARCHY



LIDAR TEST OVERVIEW

Relation to Project Success

- Success Level 1: obtain range measurements
- Success Level 2: accurate map construction

Objective

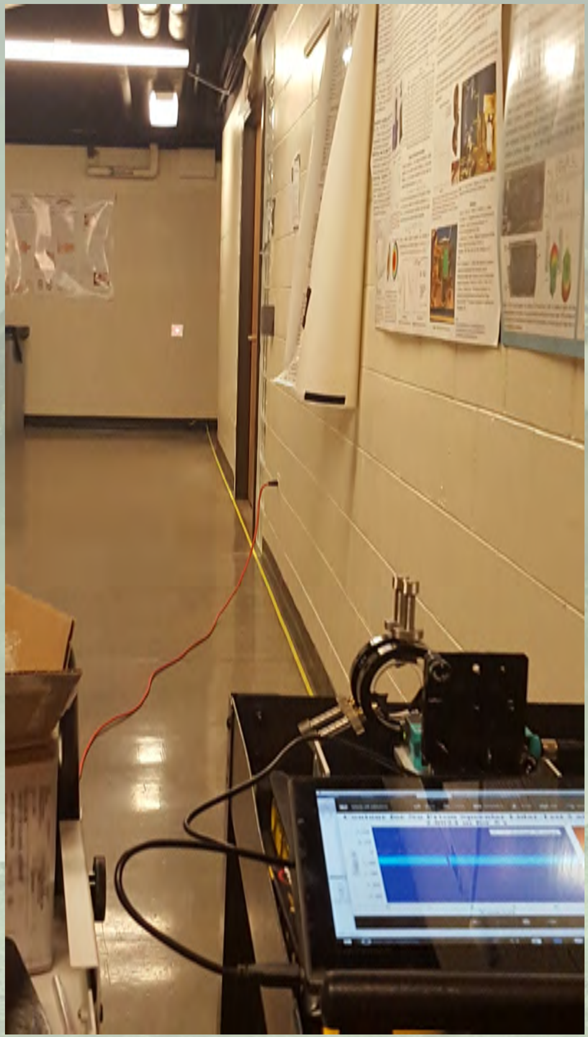
- Obtain measurements through prisms
- Characterize error

Requirements

- DR 4.1: Range of 12 -15 m
- DR 4.2: Error < 2.5 cm (1 sigma)

Procedure

- Sample range at 0.3 m increments between 12 m and 15 m with and without prisms



Drive System Test Overview

Relation to Project Success

- Success Level 1: obtain attitude measurements
- Success Level 2: accurate map construction

Objective

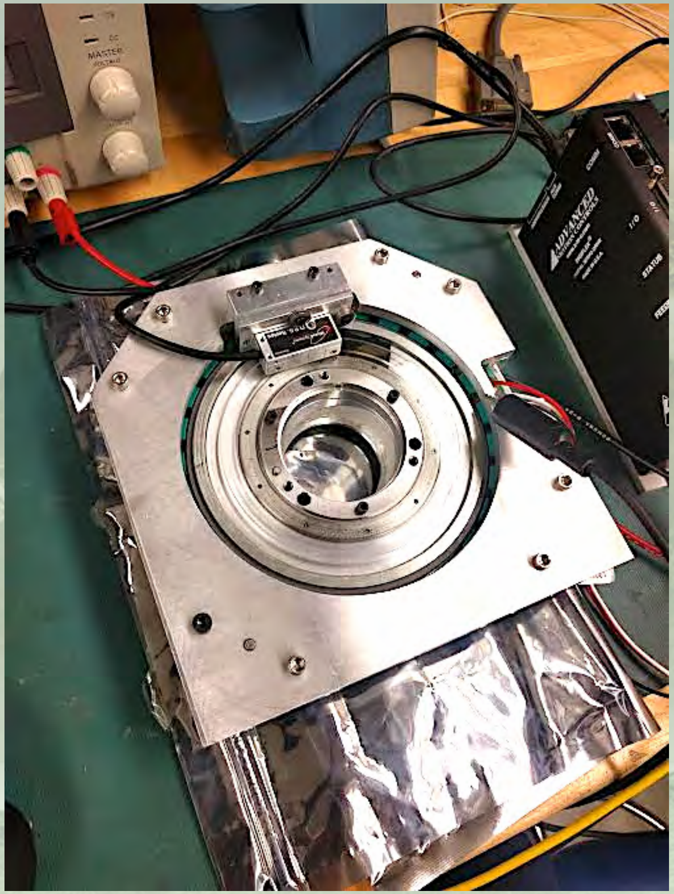
- Communication between BeagleBone and drivers
- Achieve desired scan pattern

Requirements

- DR 1.3: Scan resolution of 0.1 m
- DR 5.2.1: Motor acceleration of 15 rad/s^2
- DR 5.2.2: Motor velocity from 0.45 rad/s to 10 rad/s

Procedure

- Incremental increase in communication capability
- Command and compare with desired resolution



Software Test Overview

Relation to Project Success

- Success Level 3: analyze point cloud for hazards
- Success Level 4: select a safe landing site

Objective

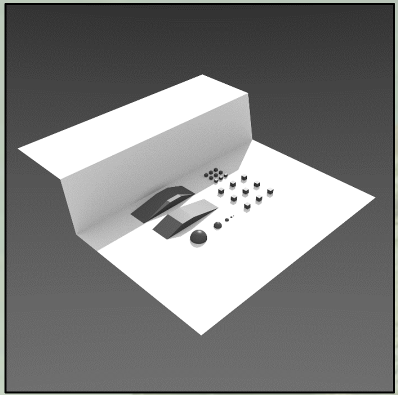
- Verify hazard detection algorithm performance
- Provide “truth” value for comparison

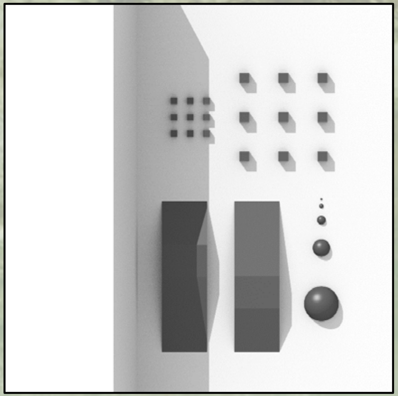
Requirements

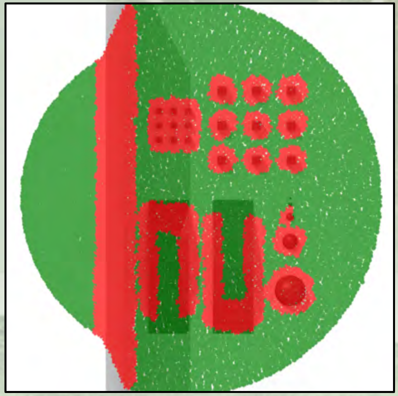
- DR 1.4: Complete hazard detection within 60 sec

Procedure

- Generate simulated point cloud
- Run morphological filter
- Compare with expected results







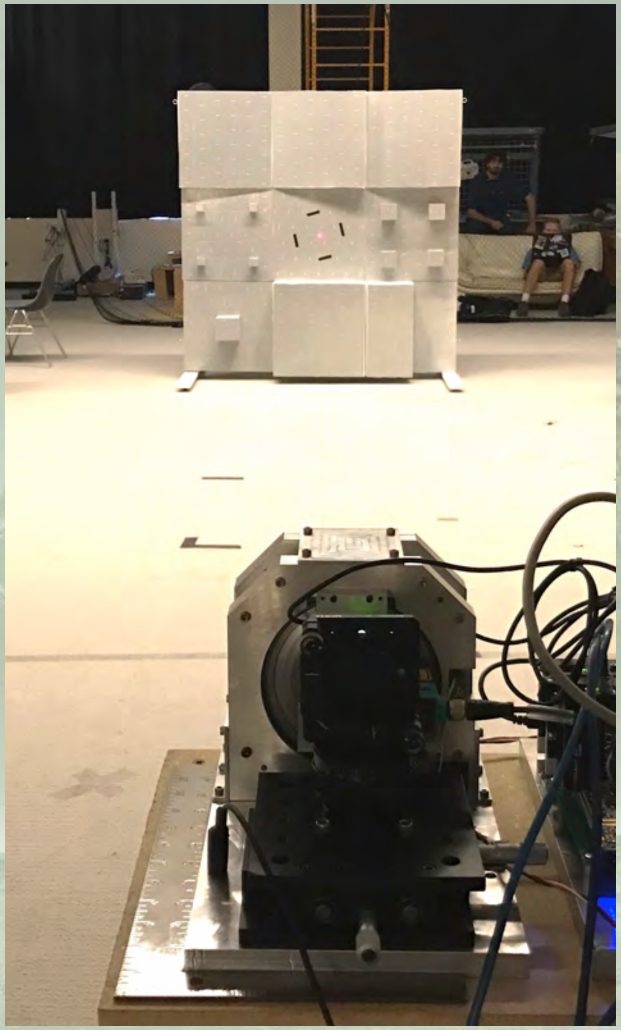
Full-System Test Overview

Relation to Project Success
- Success Levels 1-4

Objective
- Complete a full scan and analysis within 60 sec
- Complete a full scan with required accuracy

Requirements
- DR 1.1: scan up to 20° off nadir
- DR 1.3: resolution better than 0.1 m
- DR 1.4: scan and analysis in 60 sec

Procedure
- Alignment and calibration
- Perform timed scan
- Perform resolution scan
- Compare results with expected results



Test Results

Functional Requirements

FR 1: The system shall analyze a potential landing zone for a 12U CubeSat.

FR 2: The on-board processor (OBP) shall receive commands and data from a user-operated PC (UPC).

FR 3: The OBP shall command the sensor package (SP).

FR 4: The SP shall use a fixed-beam lidar sensor to obtain range measurements.

FR 5: The SP shall employ two Risley prisms to direct the lidar beam.

FR 6: The OBP shall receive data from the SP.

FR 7: The OBP shall project the SP data into a three-dimensional (3D) point cloud.

FR 8: The OBP shall analyze the 3D point cloud to identify hazardous locations.

FR 9: The on-board processor shall select an acceptable landing site.

FR 10: The OBP shall generate output readable by the UPC.

Lidar Testing

Initial results

- Successful in obtaining measurements through prisms (using manufacturer-provided tape)

Complication

- Purchased tape caused no returns at full range

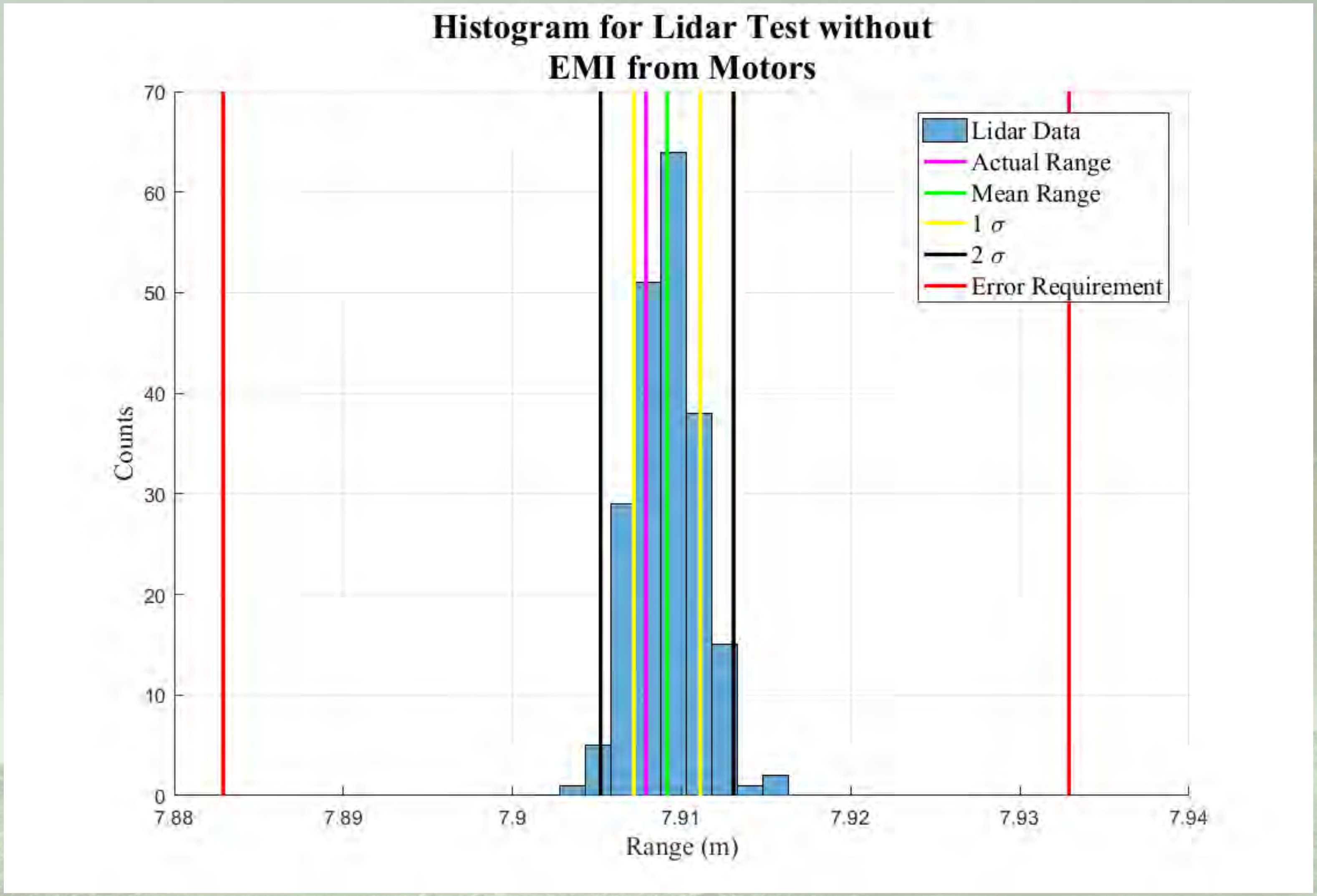
Solution

- De-scope range from 14.1 m to 8 m

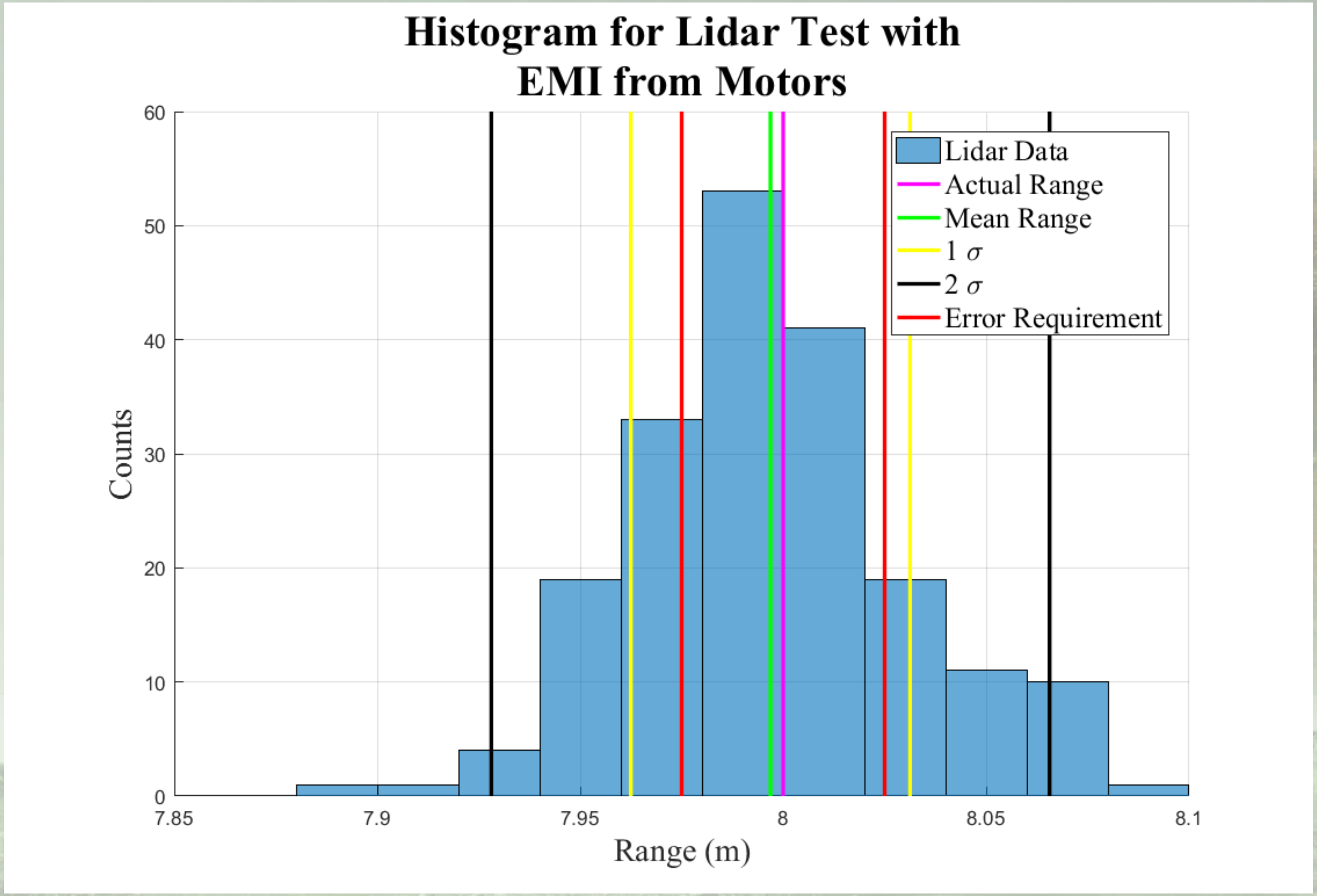
Implication

- Still able to meet all other requirements at the reduced range

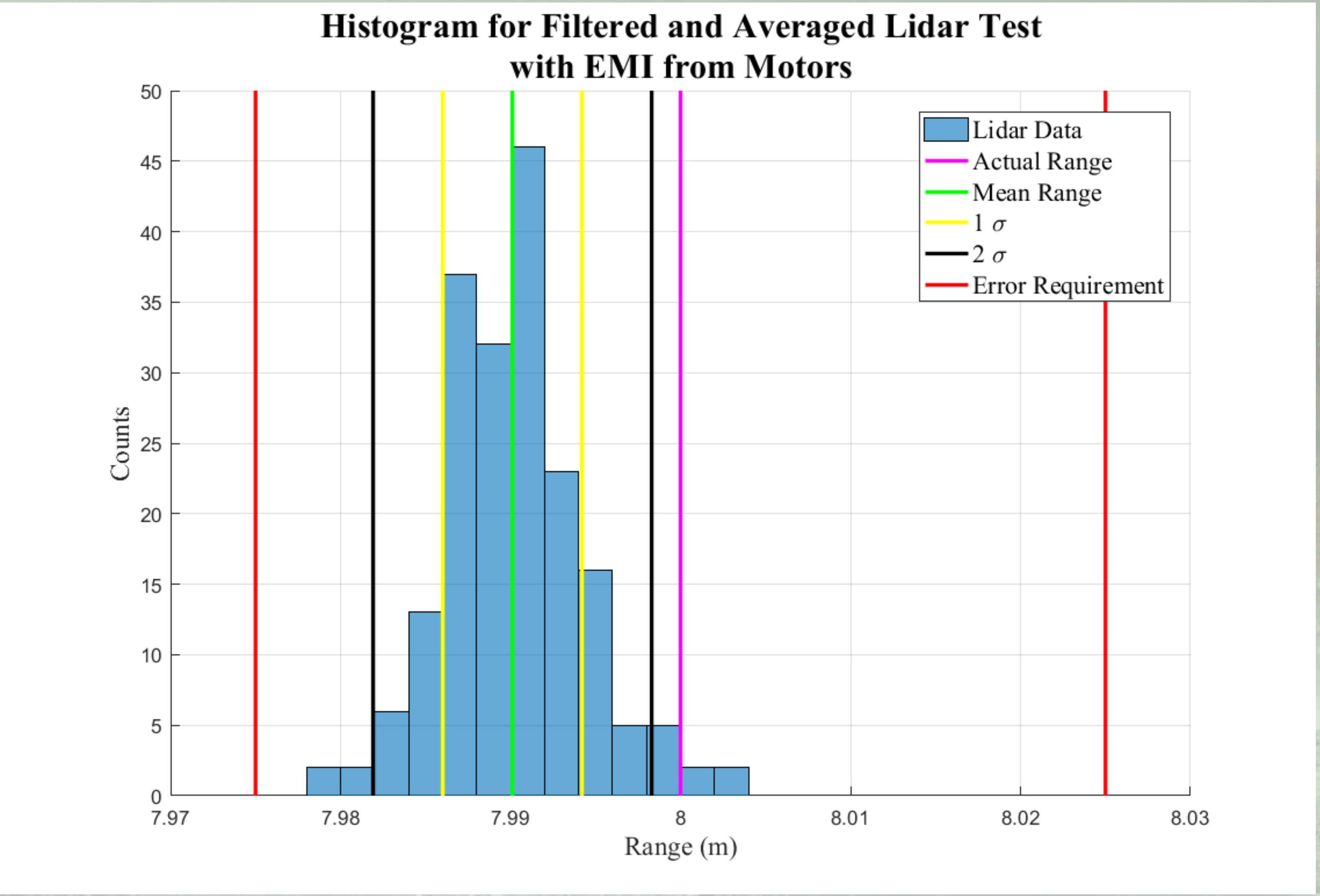
LIDAR TESTING: NO MOTORS



LIDAR TESTING: WITH MOTORS



LIDAR TESTING: WITH SOLUTION



LIDAR TESTING: SUMMARY

Requirements

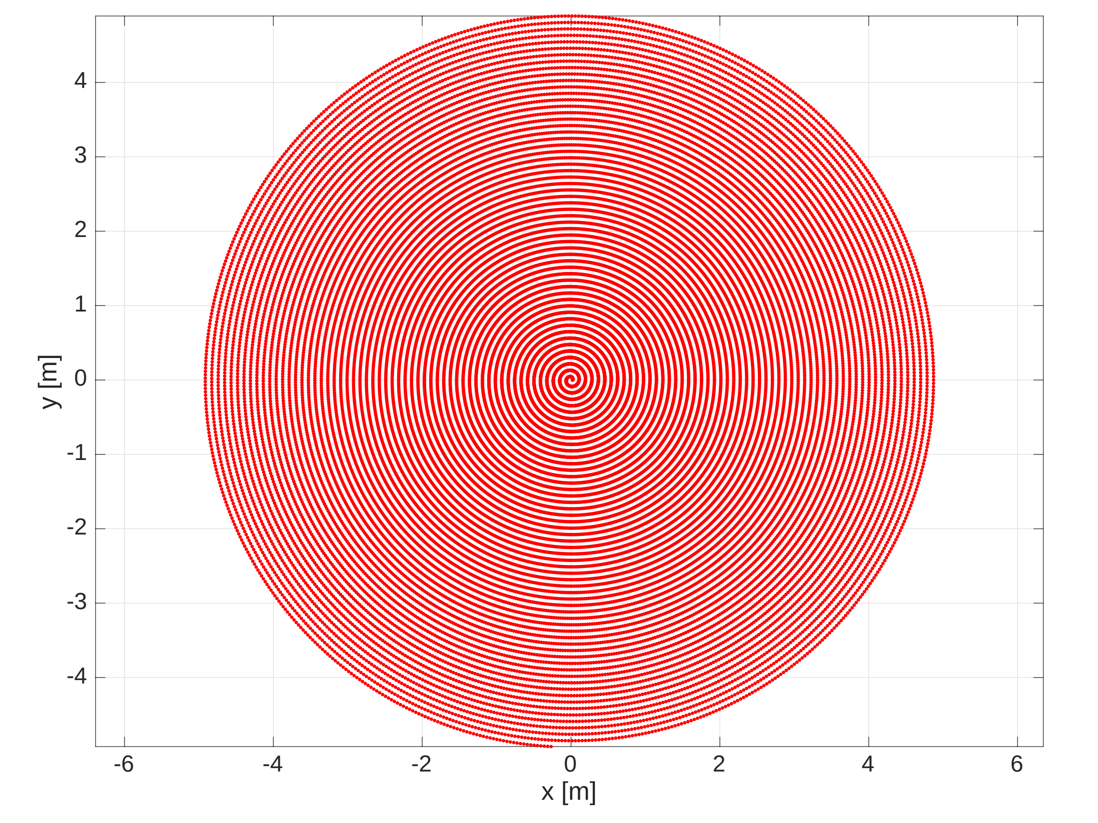
- DR 4.1: Range of 12 -15 m (partially verified)
- DR 4.2: Error < 2.5 cm (1 sigma) (verified after solution)

Test	Error (1 sigma standard deviation)
Through prisms	0.196 cm
With motors	3.440 cm
With mitigation (filtering and averaging)	0.410 cm

Challenges

- No measurements at 12 m with purchased retro-reflective tape
- De-scope full-system test to 8 m

Drive System Testing



Test	Points meeting resolution requirement (0.1 m)
Nadir	99.3%
Edge	95.1%

Drive System Testing

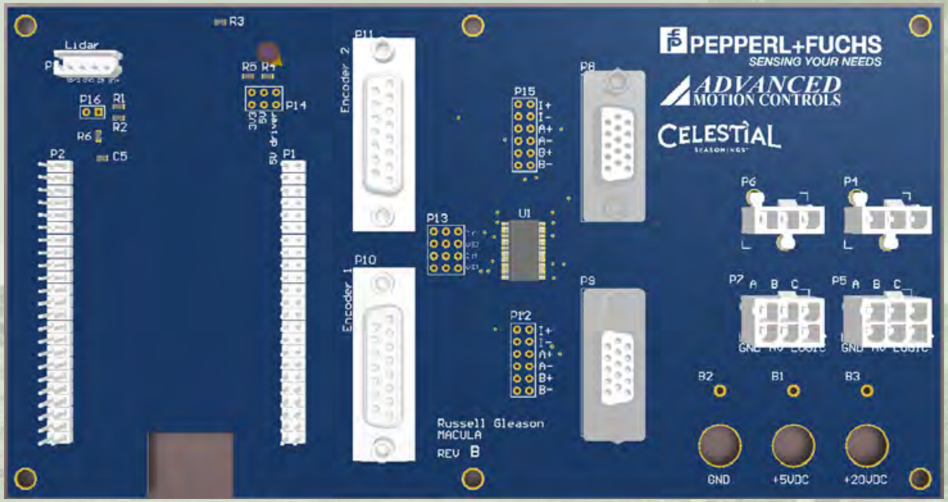
Resolution must be met for a full-speed test

BeagleBone missing counts due to signal out of TTL range

Can achieve the necessary rates, but cannot collect meaningful data

Proposed solution (in progress): revised PCB

- Incorporate uni-directional level shifter



Drive System Testing: Summary

Requirements

- DR 1.3: Scan resolution of 0.1 m
- DR 5.2.1: Motor acceleration of 15 rad/s^2
- DR 5.2.2: Motor velocity from 0.45 rad/s to 10 rad/s

Results

- DR 1.3 partially verified for slow scan but not for fast scan
- DR 5.2.1 and 5.2.2 verified by acceptance tests

Further work

- PCB Rev B to allow verification of DR 1.3 for fast scan
- Perform time test

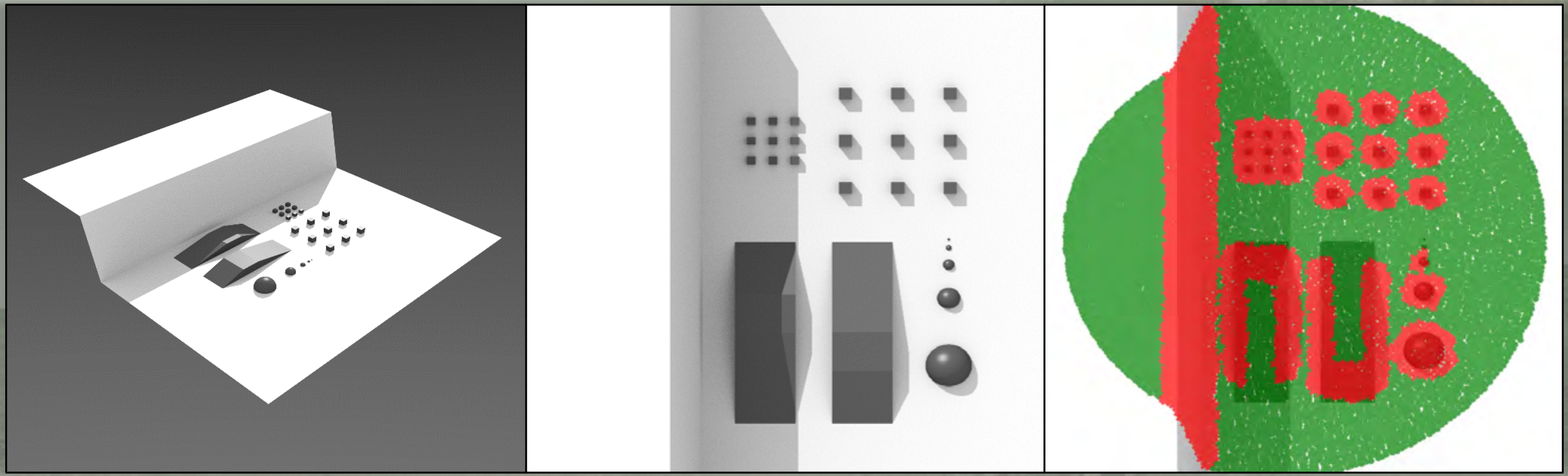
Software Testing

Requirements

- DR 1.4: Complete hazard detection within 60 sec

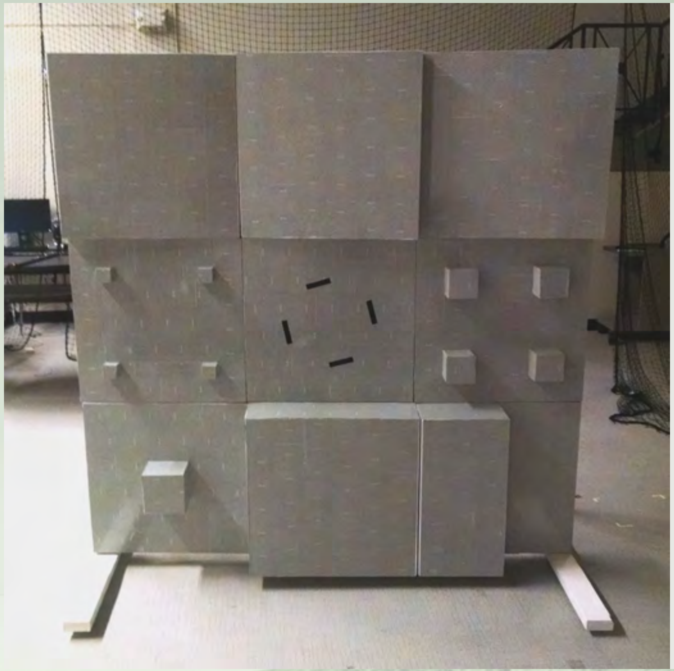
Results:

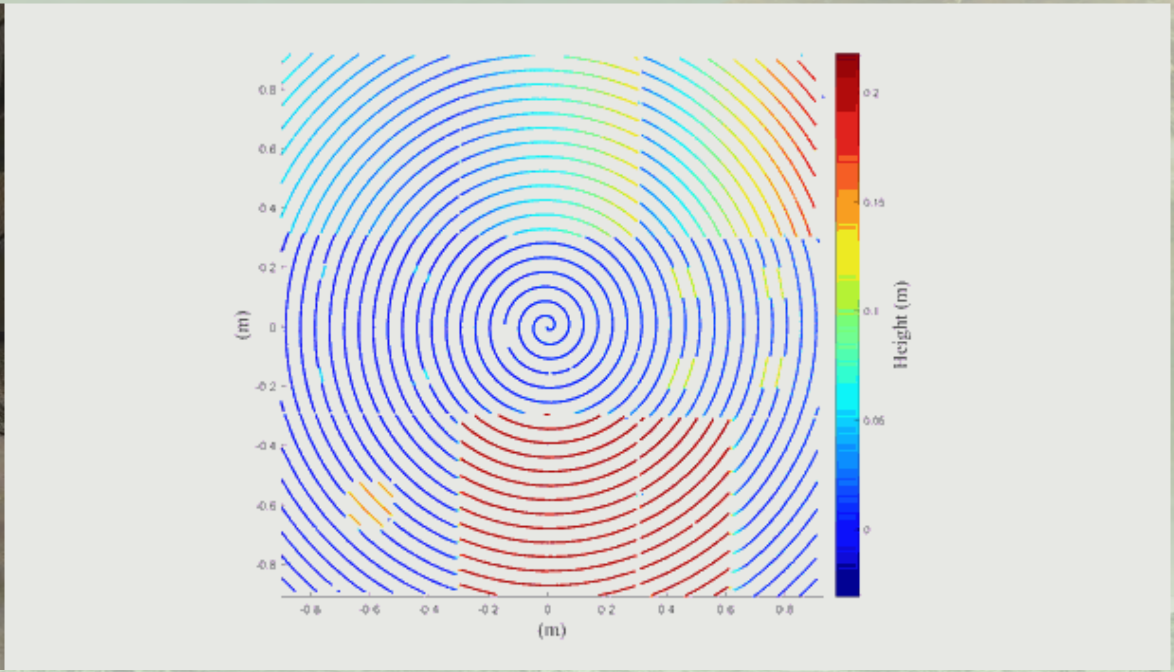
- Algorithm functions properly, can be used for full-test point cloud and validation
- 9500 points: algorithm takes 93.87 sec (DR 1.4 not verified)



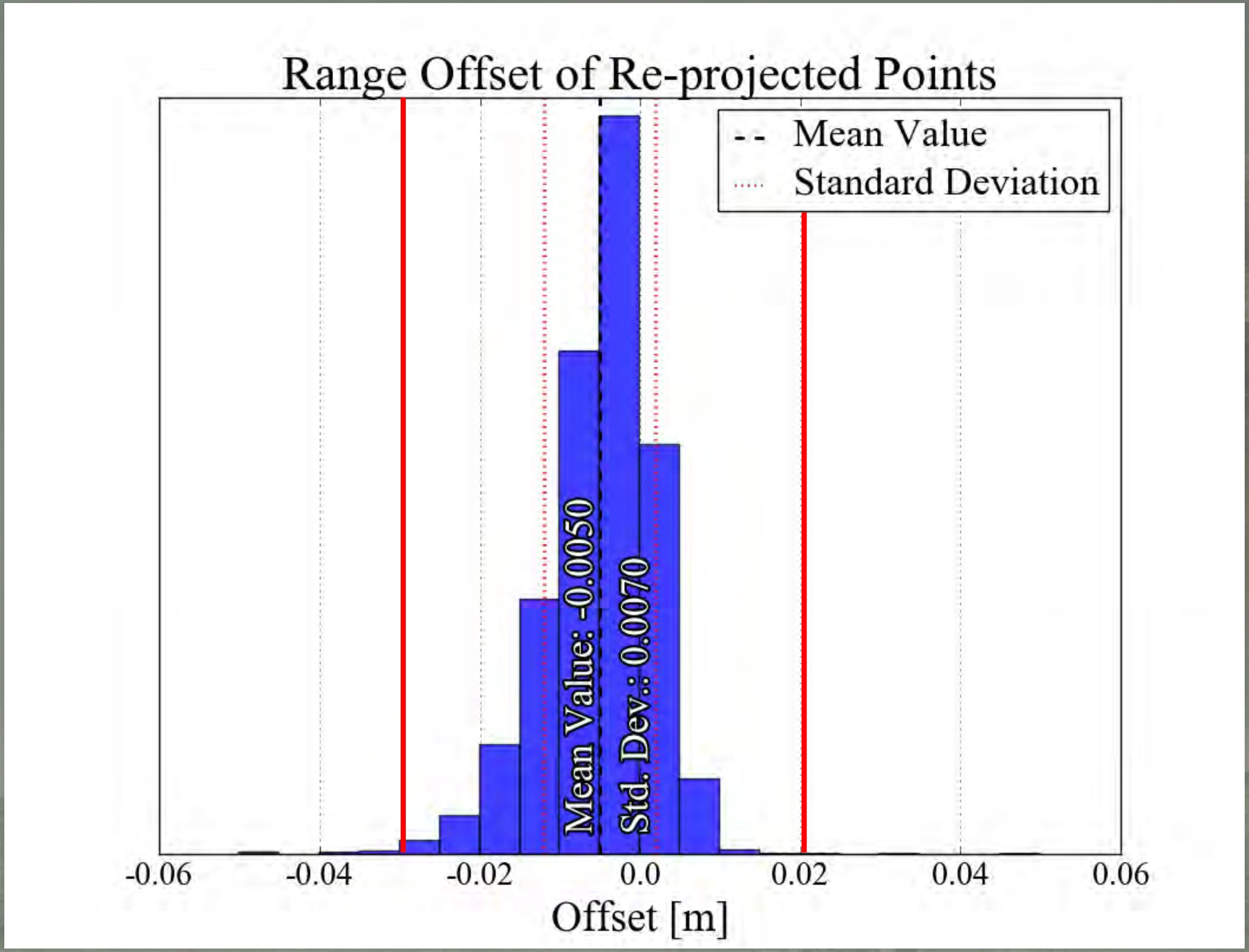
Full System: Point cloud

Results from actual scan of testbed at range of 8 m



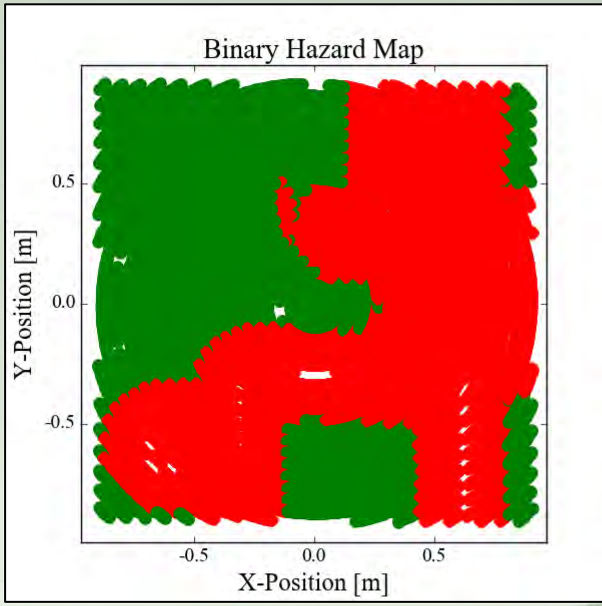


FULL SYSTEM: POINT CLOUD

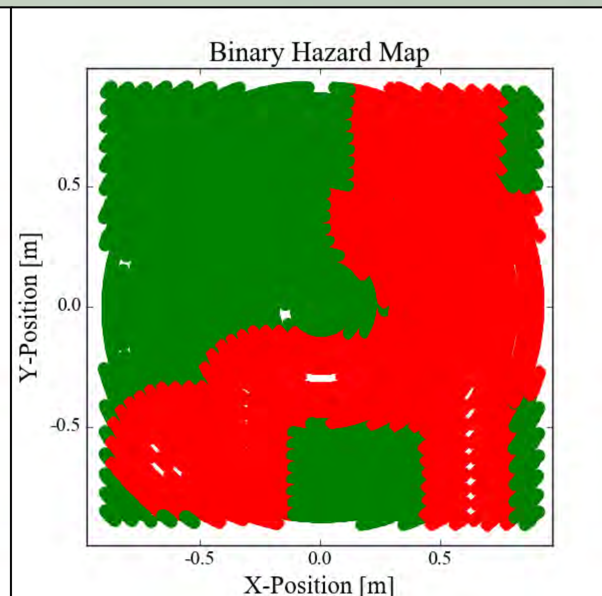


HAZARD ANALYSIS RESULTS

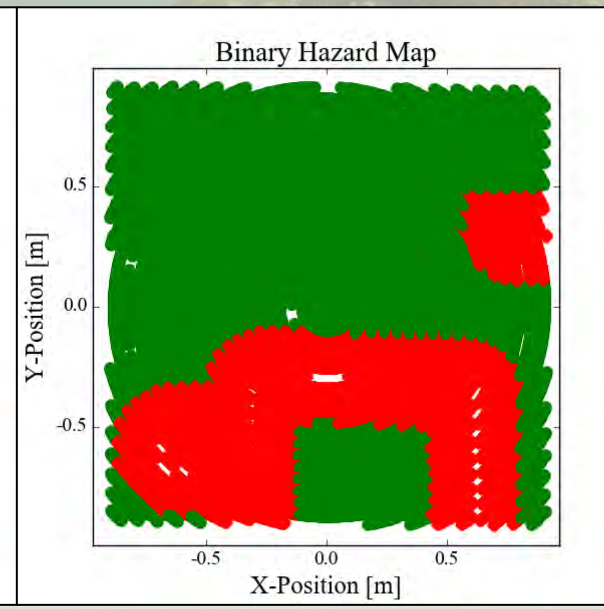
Actual result
(adjusted hazard definition)



Expected result,
adjusted hazard definition



Expected result,
original hazard definition



FULL-SYSTEM: LANDING ZONE SELECTION

Comparison of results against original hazard definition

Test	Number correct	False Negative (safe marked unsafe)	False Positive (unsafe marked safe)	Failure Probability (select unsafe landing)
Nadir 1	18378 (77.8%)	5249 (22.2%)	3 (0.01%)	0.025%
Nadir 2	18635 (78.2%)	5120 (21.8%)	5 (0.02%)	0.042%
Nadir 3	18754 (79.7%)	4781 (20.3%)	1 (0.004%)	0.008%
Edge 1	4956 (84.2%)	927 (15.8%)	0 (0%)	0%
Edge 2	4983 (84.4%)	922 (15.6%)	2 (0.03%)	0.06%
Edge 3	4763 (80.8%)	1132 (19.2%)	1 (0.02%)	0.03%

Full-System Testing: Summary

Requirements

- DR 1.1: scan up to 20° off nadir
- DR 1.3: resolution better than 0.1 m
- DR 1.4: scan and analysis in 60 sec

Results

- DR 1.1 verified
- DR 1.3 partially verified (>95% of points pass)
- DR 1.4 not verified (analysis not performed in time)
- Point cloud matches expectation with mean offset 5 mm and standard deviation 7 mm
- Hazard detection produces a maximum 0.06% chance of failure

Further work

- PCB Rev B to allow verification of DR 1.3 for fast scan
- Perform time test

Achievement of Project Objectives

Objectives from PDD

"The purpose of the MACULA project is to design, manufacture, and test a light detection and ranging (LiDAR) scanning system that a landing craft can use to dynamically select a safe area on an unknown body. On-board software will detect hazards, making this system both safer and more generally applicable than current systems."

Success Levels

Success Level	Status
1 – Correlated range and attitude	Achieved
2 – Topographic map construction	Achieved
3 – Hazard analysis	Partial – >95% accurate
4 – Landing site selection	Partial – 3 not achieved

Functional Requirements

Functional Requirement	Status
1 – Analyze landing site for 12U CubeSat	Partial – not completed in required time
2 – Commands received from user PC	Achieved
3 – Command sensor package	Achieved
4 – Use fixed-beam lidar	Achieved
5 – Use two Risley prisms	Achieved
6 – Receive sensor data	Partial – BeagleBone misses counts
7 – Construct topographic map	Achieved
8 – Hazard detection	Partial – >95% accurate
9 – Landing zone selection	Achieved
10 – Output to PC	Achieved

SYSTEMS ENGINEERING

Functional Objectives

Scan a landing environment using lidar

- Customer requirement
- Created need to steer beam and measure steering

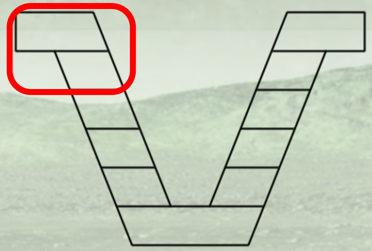
Create a 3D point cloud

- Created need for correlation of range and attitude measurements

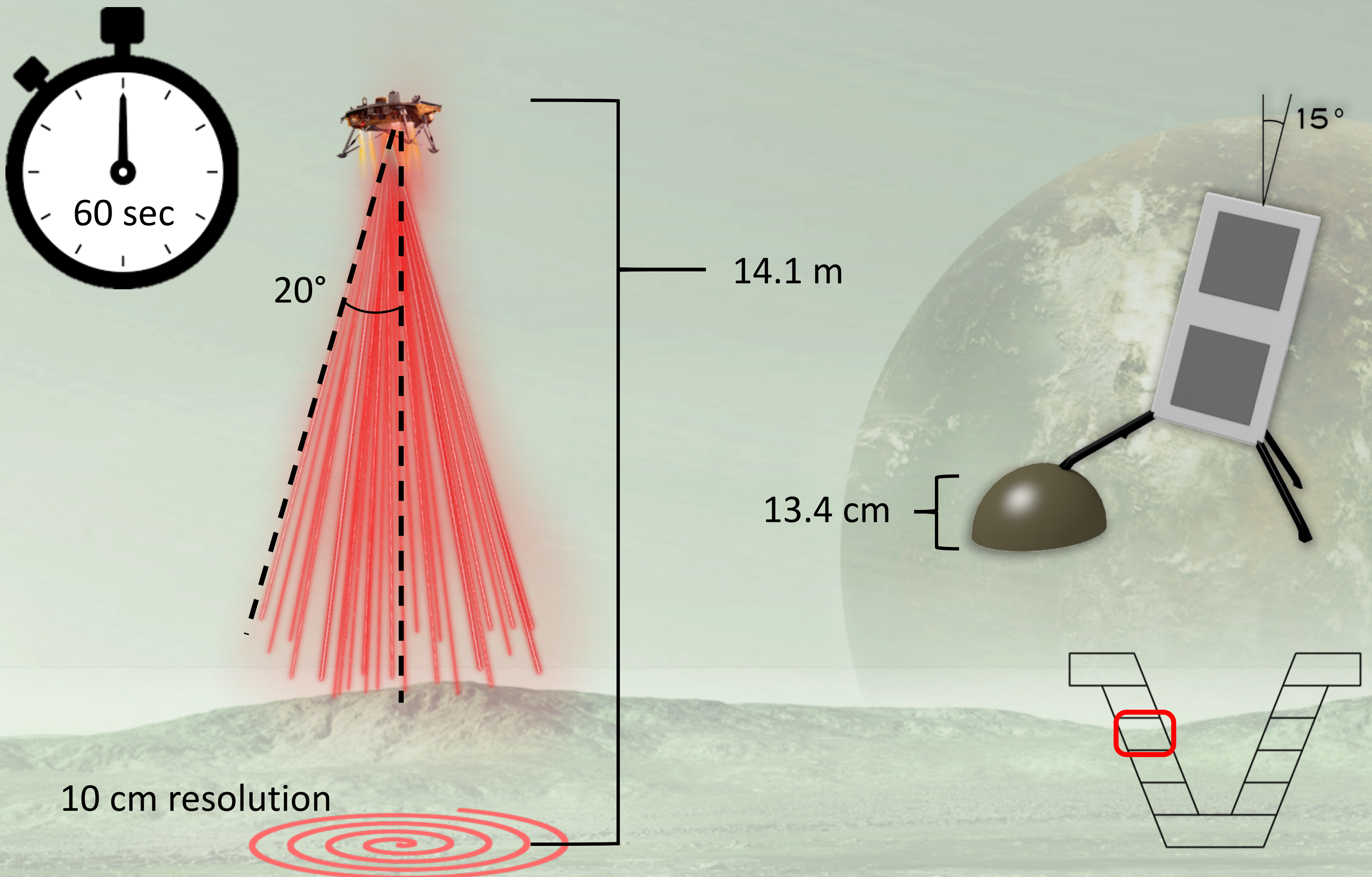
Detect hazards

- Defined scale
- Defined error requirements

Identify a safe landing zone



Driving Requirements



KEY TRADES: LIDAR

Fixed-beam 

Scanning 

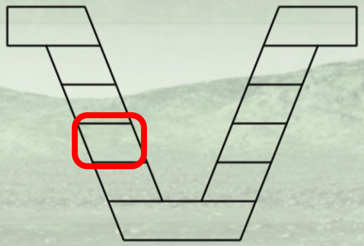
Optically Segmented 

Rationale

- Low cost
- Meets error requirements

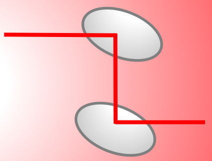
Implications

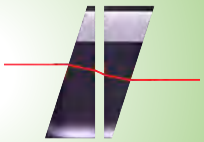
- Created need for actuation system
- Drove error requirements on mechanical system



KEY TRADES: SCANNING

Gimbals 

Mirrors 

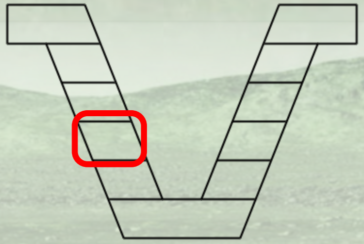
Risley Prisms 

Rationale

- Implications on pattern
- Simple actuation

Implications

- Drove design of mechanical system
- Drove design of scan pattern



SUBSYSTEM VERIFICATION

Lidar testing

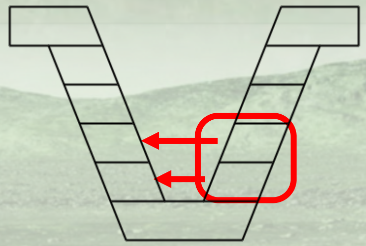
- Range measurements through prisms
- Error within requirement
- De-scope full-system test range

Motor testing

- Necessary rates/accelerations can be achieved
- Scan pattern resolution 95.1% achieved at low speed
- High-speed scan work in progress

Software testing

- Given a 3D point cloud, hazards can be detected (>95%)
- Time requirement not met



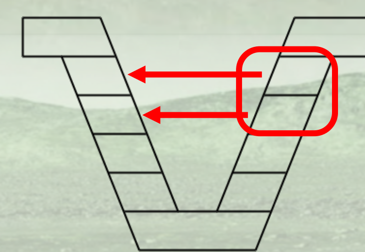
System Verification & Validation

Resolution test

- Goal:
  - Environment at given distance can be scanned
  - 3D point cloud can be created
  - Hazards of defined scale can be detected
- Result:
  - Partially validated

Time test

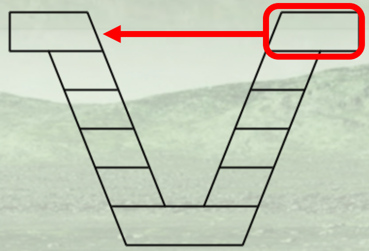
- Goal:
  - Motors can be controlled for scan under time constraint
  - Process can be completed during theoretical hover phase
- Result:
  - Incomplete



TRACEABILITY

Mission objective was to design a proof-of-concept scanning system for spacecraft landing

- Accomplishments
  - Range and attitude measurements correlated into 3D point cloud
  - 3D point cloud analyzed for hazards
  - Scalable design can be applied to different mission scenarios
- Shortcomings
  - Processing time
  - Error reduction
  - Capabilities for INS data



CDR Level Risk

R1	Reflection off of prisms causes false return
R2	Encoder mount damage occurs
R3	Limited machine shop availability
R4	Risley prism damage occurs during storage or handling
R5	Limited availability in RECUV
R6	Delays during manufacturing process
R7	Loss of calibration

Did not occur	Occured, no major impact

Issues and Challenges

Not included in risk matrix

Quality of parts from suppliers

- Hollow-core motors from Celera Motion
- Motor driver power issue

Integration issues larger than expected

- EMI induced error
- Encoder counts missed

Drivers of schedule

- Waiting for components to arrive from suppliers
- Integration and troubleshooting

LESSONS LEARNED

Subsystem integration before full-system test

- Issues not fully presented until full-system test
  - EMI induced error

Need better tracking of design requirement specifics

- Re-visit requirements throughout testing and integration

More iterations necessary on design requirements

- Higher-quality metrics to evaluate design

PROJECT MANAGEMENT

Management Successes and Difficulties

Successes:

- Setting internal deadlines
- Ensuring high-quality work
- Familiarity with project as a whole
- Ambitious scheduling and significant margin
- Conflicts resolved

Difficulties:

- Enforcing internal deadlines
- Resource allocation
- Unforeseen schedule slip
- Conflicts existed
- No incentives

MANAGEMENT LESSONS LEARNED

Margin!! (both schedule and budget)

Ambitious scheduling can be demoralizing

Maintain technical knowledge

Enforce internal deadlines

Check in regularly on tasks

Authority/incentive/respect

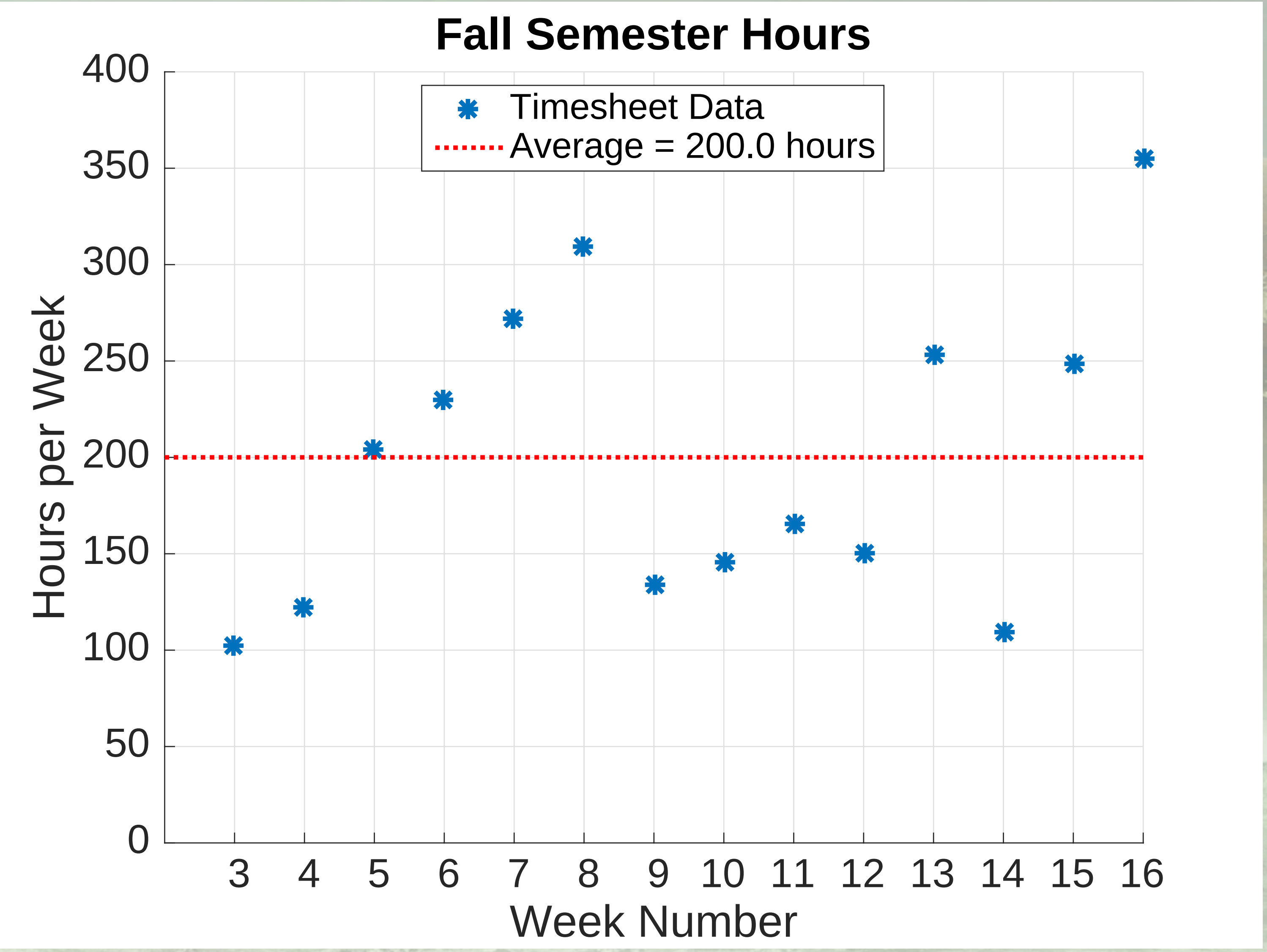
Final Budget Comparison

Item	CDR Budget	Actual Cost	Difference	Reason
Stock	$849.77	$488.58	-$361.19	Machine shop
Tooling	$812.00	$527.15	-$284.85	Machine shop
Testbed	$0	$326.50	+$326.50	Built into misc.
Misc. Materials	$466.00	$447.31	-$18.69	
Lidar	$0.00	$0.00	+$0.00	
Motors	$1033.00	$1728.30	+$695.30	Quantity/shipping
Encoders	$1120.00	$1496.15	+$376.15	Mounting cost
Bearings	$327.08	$340.75	+$13.67	
Microprocessor	$55.00	$0.00	-$55.00	Owned by team
Reflective Tape	$325.98	$367.95	+$41.97	
Motor Drivers	$847.00	$1599.74	+$752.74	Quality/shipping
Risley Prisms	$216.00	$336.00	+$120.00	Spare prism
Shipping	$330.00	$0.00	-$330.00	Built into others
Total	**$6381.83**	**$7658.43**	**+$1276.60**	

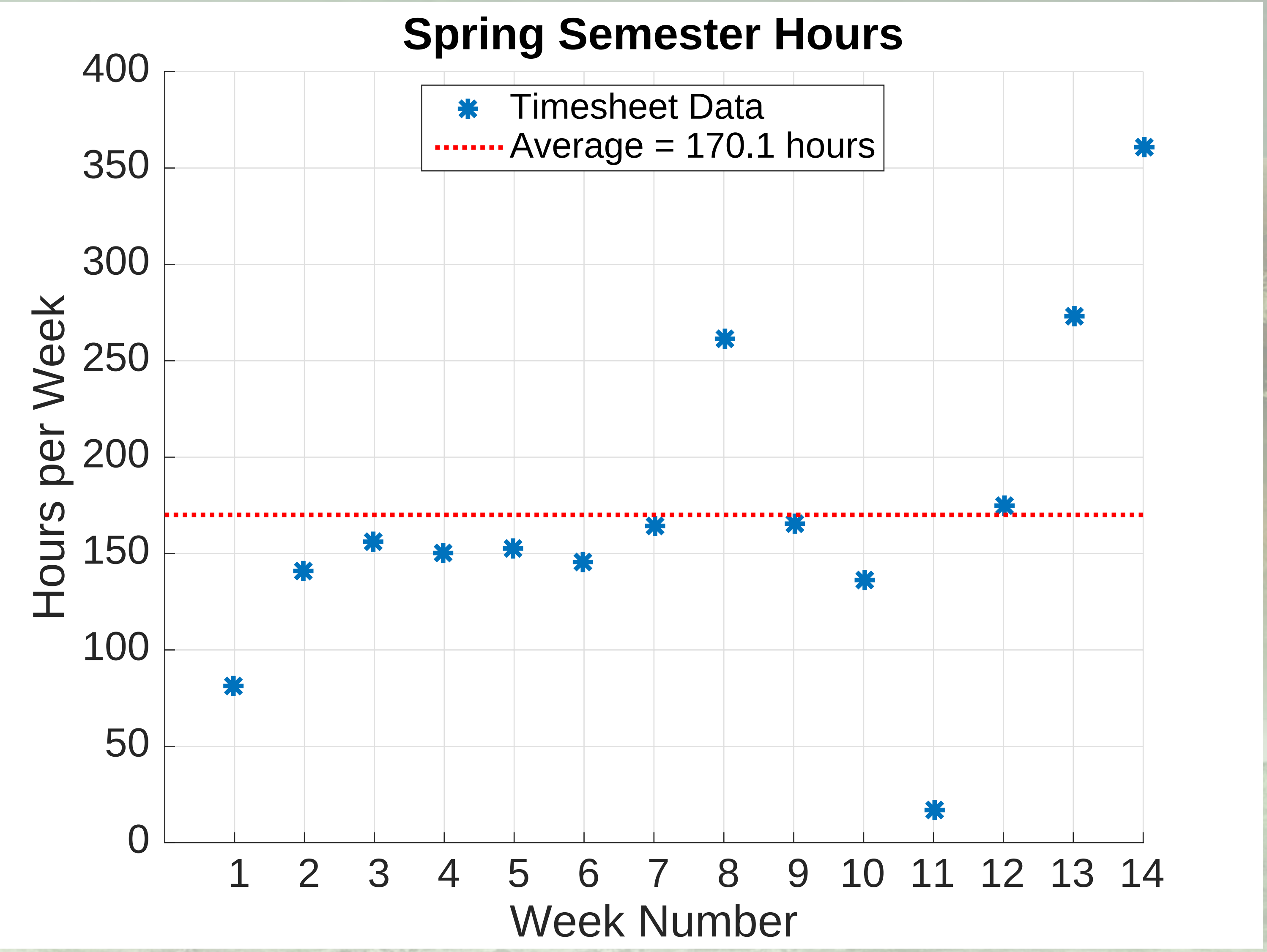
Final Budget Comparison

	CDR Budget	Actual
Expenses	$6381.83	$7658.43
Funding	$8300.00	$8300.00
Margin	$1918.17 (23.11%)	$641.57 (7.73%)

True Project Cost: Fall Hours



True Project Cost: Spring Hours



True Project Cost: Summary

Fall Semester Hours	2800.25
Spring Semester Hours (through 4/21/17)	2380.95
Total Hours	5181.20
Yearly Engineer Salary	$65,000.00 (2080 hours)
Hourly Engineer Cost	$31.25
Total Personnel Cost	$161,912.50
Total Overhead	$323,835.00
Material Cost	$7,658.43
Total Project Cost (through 4/21/17)	**$493,395.93**

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Pepperl+Fuchs: Michael Turner

Celera Motion: Michael Healey

Advanced Motion Controls

Dale Lawrence

Stephen Arrasmith

Undergraduate Research Opportunities Program

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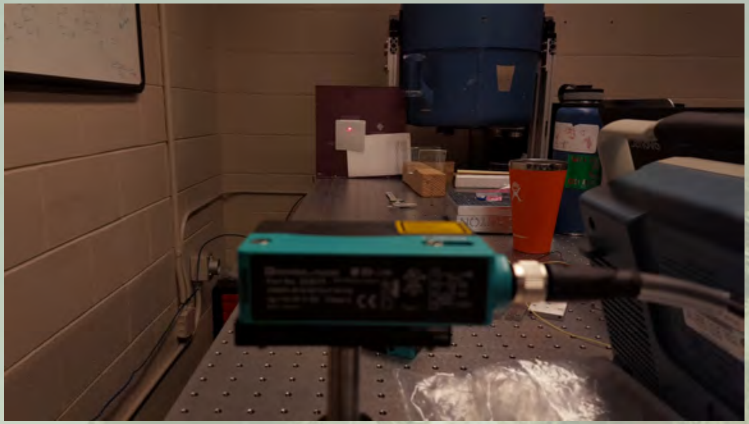
QUESTIONS?

LIDAR: SHORT RANGE

Objective

- Returns through prisms
- Characterizing short-range error
- Comparing two different lidars
- Frequency analysis



Procedure

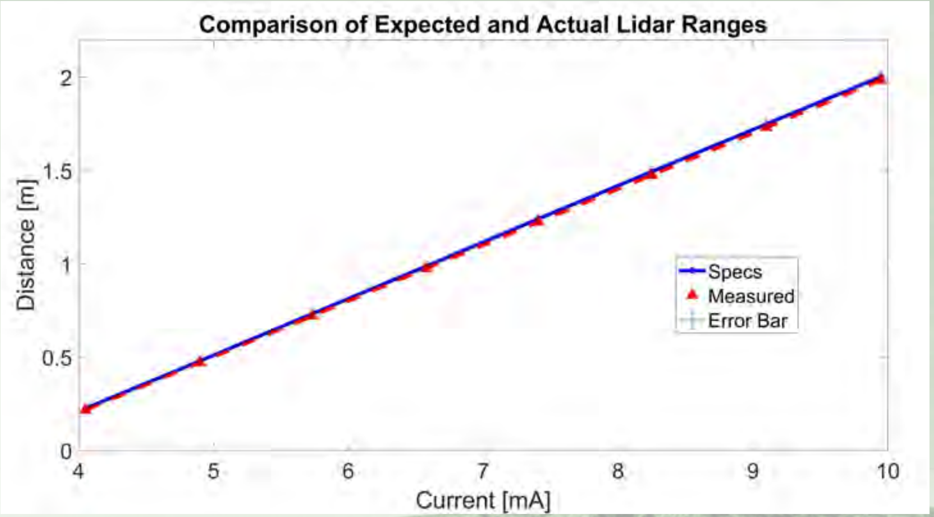
- Test range at 2 m with and without prisms
- Increase range at 10’’ increments to characterize error
- Place object in front of lidar and rapidly vary its position

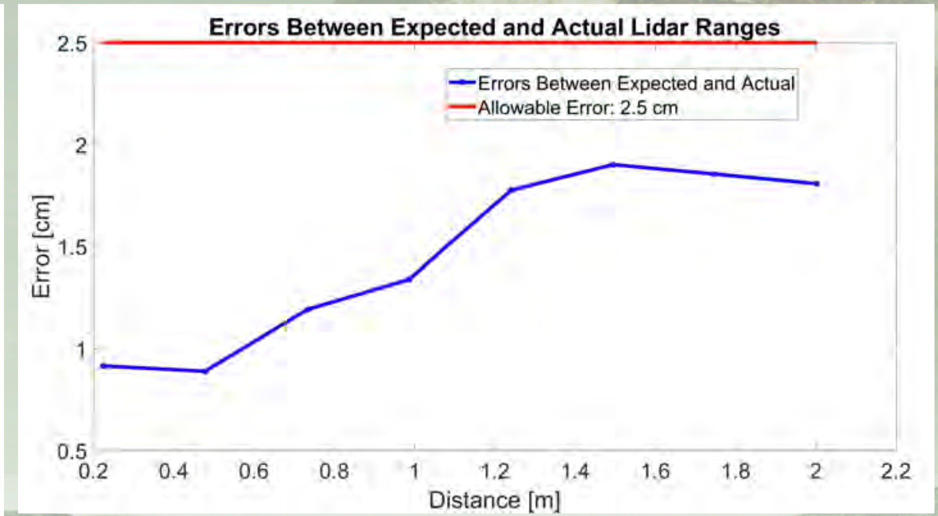
Requirements

- Verify the specifications of the lidar for current-to-distance measurements

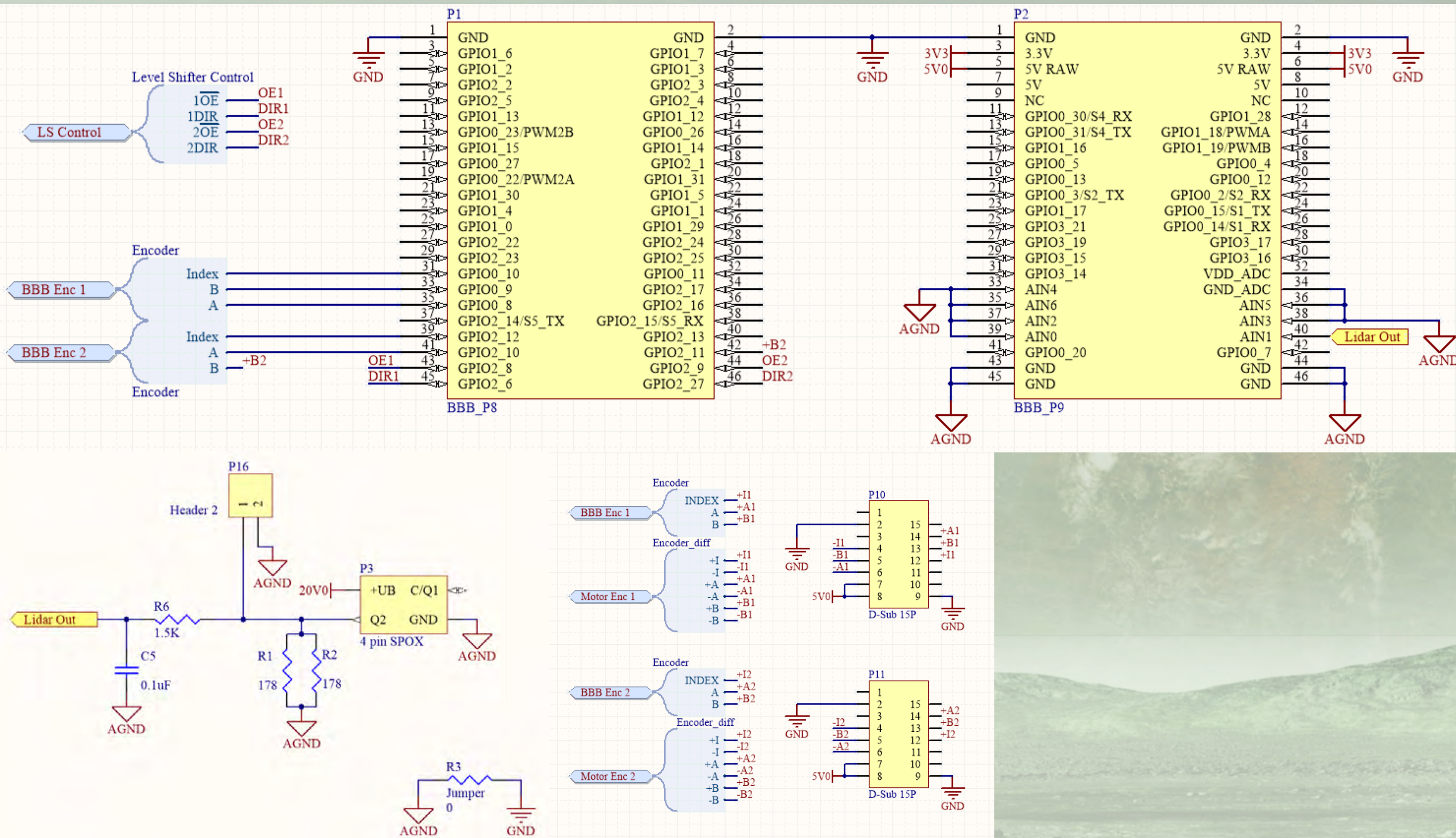
Lidar: Short Range

Stepping stone to long-range tests to confirm voltage-to-range conversions for operation



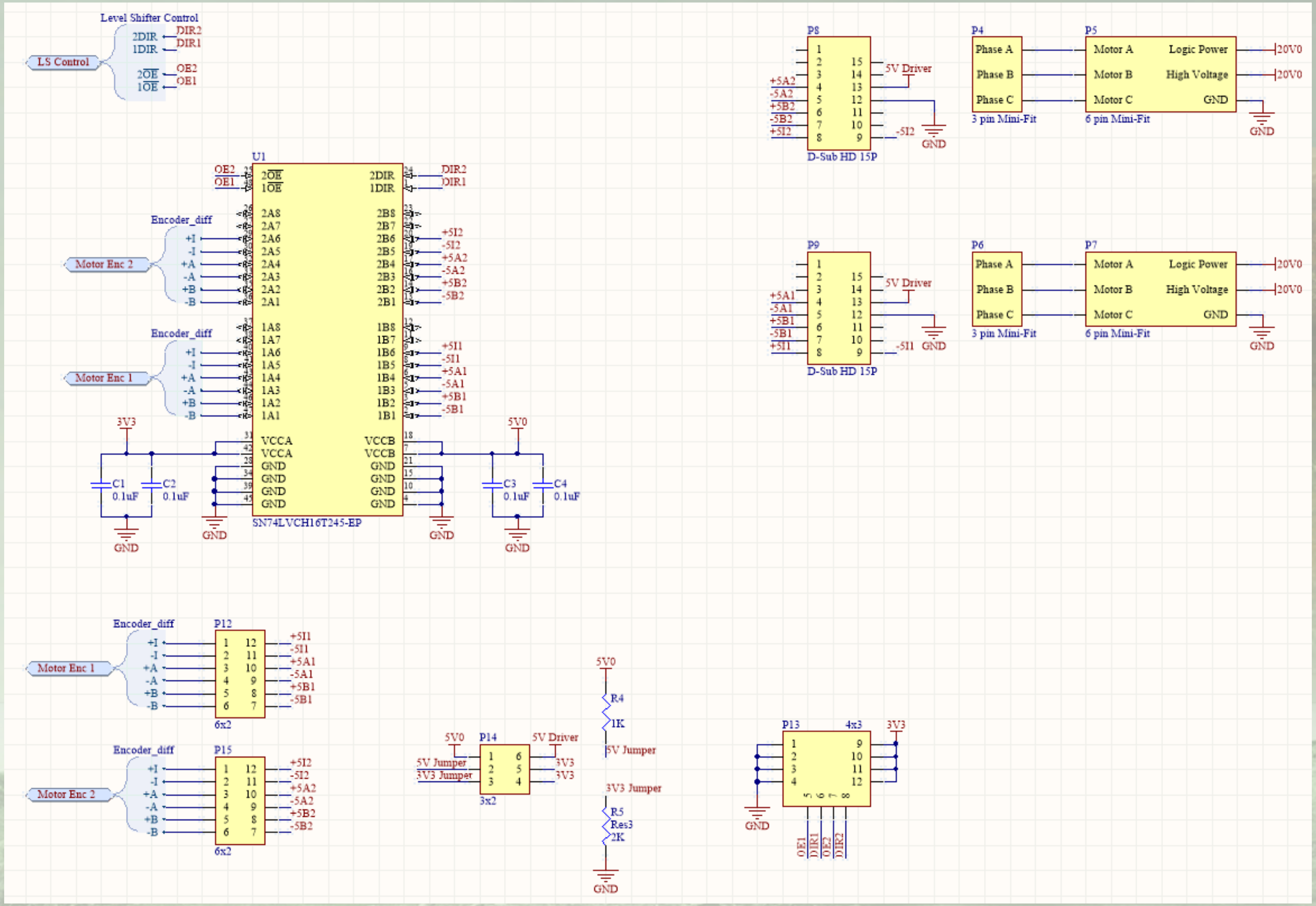


PCB

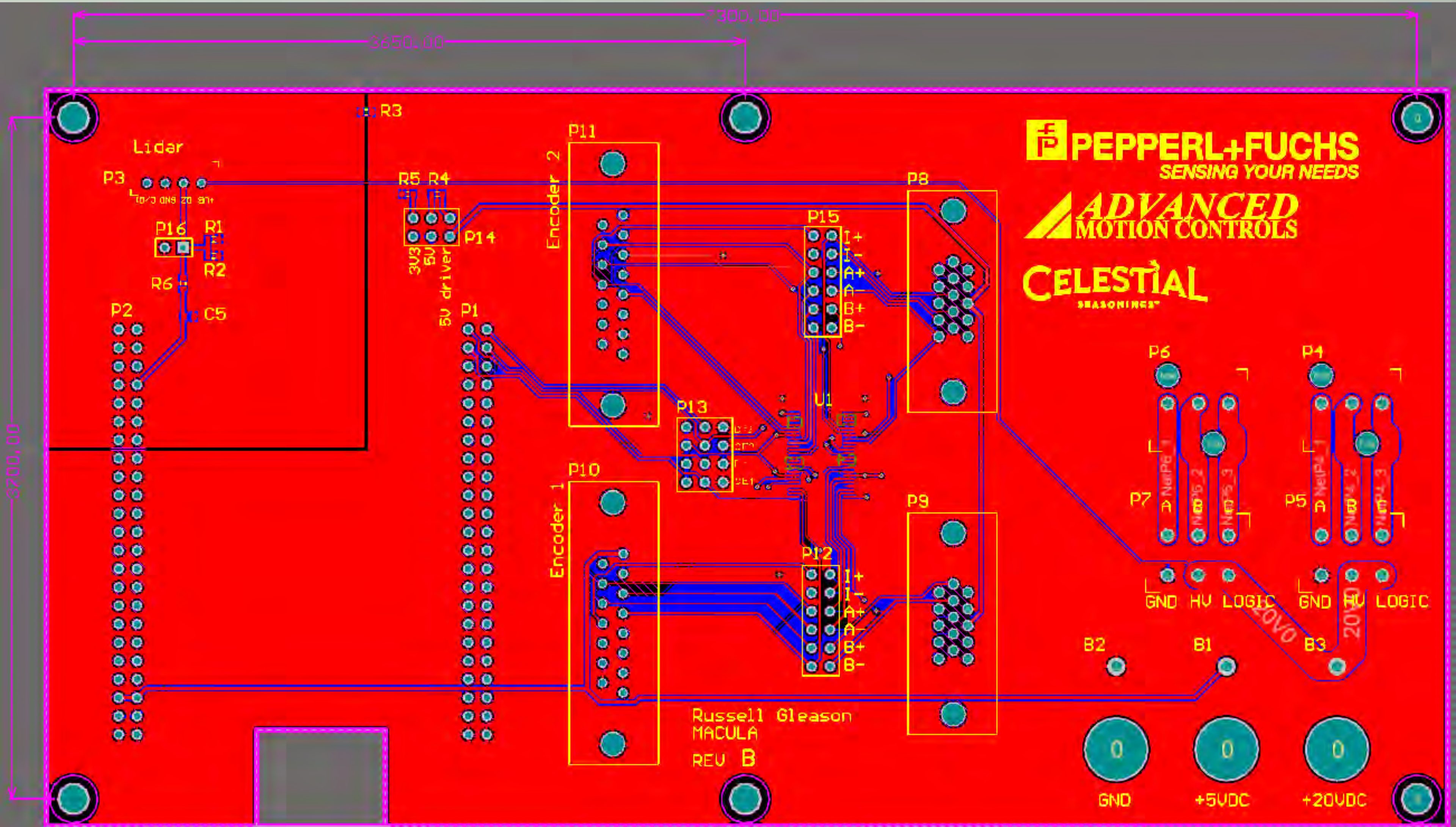


P1
BBB_P8
P2
BBB_P9
GND
AGND
3V3
5V0
Level Shifter Control
1OE
1DIR
2OE
2DIR
OE1
DIR1
OE2
DIR2
LS Control
Encoder
Index
B
A
BBB Enc 1
BBB Enc 2
+B2
Lidar Out
GND GPIO1_6 GPIO1_2 GPIO2_2 GPIO2_5 GPIO1_13 GPIO0_23/PWM2B GPIO1_15 GPIO0_27 GPIO0_22/PWM2A GPIO1_30 GPIO1_4 GPIO1_0 GPIO2_22 GPIO2_23 GPIO0_10 GPIO0_9 GPIO0_8 GPIO2_14/S5_TX GPIO2_12 GPIO2_10 GPIO2_8 GPIO2_6
GND GPIO1_7 GPIO1_3 GPIO2_3 GPIO2_4 GPIO1_12 GPIO0_26 GPIO1_14 GPIO2_1 GPIO1_31 GPIO1_5 GPIO1_1 GPIO1_29 GPIO2_24 GPIO2_25 GPIO0_11 GPIO2_17 GPIO2_16 GPIO2_15/S5_RX GPIO2_13 GPIO2_11 GPIO2_9 GPIO2_27
GND 3.3V 5V RAW 5V NC GPIO0_30/S4_RX GPIO0_31/S4_TX GPIO1_16 GPIO0_5 GPIO0_13 GPIO0_3/S2_TX GPIO1_17 GPIO3_21 GPIO3_19 GPIO3_15 GPIO3_14 AIN4 AIN6 AIN2 AIN0 GPIO0_20 GND GND
GND 3.3V 5V RAW 5V NC GPIO1_28 GPIO1_18/PWMA GPIO1_19/PWMB GPIO0_4 GPIO0_12 GPIO0_2/S2_RX GPIO0_15/S1_TX GPIO0_14/S1_RX GPIO3_17 GPIO3_16 VDD_ADC GND_ADC AIN5 AIN3 AIN1 GPIO0_7 GND GND
P16
Header 2
20V0
P3
+UB
C/Q1
Q2
GND
4 pin SPOX
R6
1.5K
C5
0.1uF
R1
178
R2
178
R3
Jumper
0
Encoder
INDEX
Encoder_diff
Motor Enc 1
Motor Enc 2
+I1 +A1 +B1 -I1 -A1 -B1
+I2 +A2 +B2 -I2 -A2 -B2
+I -I +A -A +B -B
P10
P11
D-Sub 15P

PCB

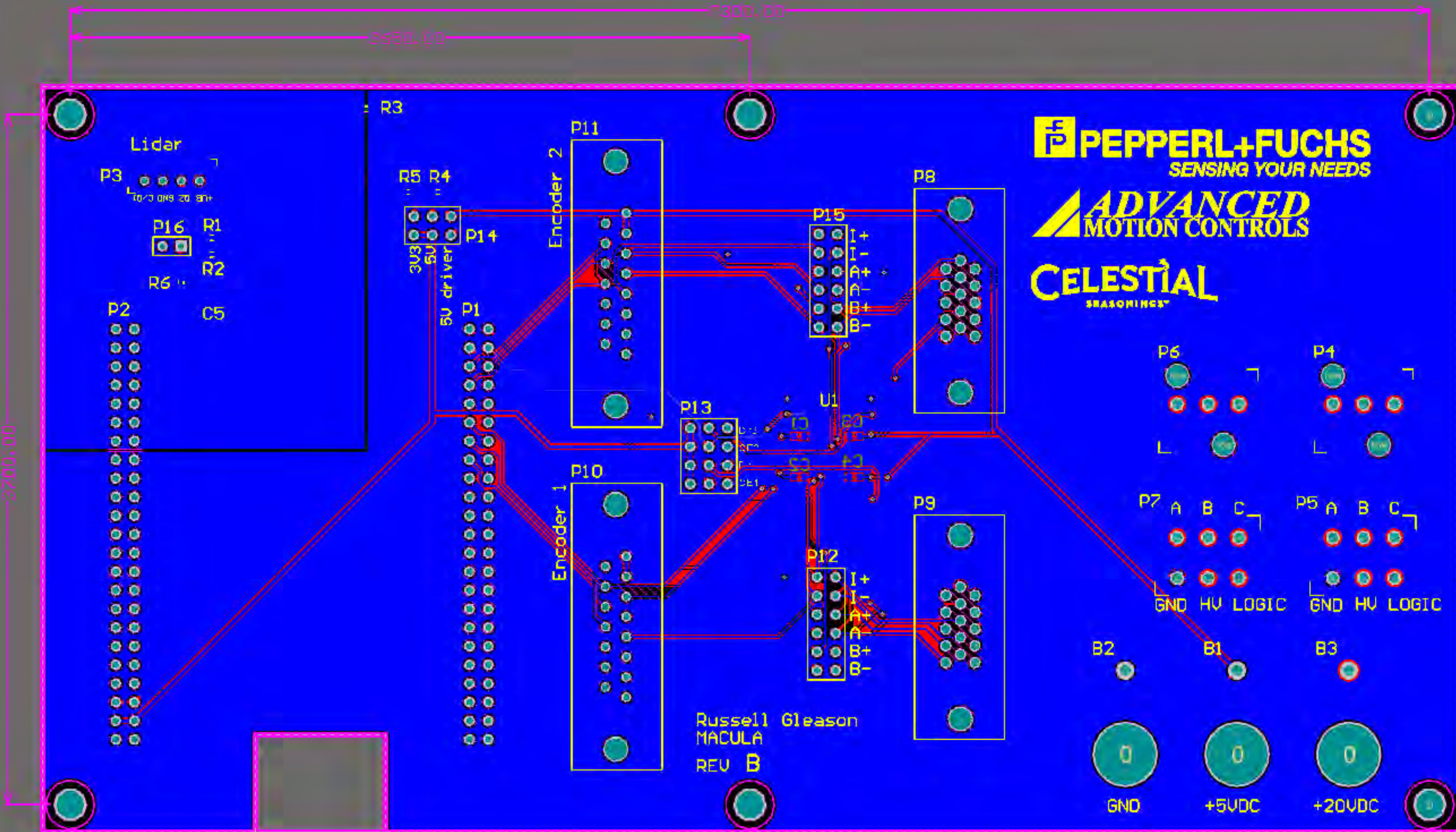

Level Shifter Control
LS Control
U1
SN74LVCH16T245-EP
Encoder_diff
Motor Enc 2
Motor Enc 1
P8
D-Sub HD 15P
P9
P4
P5
P6
P7
Phase A
Phase B
Phase C
3 pin Mini-Fit
Motor A
Motor B
Motor C
Logic Power
High Voltage
GND
6 pin Mini-Fit
20V0
5V Driver
C1 0.1uF
C2 0.1uF
C3 0.1uF
C4 0.1uF
3V3
5V0
P12
P15
6x2
P14
3x2
5V Jumper
3V3 Jumper
R4 1K
R5 Res3 2K
P13
4x3

PCB



R3
Lidar
P3
P16
R1
R2
R6
C5
P2
R5 R4
P14
3V3
5V
5V driver
P1
P11
Encoder 2
P10
Encoder 1
P13
P15
I+
I-
A+
A-
B+
B-
U1
P12
P8
P9
PEPPERL+FUCHS
SENSING YOUR NEEDS
ADVANCED
MOTION CONTROLS
CELESTIAL
SEASONINGS
P6
P4
P7
P5
A
B
C
GND
HV
LOGIC
B2
B1
B3
Russell Gleason
MACULA
REV B
GND
+5VDC
+20VDC

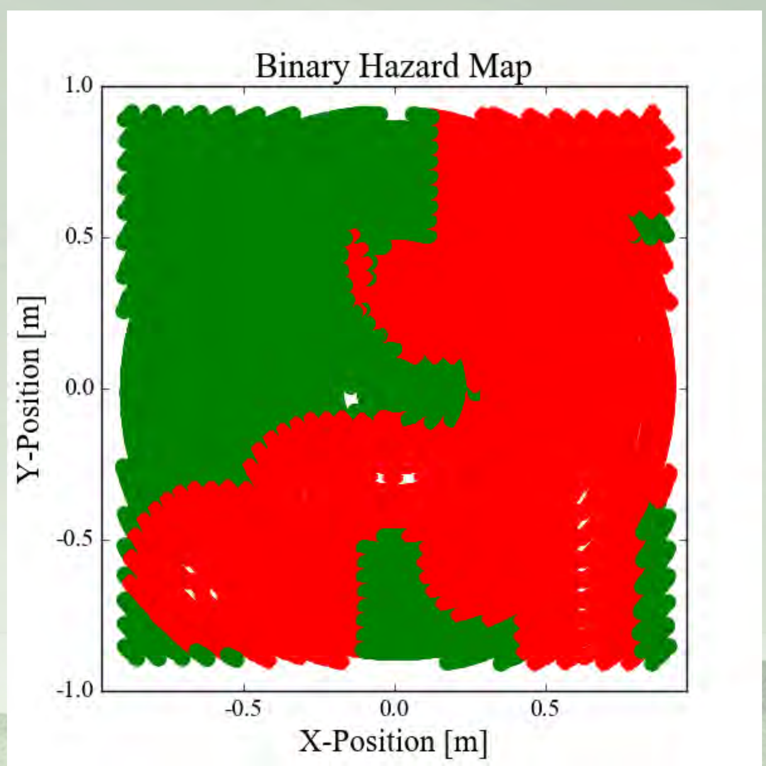
PCB

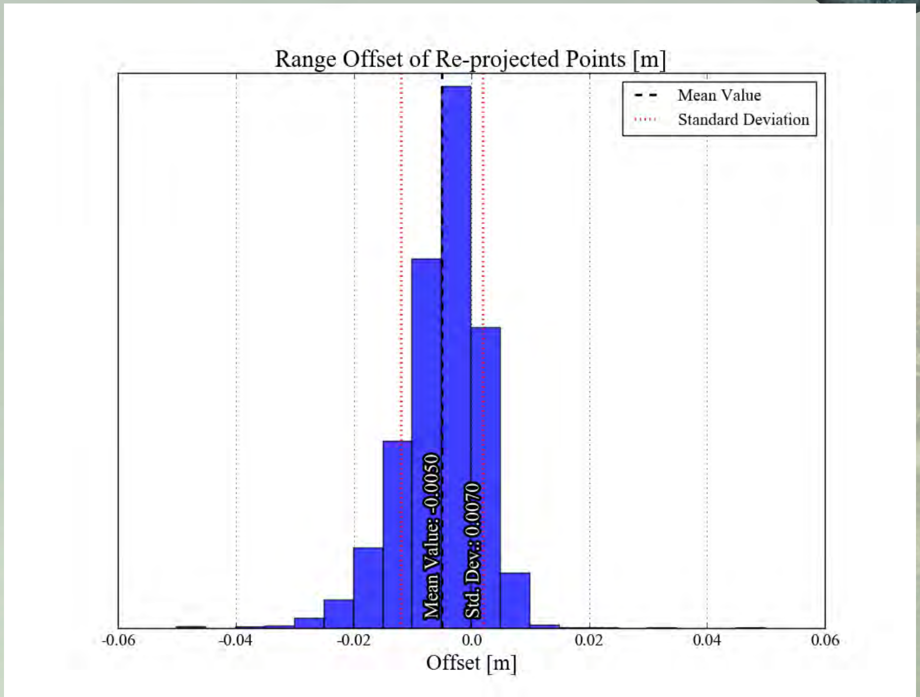


Lidar
P3
P16
R1
R2
R3
R6
P2
C5
R5 R4
P14
3V3
5V
5V driver
P1
Encoder 2
P11
Encoder 1
P10
P13
U1
P15
I+
I-
A+
A-
B+
B-
P12
I+
I-
A+
A-
B+
B-
P8
P9
PEPPERL+FUCHS
SENSING YOUR NEEDS
ADVANCED MOTION CONTROLS
CELESTIAL
SEASONINGS
P6
P4
P7 A B C
P5 A B C
GND HV LOGIC
GND HV LOGIC
B2
B1
B3
GND
+5VDC
+20VDC
Russell Gleason
MACULA
REV B

Hazard Analysis Results

Nadir 1





Actual data: num safe: 11672
Actual data: num hazardous: 11958

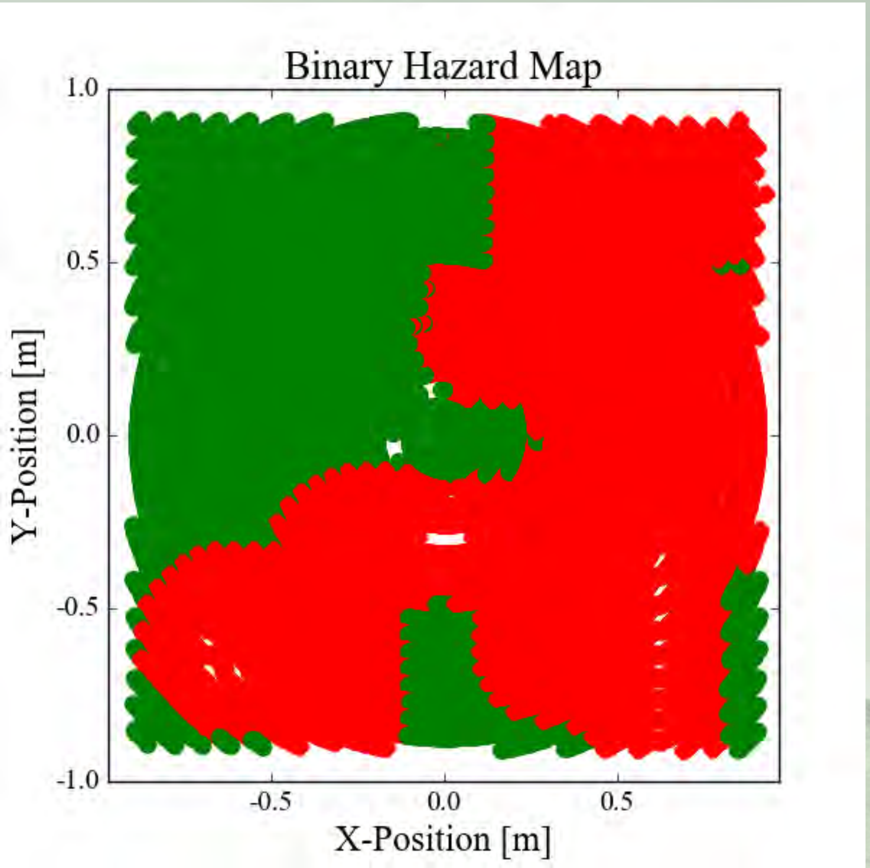
Comp data: num safe: 12660
Comp data: num hazardous: 10970

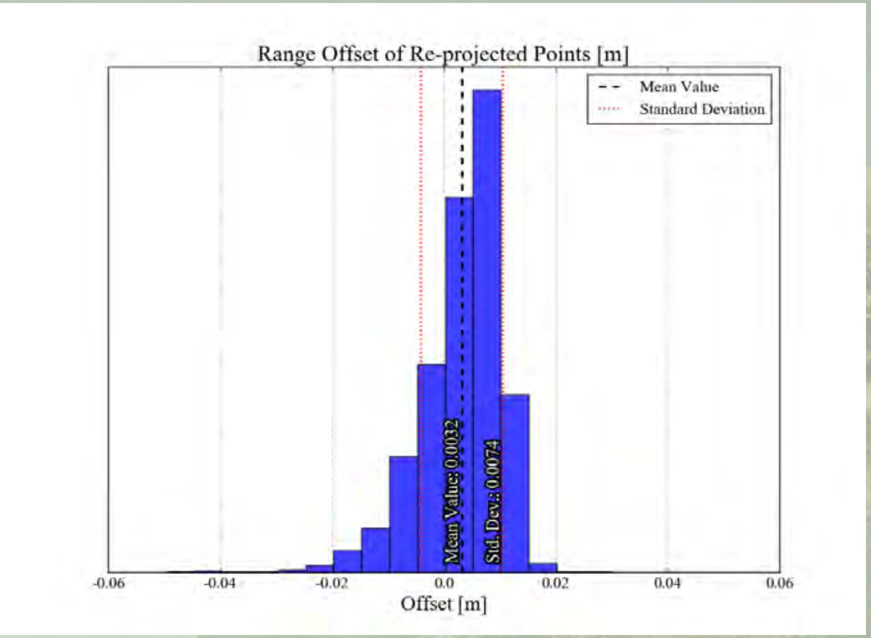
Num correct: 22624
Num hazardous should be safe: 997
Num safe should be hazardous: 9

Portion correct: 0.9574269995768091
Portion hazardous should be safe: 0.04219212865002116
Portion safe should be hazardous: 0.0003808717731696995

HAZARD ANALYSIS RESULTS

Nadir 2





Actual data: num safe: 11682
Actual data: num hazardous: 11808

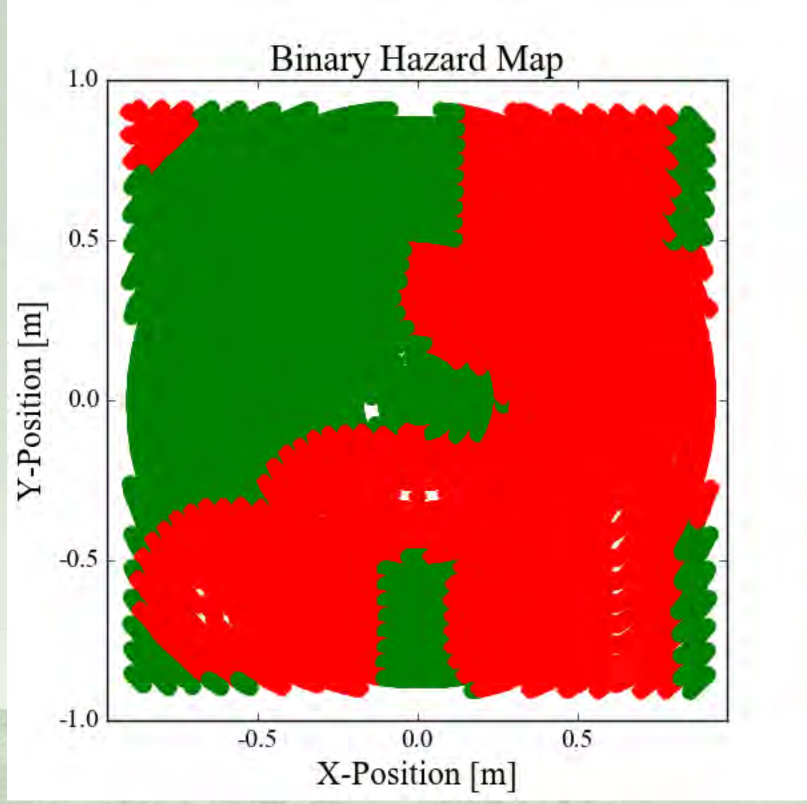
Comp data: num safe: 12544
Comp data: num hazardous: 10946

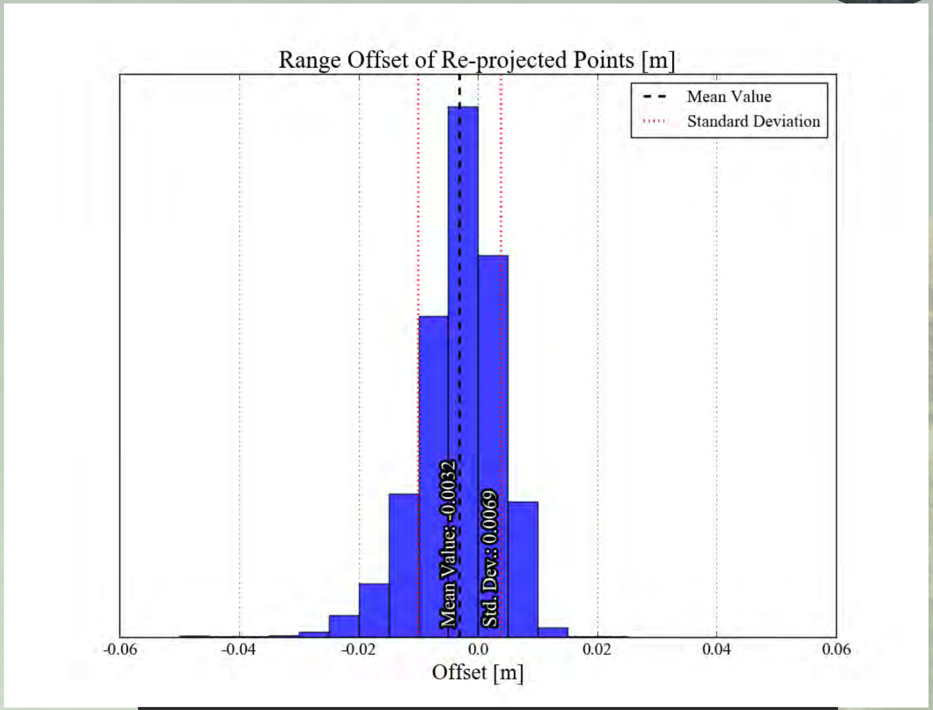
Num correct: 22616
Num hazardous should be safe: 868
Num safe should be hazardous: 6

Portion correct: 0.9627926777352065
Portion hazardous should be safe: 0.036951894423158 79
Portion safe should be hazardous: 0.000255427841634 7382

HAZARD ANALYSIS RESULTS

Nadir 3





Actual data: num safe: 12051
Actual data: num hazardous: 11485

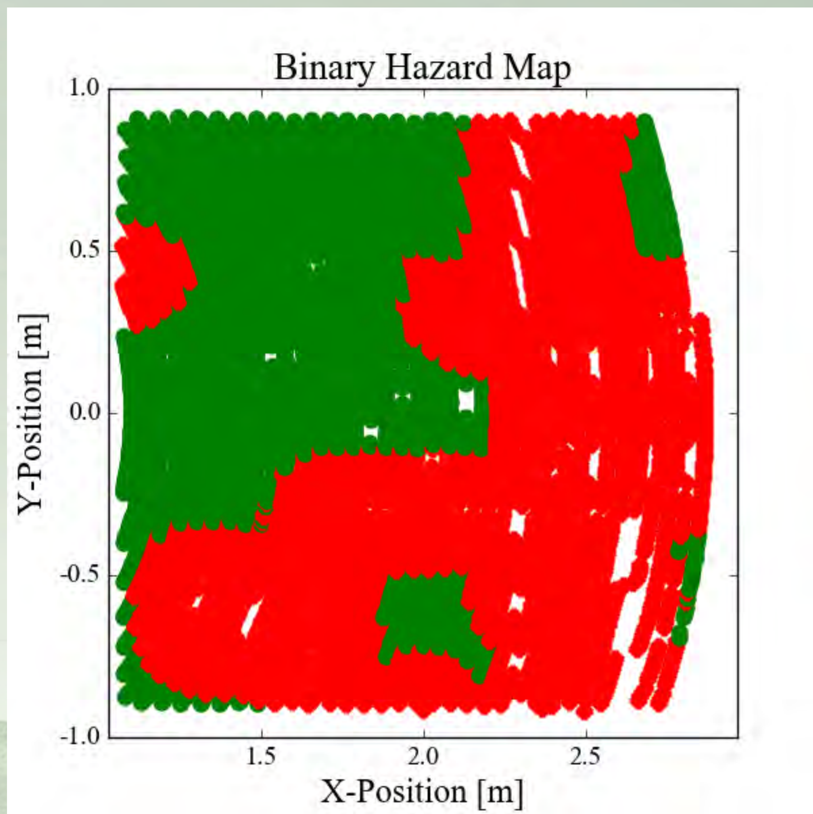
Comp data: num safe: 12586
Comp data: num hazardous: 10950

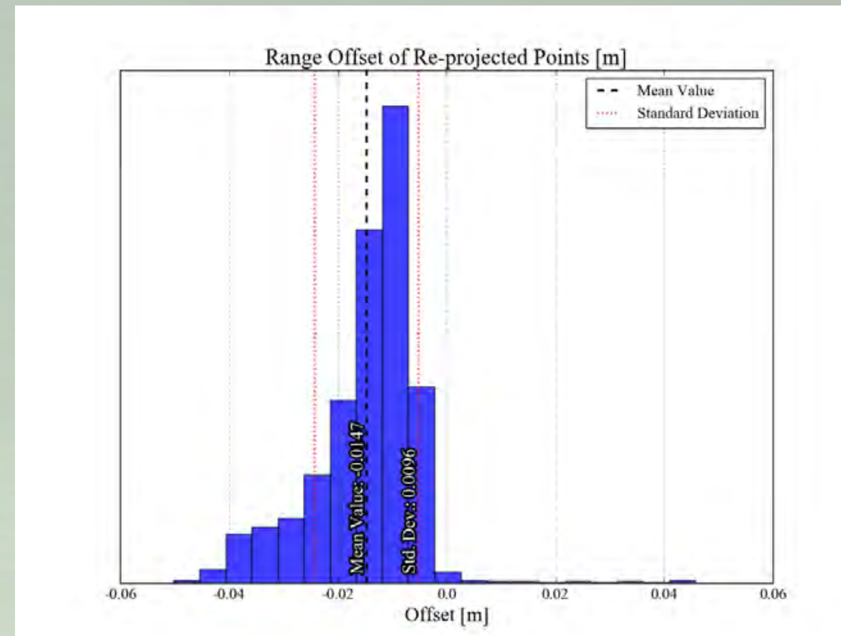
Num correct: 22997
Num hazardous should be safe: 537
Num safe should be hazardous: 2

Portion correct: 0.9770989123045547
Portion hazardous should be safe: 0.022816111148878314
Portion safe should be hazardous: 8.49762066621346e-05

HAZARD ANALYSIS RESULTS

Edge 1





Acutal data: num safe: 3329
Actual data: num hazardous: 2554

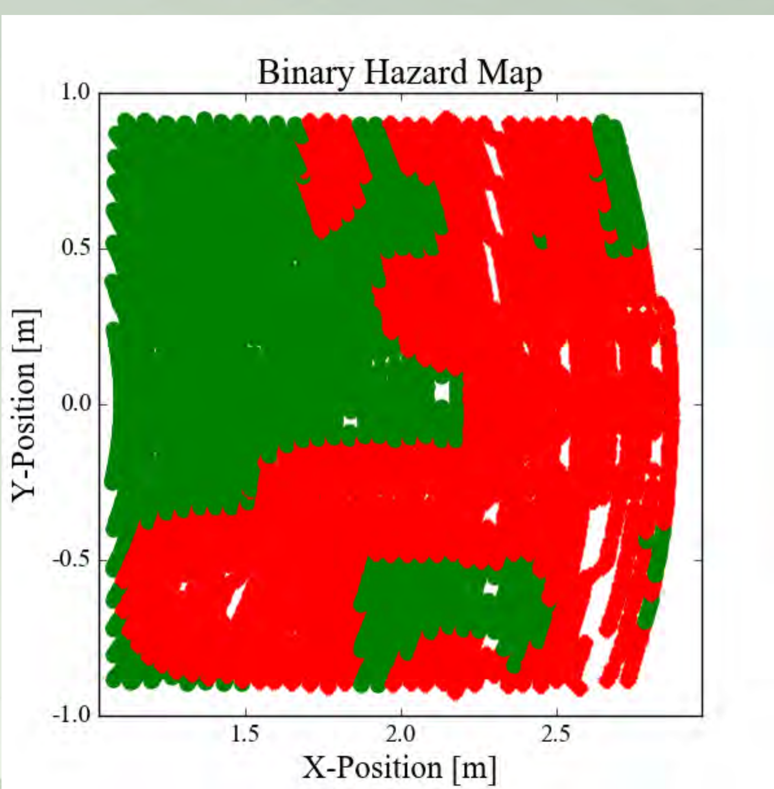
Comp data: num safe: 3547
Comp data: num hazardous: 2336

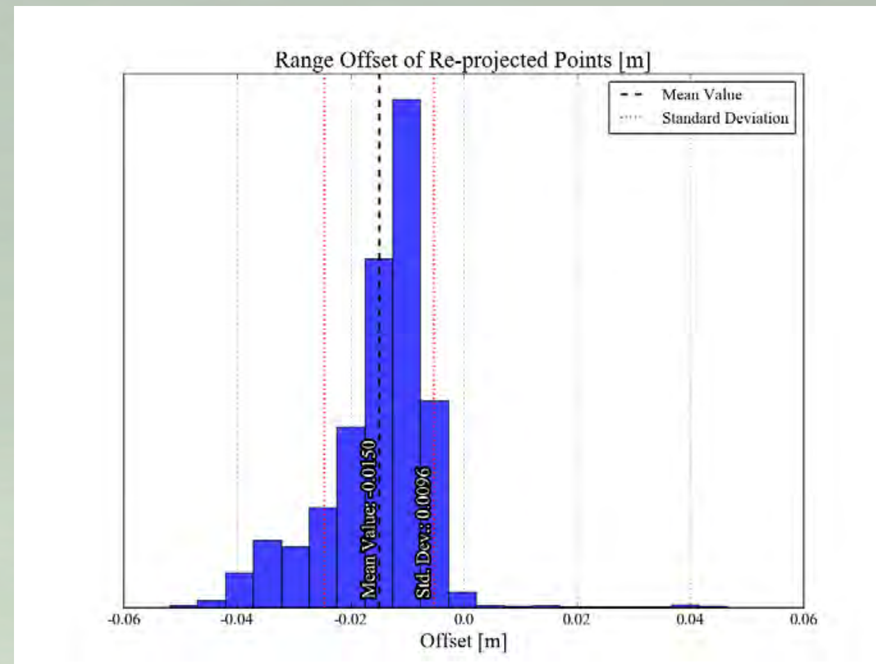
Num correct: 5505
Num hazardous should be safe: 298
Num safe should be hazardous: 80

Portion correct: 0.9357470678225395
Portion hazardous should be safe: 0.05065442801291858
Portion safe should be hazardous: 0.0135985041645419

HAZARD ANALYSIS RESULTS

Edge 2





Actual data: num safe: 3357
Actual data: num hazardous: 2550

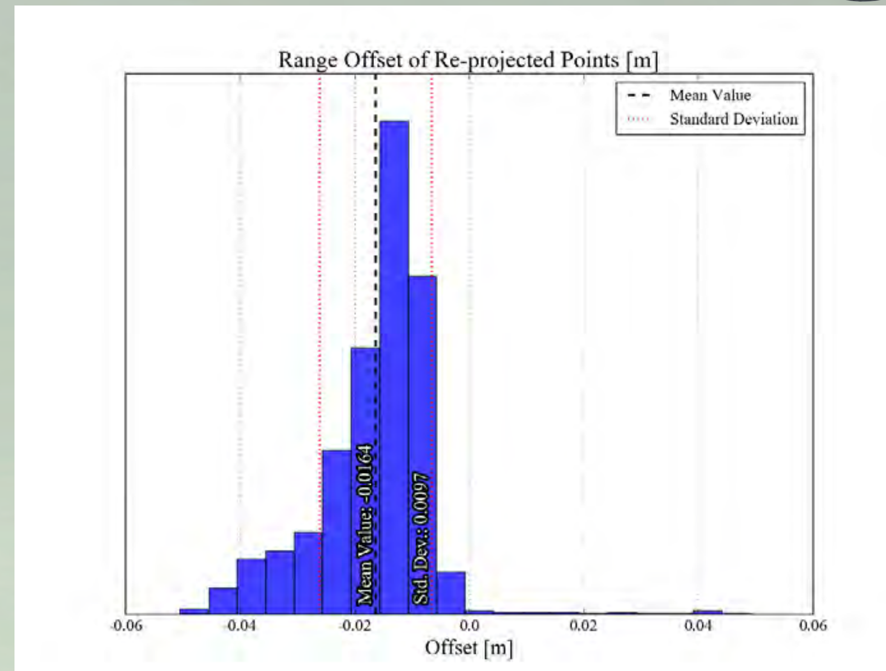
Comp data: num safe: 3597
Comp data: num hazardous: 2310

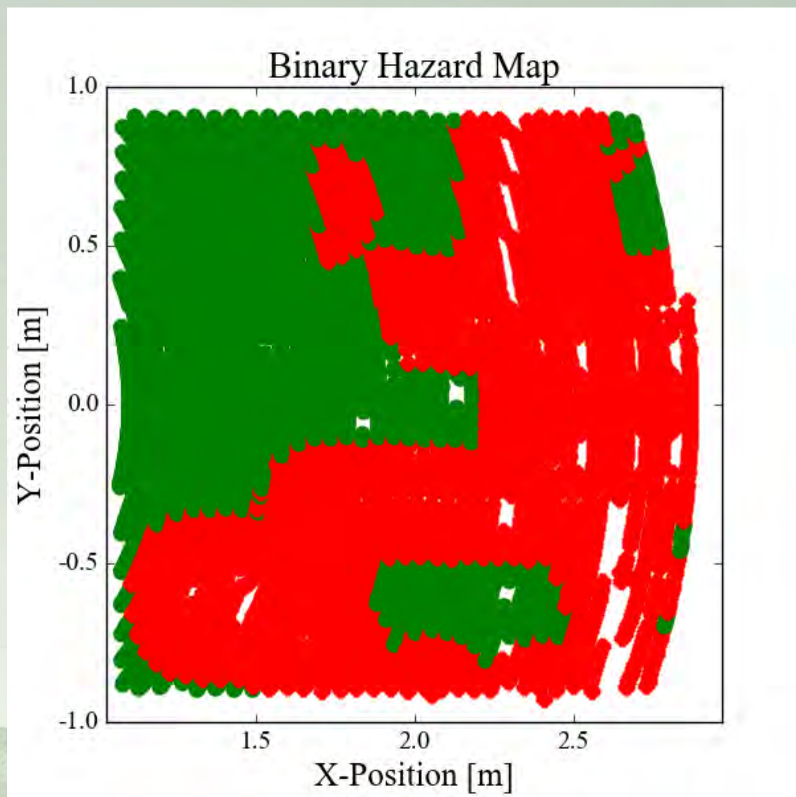
Num correct: 5597
Num hazardous should be safe: 275
Num safe should be hazardous: 35

Portion correct: 0.9475198916539699
Portion hazardous should be safe: 0.046554934823091225
Portion safe should be hazardous: 0.005925173522938886

Hazard Analysis Results

Edge 3





Actual data: num safe: 3131
Actual data: num hazardous: 2765

Comp data: num safe: 3545
Comp data: num hazardous: 2351

Num correct: 5324
Num hazardous should be safe: 493
Num safe should be hazardous: 79

Portion correct: 0.9029850746268657
Portion hazardous should be safe: 0.08361601085481682
Portion safe should be hazardous: 0.013398914518317503

FULL-SYSTEM: LANDING ZONE SELECTION

MACULA

Comparison of results for adjusted hazard definition

Test	Number correct	False Negative (safe marked unsafe)	False Positive (unsafe marked safe)	Failure Probability (select unsafe landing)
Nadir 1	22624 (95.7%)	997 (4.2%)	9 (0.04%)	0.071%
Nadir 2	22616 (96.3%)	868 (3.7%)	6 (0.03%)	0.048%
Nadir 3	22997 (97.7%)	537 (2.3%)	2 (0.008%)	0.016%
Edge 1	5505 (93.6%)	298 (5.1%)	80 (1.4%)	2.3%
Edge 2	5597 (94.8%)	275 (4.7%)	35 (0.6%)	0.97%
Edge 3	5324 (90.3%)	493 (8.4%)	79 (1.3%)	2.2%