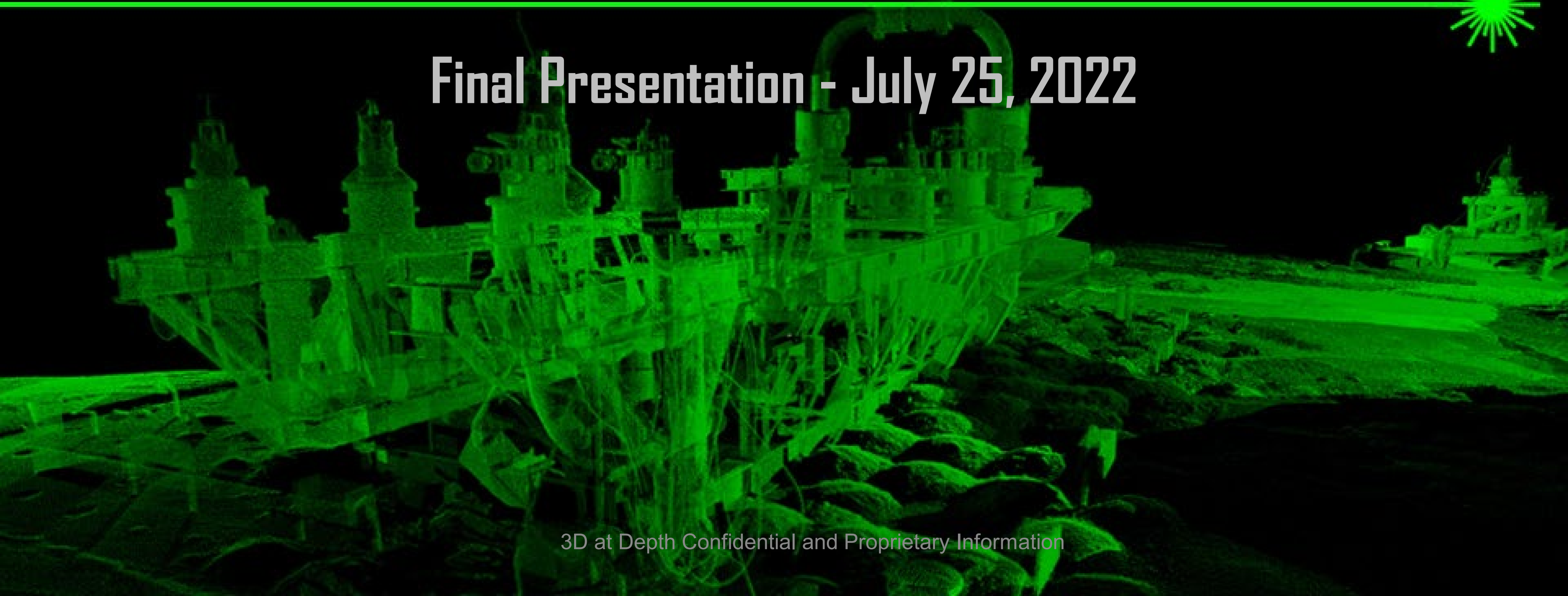
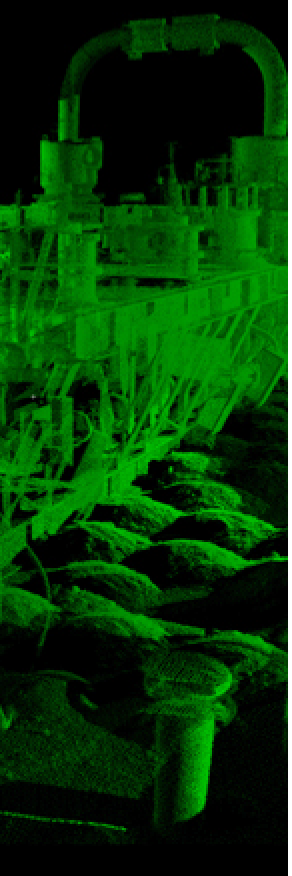
3D at Depth

MBARI WISSL G2 FEASIBILITY / PRELIMINARY DESIGN

Final Presentation - July 25, 2022

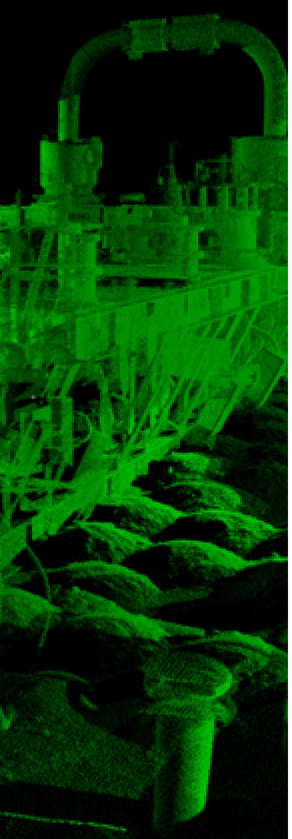


TOPICS



- Proprietary Information
- Requirements
- Design Architecture Goal
- Point Spacing Calculations
- 350kHz PRF Data Capture and Processing Tests
- Software CCI and Data Outputs
- LiDAR modeling
  - 3D
  - Temperature
- Housing Analysis
- Window
  - 360°
  - Flat window
  - Curved window
- Scanner
- MBARI Feedback and Next Steps

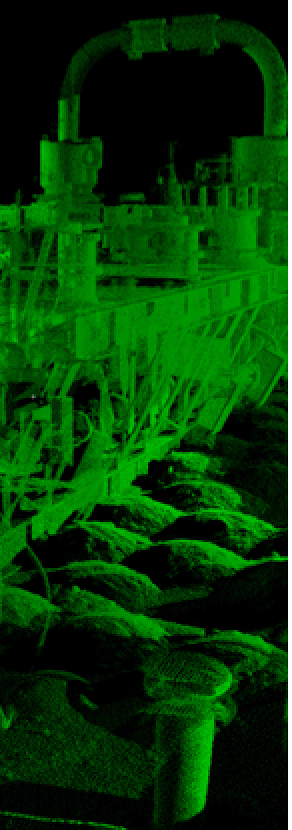
PROPRIETARY INFORMATION



NOTICE: This presentation contains 3D at Depth Confidential and Proprietary information.

In order to better describe some of the design decisions and options, this presentation contains details about the internal architecture and design decisions for 3D at Depth's current 3D laser scanning products. Therefore, this information should ONLY be shared with MBARI employees who need to read and evaluate the presentation. 3D at Depth appreciates our customers taking the appropriate safety measures when distributing this information internally.

UPDATE FROM JUNE REVIEW



This presentation is a repeat of the June presentation with updates / modifications highlighted in green, or otherwise noted. This is done in an attempt to keep all information in one presentation.

REQUIREMENTS – WISSL GEN 2

- Reference WiSSL Upgrades Wishlist_R1_1.PDF

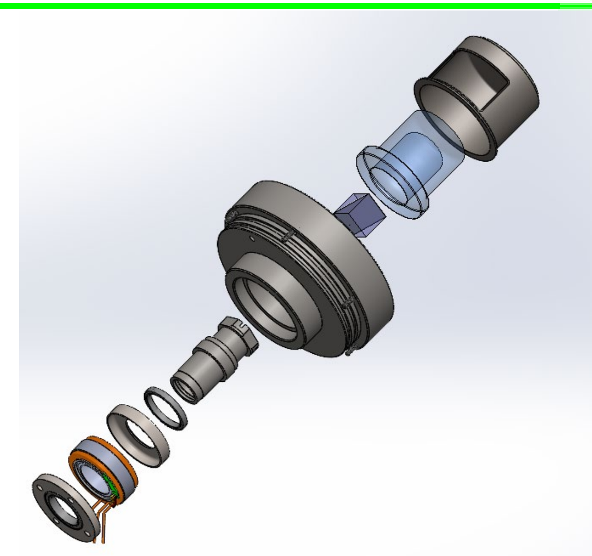
Highlighted Requirements	Must	Goal
Depth Rating	4000m	
Size	< 20” diameter, < 3ft long	6.25” diameter, < 17.5” long
Field of View (FoV)	80°	~~100~~° 90° (360° possible)
Range	1-meter to 7-meter NADIR, (10-meter LOS max)	1-meter to 7-meter NADIR, (10-meter LOS max)
Range Precision	Same as Gen 1 (<3mm)	
Angular Precision	Same as Gen 1 (<100µrad)	
Electrical Interface	• 18-36VDC • Isolate all peripherals • Less than Gen 1 (~400W)	Less than 200W while scanning Probably < 100W
Timing Requirements	Same as Gen 1 (ZDA + PPS)	PTP
Software Interface	SL3 plus updates as defined in Documentation	
Scan Rate	< 1cm spacing at 0.5m/s. Current surveys at 3m altitude and 0.2m/s	< 9mm spacing at 0.5m/s at max altitude < 5mm spacing at 0.5m/s at 3m altitude
Temperature		-2.5° C to 350° C per pulse Precision: +/-1° C

DESIGN ARCHITECTURE GOAL

- Primary Design Goal
  - Single housing capable of full 100° FOV that includes both optical components and electronics This bottle connects to the ROV/AUV.
- ROV /AUV Connection: 1x 13 pin connector

  - 18 – 36 VDC (4 wire)
  - 10/100 TCP/IP Ethernet connection (2 twisted pair)
  - 1PPS Timing connection (1PPS twisted pair)
- If can implement PTP timing then can switch to 1Gbps TCP/IP Ethernet connection with same connector
  - WiSSL Gen 2 could support PTP directly
  - Will require MBARI to convert from ZDA & PPS to PTP for WiSSL G2
  - Identified two options for generating PTP using Raspberry Pi4
    - Real time hat: https://innoroute.com/realtimehat/
    - Pi4 can also be used directly to measure/generate PTP https://github.com/raspberrypi/linux/issues/4151

POINT SPACING CALCULATIONS



Desired

FOV = ~~100~~° 90° (can go up to 360°)

NADIR = 7 meter

Speed = 0.5m/s

Desired Point Spacing = ~~5mm~~ 10mm

Calculations

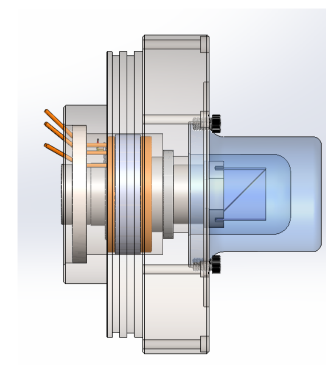
LOS = ~~10.9m~~ 10m

Swath = ~~16.7m~~ 14m

Number of points per Swath = ~~3,337~~ 1,400

Number of Forward Track Points per Second = ~~100~~ 50

Goal PRF = 350kHz



Given scanner implementation:

Forward Track Point Spacing = ~~5mm~~ 10mm

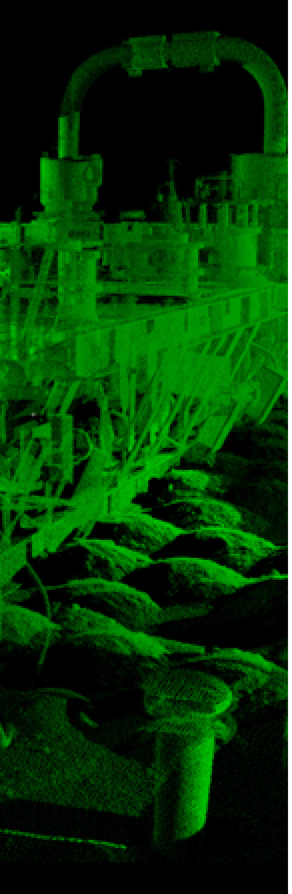
Cross Track Point Spacing = ~~8.5~~ 8mm at 7m altitude

Cross Track Point Spacing = ~~6.1~~ 5.7mm at 5m altitude

Cross Track Point Spacing = ~~3.7~~ 3.4mm at 3m altitude

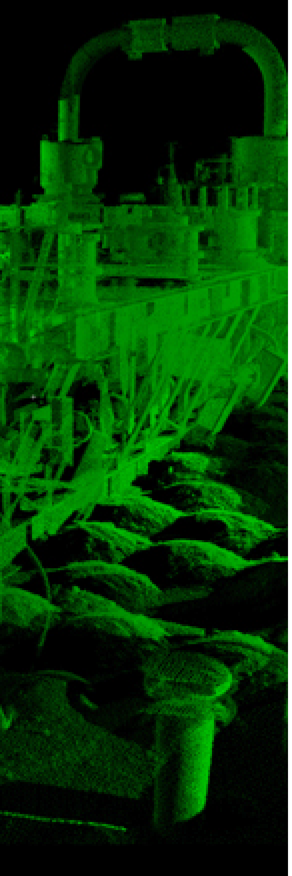
Speed = 0.3m/s

Forward Track Point Spacing = 6mm



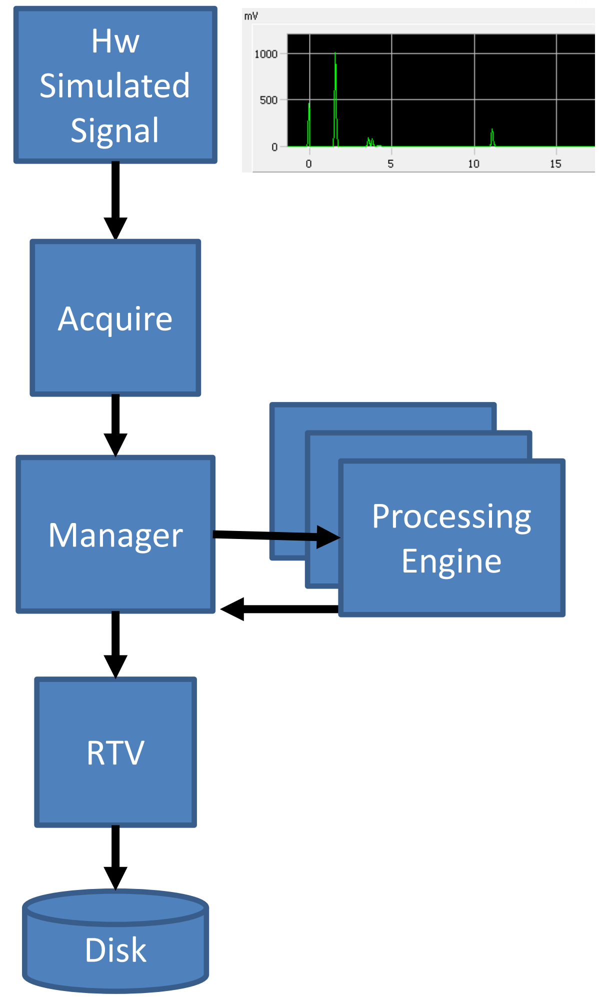
350KHZ DATA CAPTURE AND PROCESSING TESTS

350KHZ DATA CAPTURE TESTS

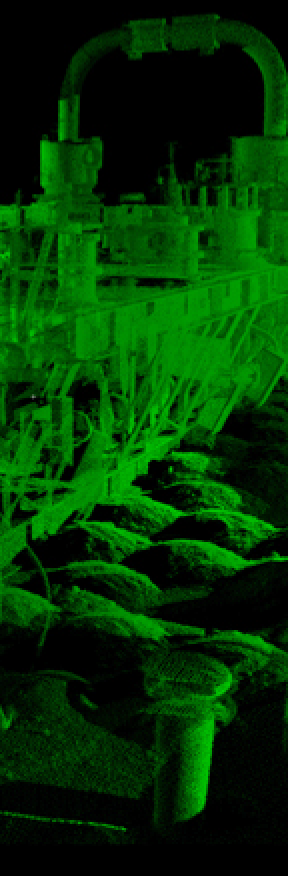


- Simulated Data through system, direct data path (not going through A2D conversion process)
- Set PRF to 350,140 Hz (350 KHz goal)
- 1000x1000 point file
- Capture data at full speed, no skips, 2.857 seconds/file
- Processing takes 7.8 seconds (5 returns, continuous)
- 100 / 180 degrees = 55%
- 3 / 5 returns = 60%
- 7.8 / 2.85 processing to acquire time * 0.55 (data clipping) * 0.6 (number returns) = 0.91 ratio

Simulation verifies real time data processing



350KHZ DATA CAPTURE TESTS

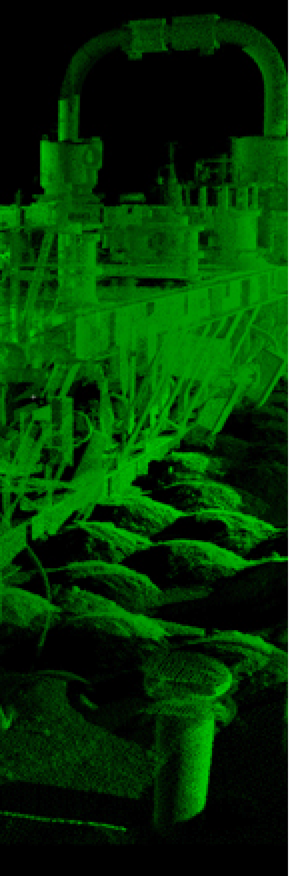


- This does show that we are not keeping up with data generation in real time, since we are still keeping 5 returns and all data, RawQ is completely full.
- Actual Data rate will be less, estimate at 17.4 MB/s for RIAAT / much less if we process into MBARI custom format which will be targeted for a slower connection (less than 100 Mbit/sec)
- 65 MB/s * 0.55 (clipping data) *0.6 (number returns) = 21.45 MB/s

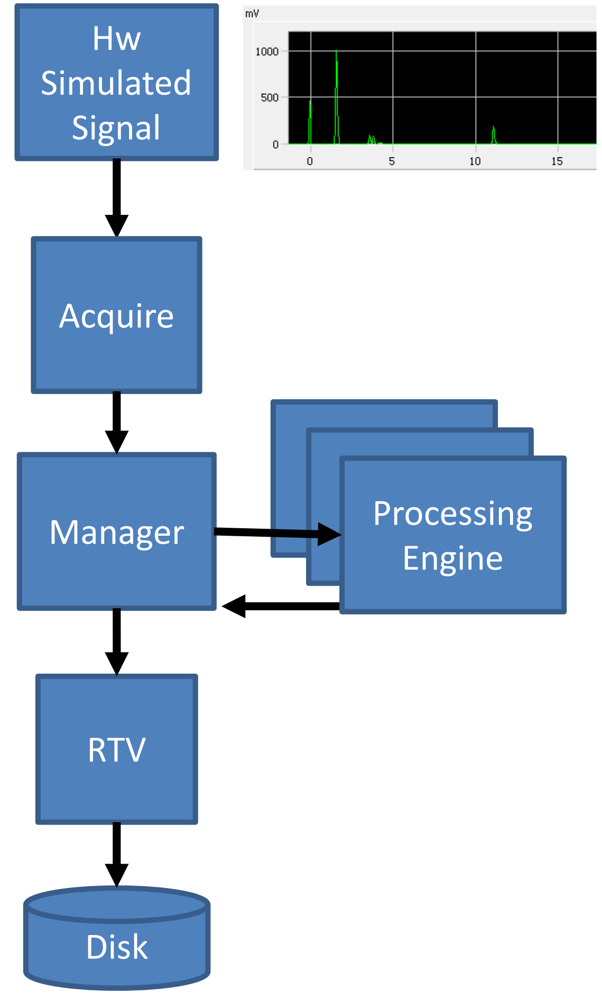
```
Mar 31 23:04:37 sl4n-001.local InstaCloud: RawQ: 0%, ProcE: 85%, In:  12.11 MBytes/s, Out:  64.13 MBytes/s
Mar 31 23:04:38 sl4n-001.local InstaCloud: RawQ: 0%, ProcE: 86%, In:  12.22 MBytes/s, Out:  62.49 MBytes/s
Mar 31 23:04:39 sl4n-001.local InstaCloud: RawQ: 0%, ProcE: 86%, In:  12.33 MBytes/s, Out:  62.92 MBytes/s
Mar 31 23:04:40 sl4n-001.local InstaCloud: RawQ: 0%, ProcE: 86%, In:  12.39 MBytes/s, Out:  63.97 MBytes/s
Mar 31 23:04:41 sl4n-001.local InstaCloud: RawQ: 0%, ProcE: 83%, In:  12.41 MBytes/s, Out:  64.05 MBytes/s
Mar 31 23:04:42 sl4n-001.local InstaCloud: RawQ: 0%, ProcE: 83%, In:  11.38 MBytes/s, Out:  59.70 MBytes/s
```

```
Mar 31 22:17:45 sl4n-001.local EC: TPH: Progressing to cart /tmp/scans/sl4_15
Mar 31 22:17:45 sl4n-001.local EC: TPH: Progressing to cart /tmp/scans/sl4_16
Mar 31 22:17:45 sl4n-001.local EC: TPH: Progressing to cart /tmp/scans/sl4_17
Mar 31 22:17:45 sl4n-001.local EC: TPH: Progressing to cart /tmp/scans/sl4_18
Mar 31 22:17:45 sl4n-001.local EC: TPH: Progressing to cart /tmp/scans/sl4_19
Mar 31 22:17:45 sl4n-001.local EC:    Laser Shots per Second: 349565
Mar 31 22:17:46 sl4n-001.local EC: TPH: Progressing to cart /tmp/scans/sl4_20
Mar 31 22:17:46 sl4n-001.local EC: TPH: Progressing to cart /tmp/scans/sl4_21
Mar 31 22:17:46 sl4n-001.local EC: TPH: Progressing to cart /tmp/scans/sl4_22
Mar 31 22:17:46 sl4n-001.local EC: TPH: Progressing to cart /tmp/scans/sl4_23
Mar 31 22:17:46 sl4n-001.local EC:    Laser Shots per Second: 349647
```

194KHZ DATA CAPTURE TESTS



- Hardware loopback test(is going through A2D conversion process, real noise)
- Set PRF to 194,553 Hz (Same data rate)
- 1450x1450 point file
- Capture data at full speed, no skips, 10.8 seconds/file
- Processing takes 21 seconds (5 returns, continuous)
- 3 / 5 returns = 60% (estimate) 12.6 sec
- 2 / 5 returns = 40% (estimate) 8.4 sec
- Near the challenging edge of data processing time.
- May need further processing optimizations and/or add more Processing Engines to buy margin

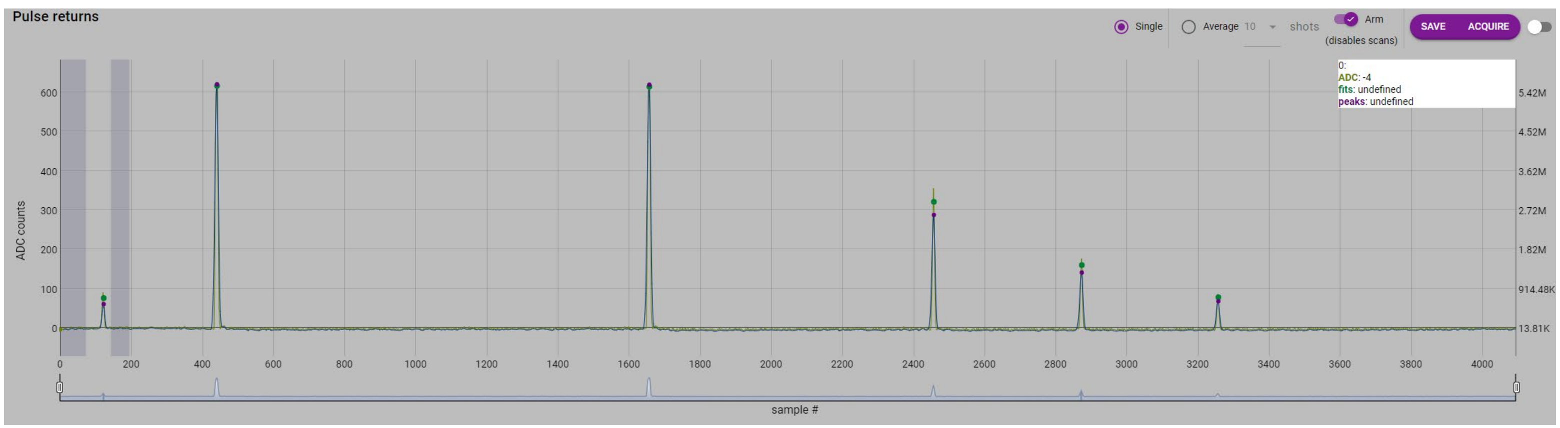


Risk: 3 Return Yellow / 2 Return Green

194KHZ DATA CAPTURE TESTS

- This does show that we are not keeping up with data generation in real time, since we are still keeping 5 returns and all data, RawQ is completely full.

May 04 17:45:40 sl4n-001.local InstaCloud[6760]:   Laser Shots per Second: 193902
May 04 17:45:41 sl4n-001.local InstaCloud[6760]: RawQ: 39%, ProcE: 100%, In: 4.01 MBytes/s, Out: 20.94 MBytes/s
May 04 17:45:42 sl4n-001.local InstaCloud[6760]: RawQ: 0%, ProcE: 100%, In: 18.92 MBytes/s, Out: 63.17 MBytes/s
May 04 17:45:43 sl4n-001.local InstaCloud[6760]: RawQ: 0%, ProcE: 100%, In: 10.36 MBytes/s, Out: 63.79 MBytes/s
May 04 17:45:44 sl4n-001.local InstaCloud[6760]: RawQ: 0%, ProcE: 100%, In: 8.82 MBytes/s, Out: 59.89 MBytes/s
May 04 17:45:45 sl4n-001.local InstaCloud[6760]: RawQ: 0%, ProcE: 100%, In: 8.55 MBytes/s, Out: 59.37 MBytes/s
May 04 17:45:46 sl4n-001.local InstaCloud[6760]: RawQ: 0%, ProcE: 81%, In: 8.31 MBytes/s, Out: 64.06 MBytes/s
May 04 17:45:47 sl4n-001.local InstaCloud[6760]: RawQ: 0%, ProcE: 81%, In: 8.83 MBytes/s, Out: 63.46 MBytes/s



SW CCI AND DATA OUTPUTS

Separate Documents

SW SUMMARY

<u>High-Level</u>

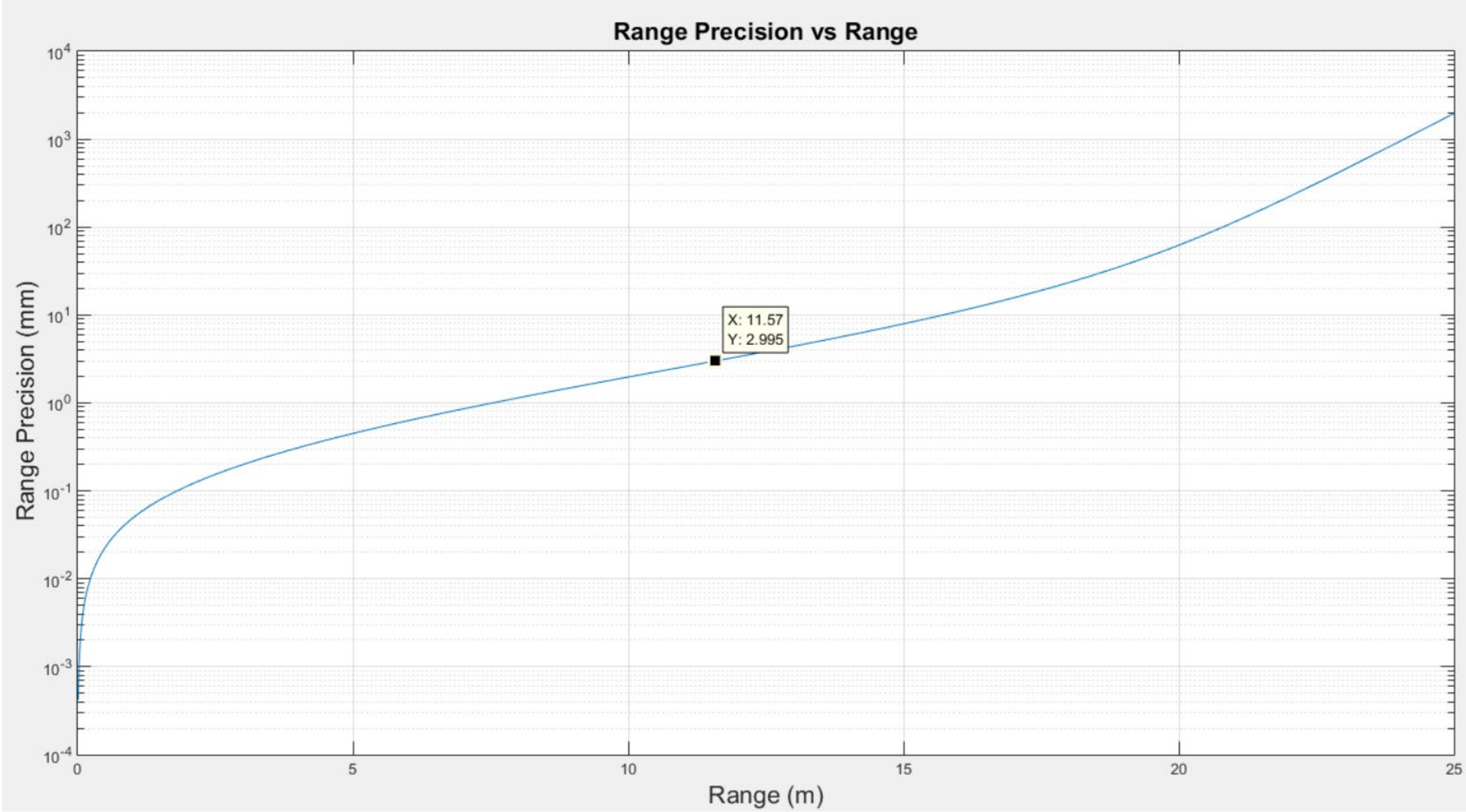
- Created definition of SW requirements for autonomous operation, output data packets, and low bandwidth support
  - SL Sensor CCI_Manual_C4.pdf
  - RTV CCI Communication Manual_C4.pdf
  - SL Sensor ICD_C9.pdf
  - 3DatDepth_CCI_packets_Revc7.pdf
- Heavily leverages current 3D at Depth SL4 software to minimize development time
- Enables MBARI to take advantage of continual upgrades to SL4 electronics

<u>Modifications from Standard SL4 software</u>

- Will provide option to return 2 or 3 points per line of sight, but may impact data collection rate and required bandwidth
- Supports 100Mb/s links in case of network or vehicle issues
- Ability to flag data as opposed to delete data. Can create classifications
- More customization is available

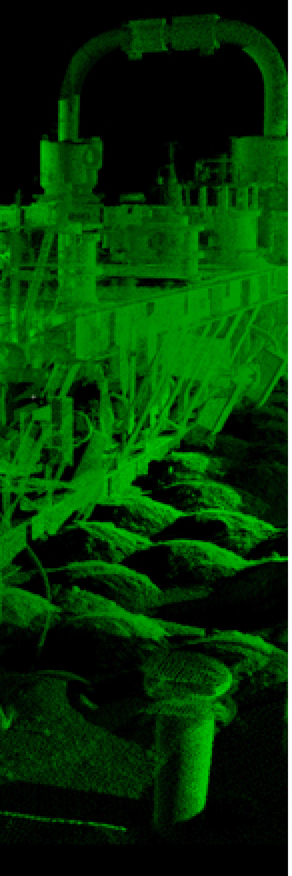
LIDAR MODELING

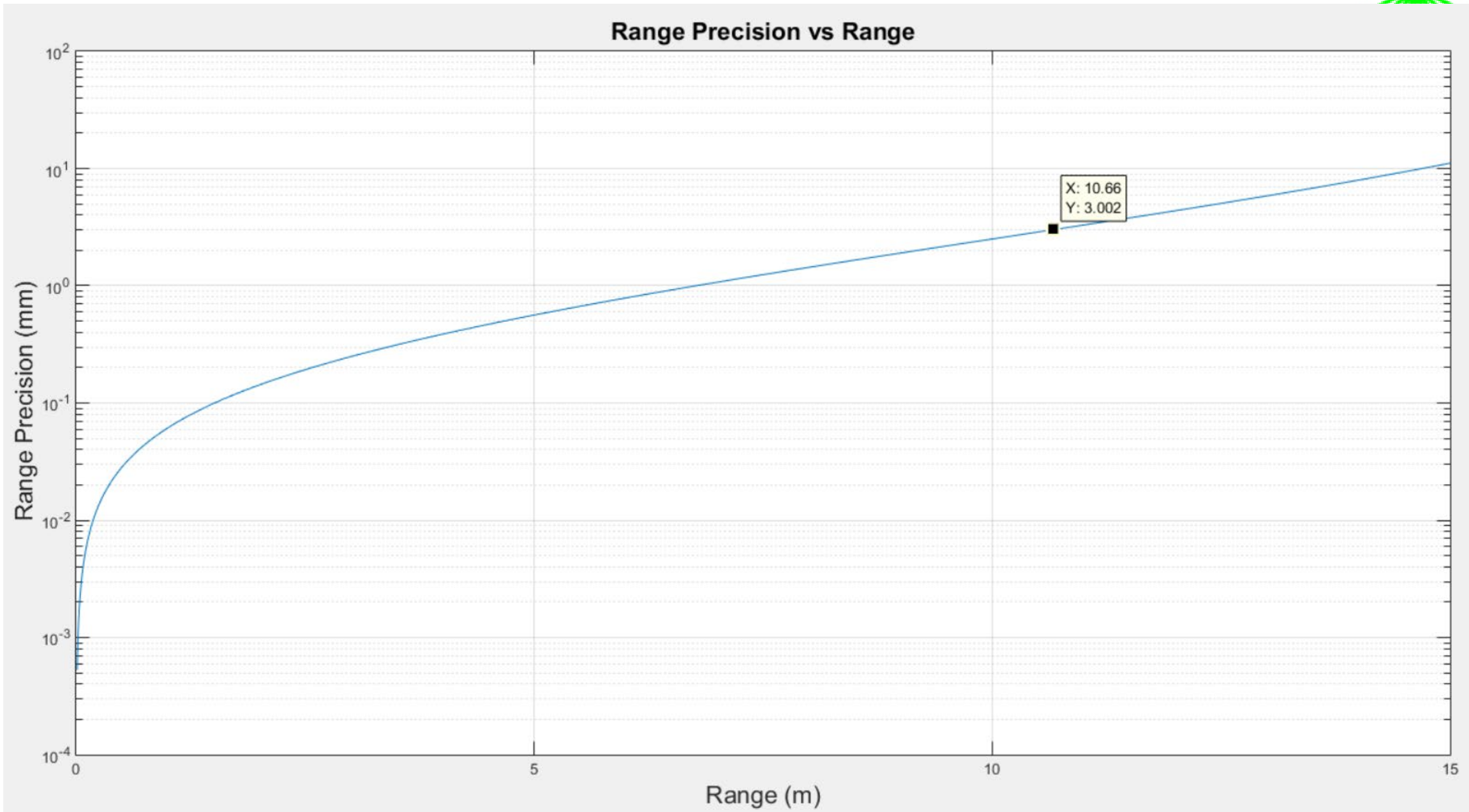
LIDAR MODELING – WISSL GEN 1



- Goal = 7m NADIR, 11m LOS range
- Water model: Jerlov Type III
- Target model: Lambertian, 10% reflectivity, normal incidence
- Background light: a 'typical' Kongsberg ROV light illumination and color temp
- Detector Gain setting: High

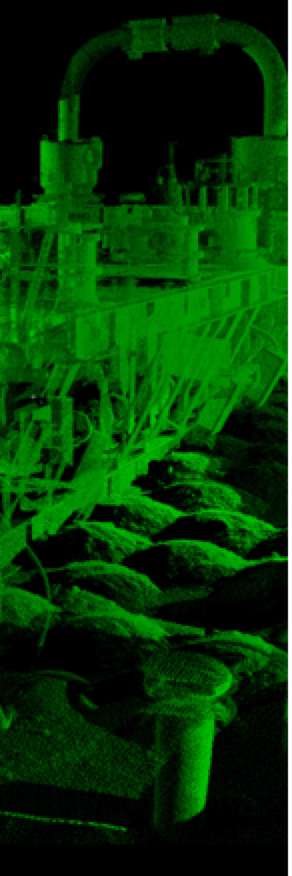
LIDAR MODELING – WISSL GEN 1

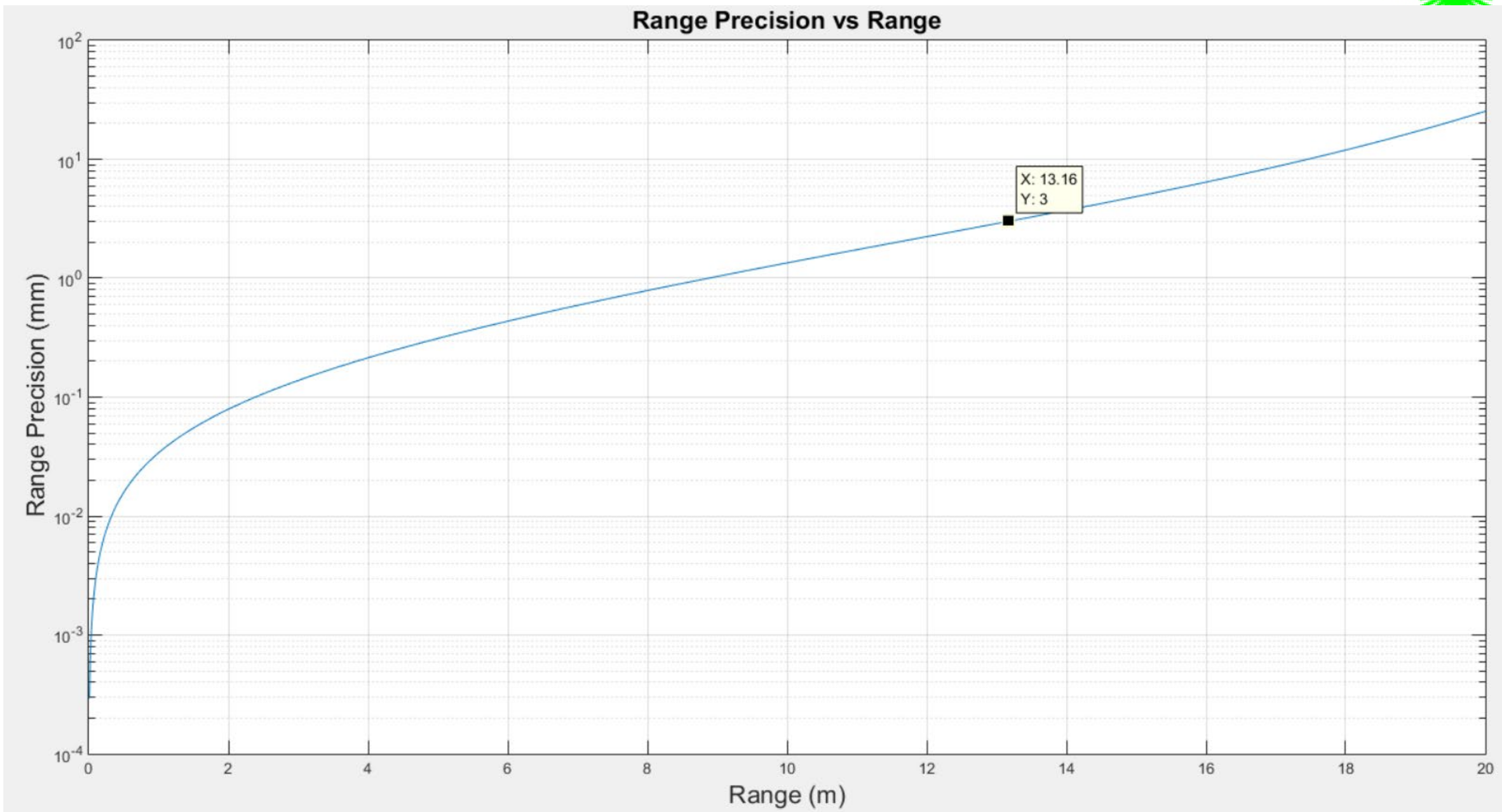




- 50° incidence angle with Lambertian target decreases range below 11m LOS goal
- Water model: Jerlov Type III
- Target model: Lambertian, 10% reflectivity, 50° incidence – below 11m goal
- Background light: a 'typical' Kongsberg ROV light illumination and color temp
- Detector Gain setting: High

LIDAR MODELING – WISSL GEN 2 – RECOMMENDED DESIGN





- 13m LOS range. ~ 3x increase in clear aperture area. ~ 30% increase in pulse energy
- Water model: Jerlov Type III
- Target model: Lambertian, 10% reflectivity, 50° incidence
- Background light: a ‘typical’ Kongsberg ROV light illumination and color temp
- Detector Gain setting: High

LIDAR MODELING – TEMPERATURE TRADE SPACE

Use WiSSL Gen 2 design from above, estimate ~ 3m LOS range (~2m NADIR)

Range NADIR / Max LOS (50°)	Aperture Area	Laser Energy
2m / 3.1m	1	1
5m / 7.8m	~59x	1
7m / 10.9m	~650x	1

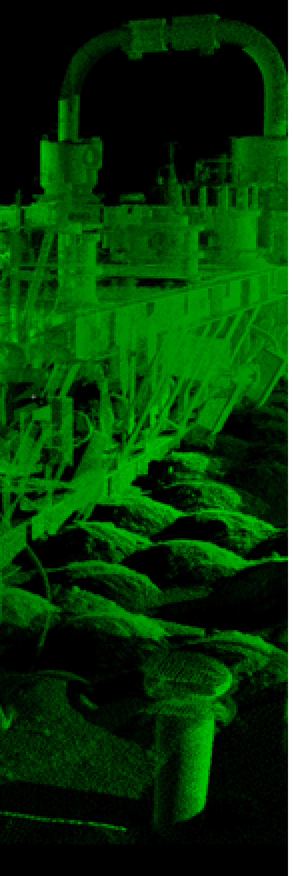
Range NADIR / Max LOS (50°)	Aperture Area	Laser Energy
2m / 3.1m	1	1
5m / 7.8m	1	~60x, ~6kHz laser
7m / 10.9m	1	~600x, 583Hz

Range NADIR / Max LOS (50°)	Aperture Area	Laser Energy
2m / 3.1m	1	1
5m / 7.8m	~6.5x	10x, 35kHz

LIDAR MODELING – TEMPERATURE TRADE SPACE

Range NADIR / Max LOS (50°)	Aperture Area	Laser Energy
2m / 3.1m	1	1
3m / 4.67m	~5x	1
3m / 4.67m	1	~5x, 70kHz
3m / 4.67m	~2.25x* back to custom scanner	~2x, 175kHz
3m / 3.5m (30°) = 60° FOV	~1	~1
3m / 4.67m w/ 100 spatial ave	1	1

- Spatial Averaging should allow us to use the same LiDAR design and reach the full 4.67m LOS range.
- Expect ~ +/- 2° C accuracy



TEMPERATURE – SPATIAL AVERAGING

- Pulse width ~ 8.5cm in water
- At 3m altitude
  - Cross track point spacing = 3.67mm
  - Forward track point spacing = 5mm

<u>Scenario 1</u>

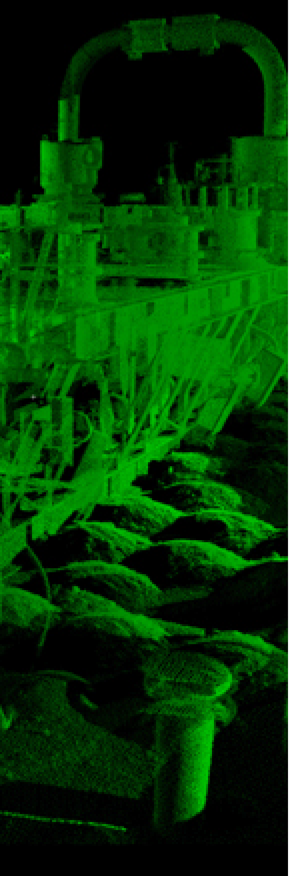
- Create ~8.5cm square on seafloor to spatial average for temperature
- Equates to 23 cross track pts x 17 forward track points = 389 pts to average
- Takes 170ms to acquire this data

<u>Scenario 2</u>

- Can use more cross track points than forward track points to decrease data collection time
- MBARI agrees that a lateral resolution of 10cm is acceptable
- Spatial averaging will require the temperature cell / feature size to be ~ uniform over the spatial and temporal sample size

<u>Comments from June Review</u>

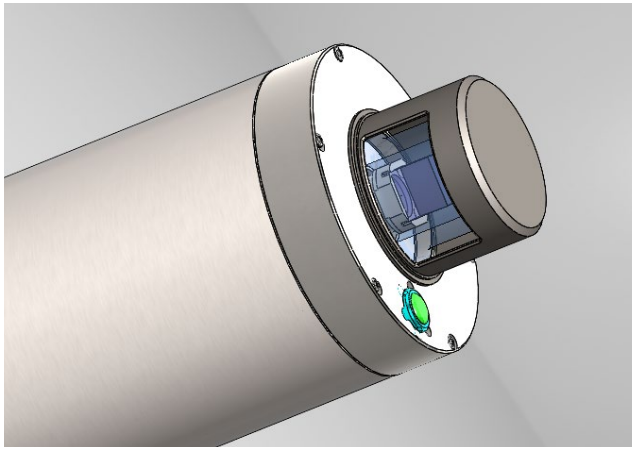
- Spectral band filters are ~ 10nm wide. Laser spec is 531nm min to 533nm max. Therefore can handle shifts in transmitter spectrum.
- Modeled number of return Raman scattered photons at 4.7m LOS range = 43 (which is why we need to average)

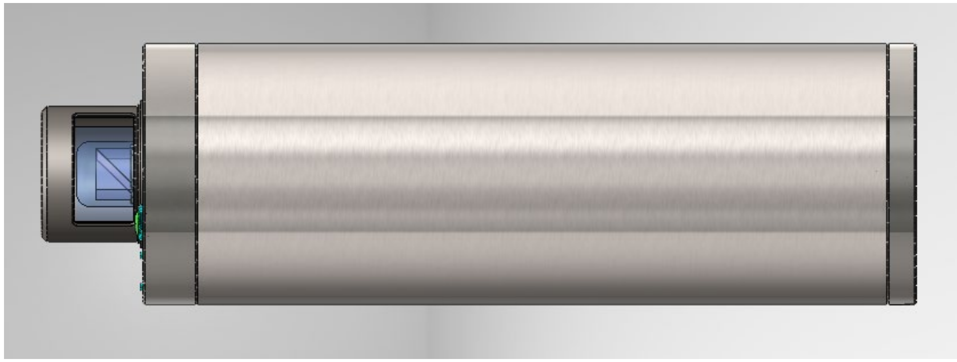


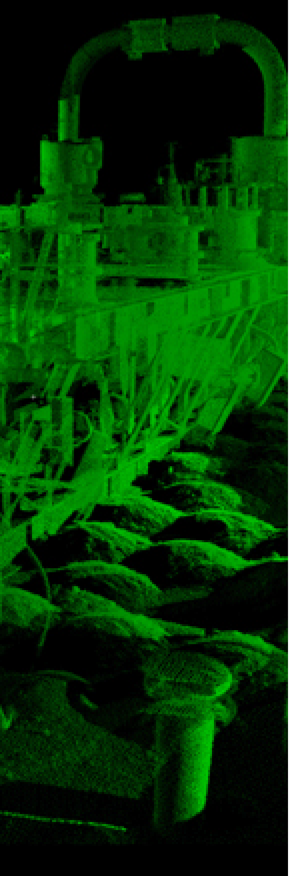
WINDOW - NEW DESIGN AND ANALYSIS

OVERVIEW

- Based upon MBARI feedback from June design review, 3D at Depth further investigated the window and scanner options to reduce design risk on the window
- Results is a new window and scanner concept
- Window mounted to tube end
- Window easier to manufacture
- All bond stresses are the same as 3D at Depth current designs
- Rotating prism inside window
- Custom spinning scanner assembly

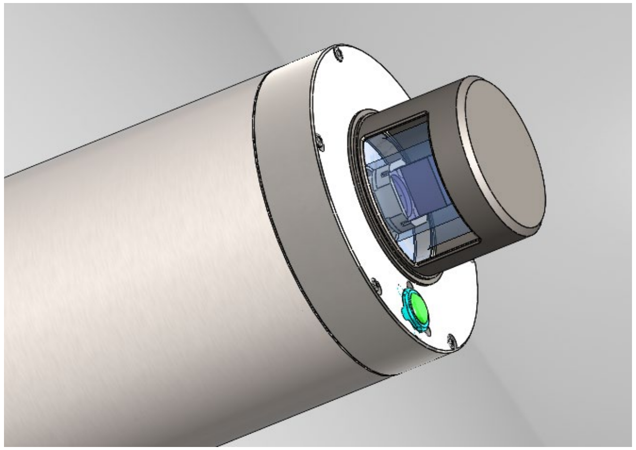


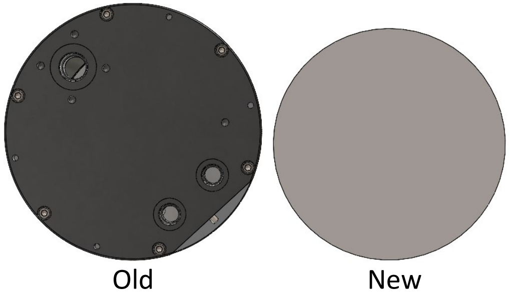


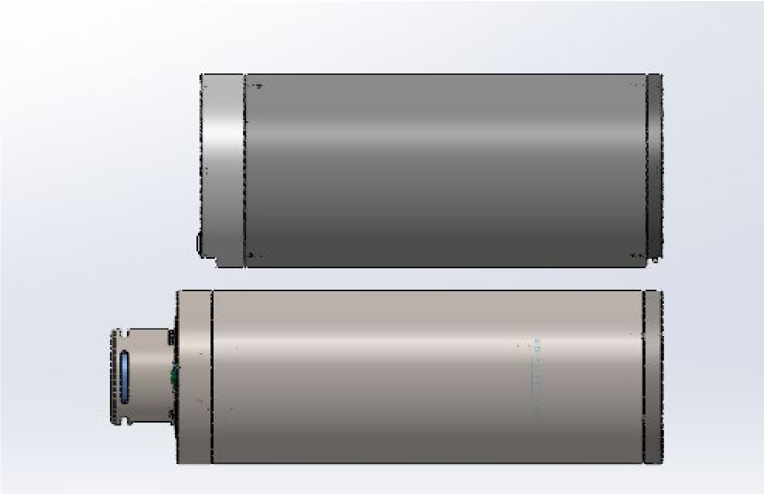


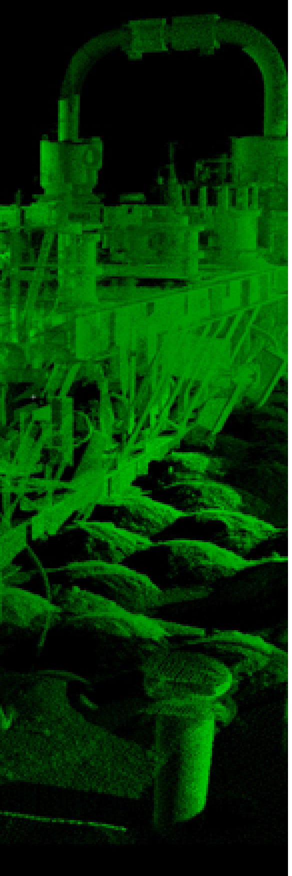
WEIGHT AND SIZE

- Housing about 2 lbs lighter than MBARI Gen1 optical housing
- About 20” long from end to end (Might be more). Current optical head = 16.6”
- OD: 6.94” -> 6.25”



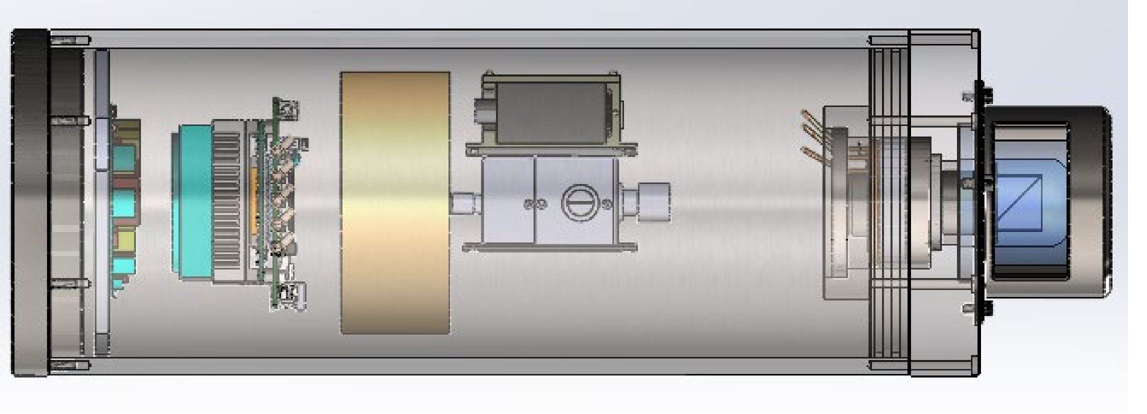






INTERNAL COMPONENTS

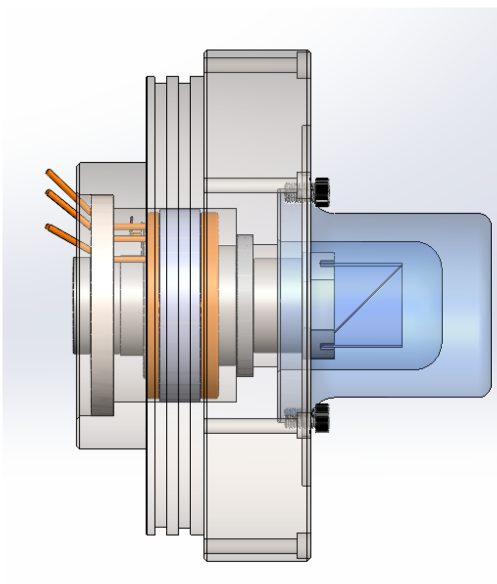
<u>Internal components listed in order from left to right</u>

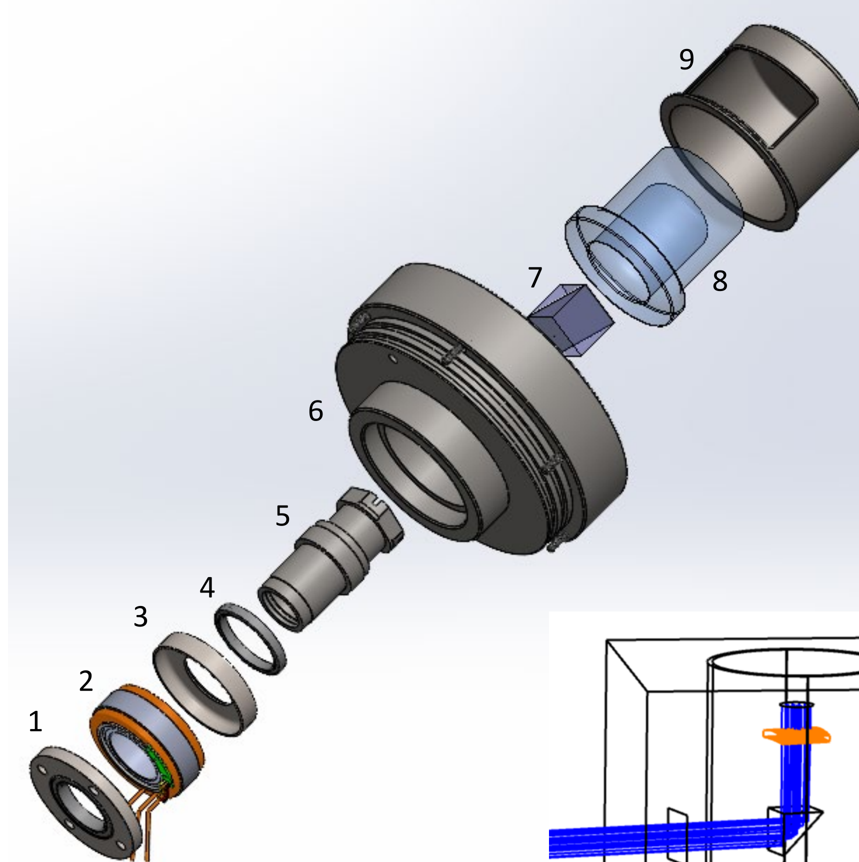


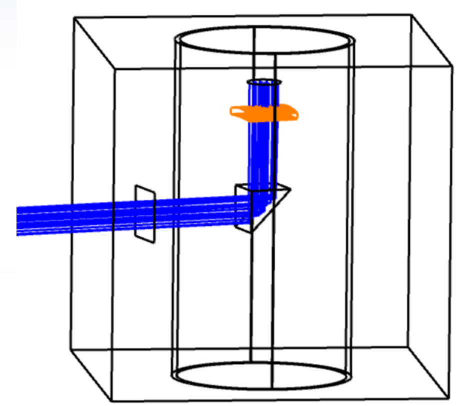
- Power board
- CPU
- Laser electronics
- Laser
- Receiver
- Scanner assembly
- Window
- Shroud
- Housing length may need to grow during detailed design

EXPLODED VIEW – SCANNER ASSEMBLY CONCEPT

1. Ball bearing with outer ring
2. Motor
3. Spacer
4. Ball bearing
5. Shaft: high stiffness SS
6. Endcap
7. Mirror
8. Window
9. Shroud

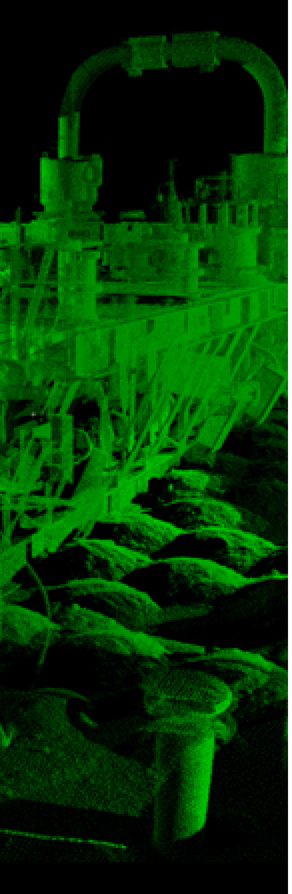


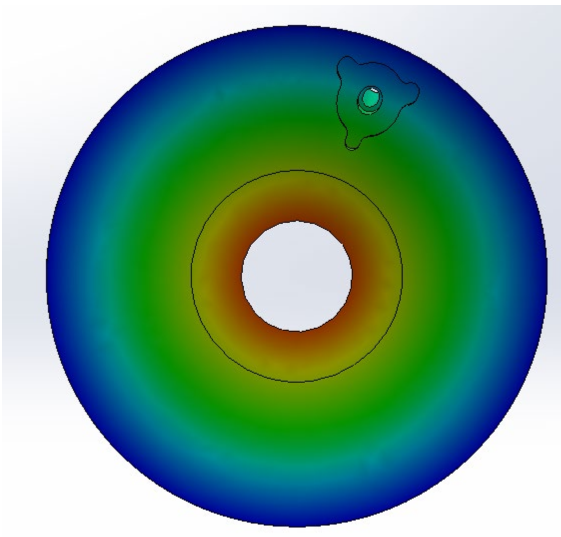




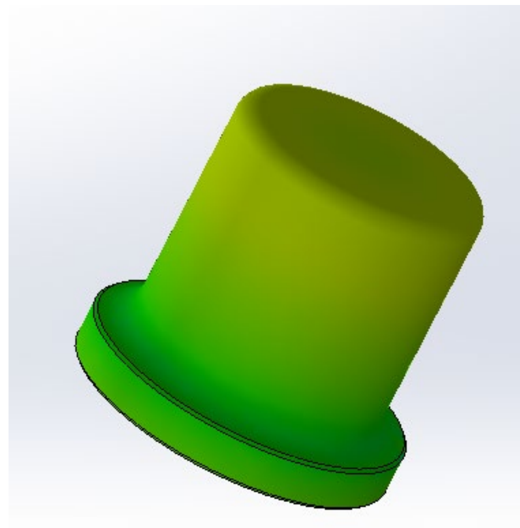
FEA SUMMARY – 6,723 PSI (4,600M)

- Acceptable deflections and stresses
- Less endcap deflection than current product
- Comparable window stress to current product

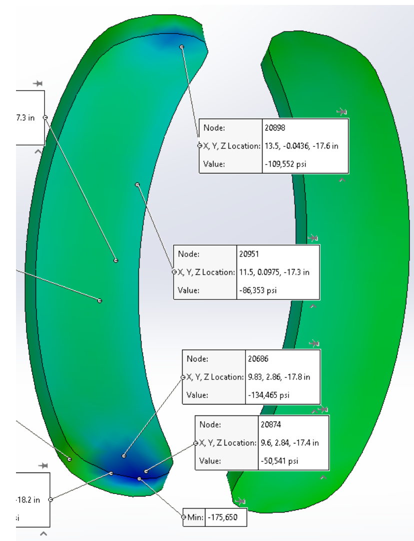




Uniform Deflection



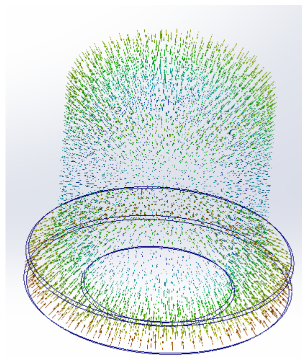
Uniform Stress

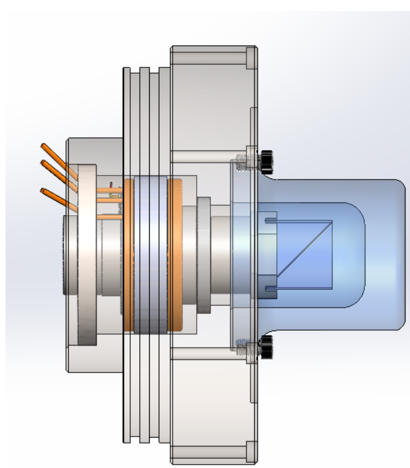


Eliminates concerns from previous design

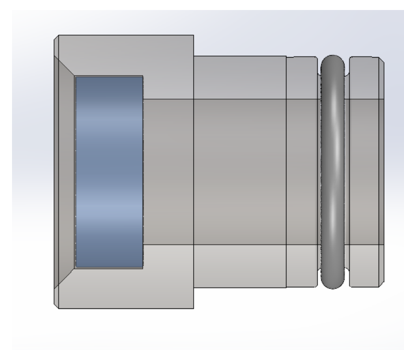
BONDING ANALYSIS AND PROOF TEST

- Bonding modeled at 6,723psi (4,600m) and 23°C / 0°C
- All analysis showed no issues for 3D at Depth bonding capability (all within proven designs)





- Flat window - end cap configuration was designed and pressure tested in house at 10ksi
- Similar forces and deflections to MBARI



SCANNER ASSEMBLY INTERFERENCE FITS AT 6,723 PSI

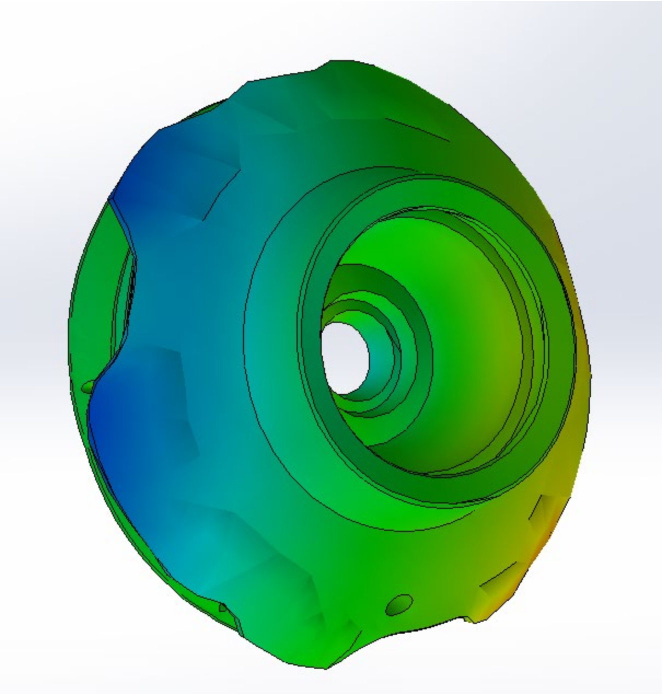
- Analysis of scanner assembly interference fits at temperature and pressure
- Results show max change in interference fits to be 0.00054” max
- The induced stress is about half the allowable maximum stress

Temperature / Pressure	Larger bearing change in diameter housing	Motor change in diameter housing	Smaller bearing change in diameter housing
23 C at 6,723 psi	+0.0007	+0.00068	-0.0006
0 C at 6,723 psi	-0.00052	-0.00032	-0.00122

Temperature / Pressure	Bearing OD change at larger bearing	Motor OD change	Bearing OD change at smaller bearing
0 C at 0 ksi	-0.0007	-0.00086	-0.00049

Temperature / Pressure	Change in interference at larger bearing	Change in interference at motor	Change in interference at smaller bearing
Combined 0 C at 6,723 psi	0.00018 gap	0.00054 gap	-0.00073 interference

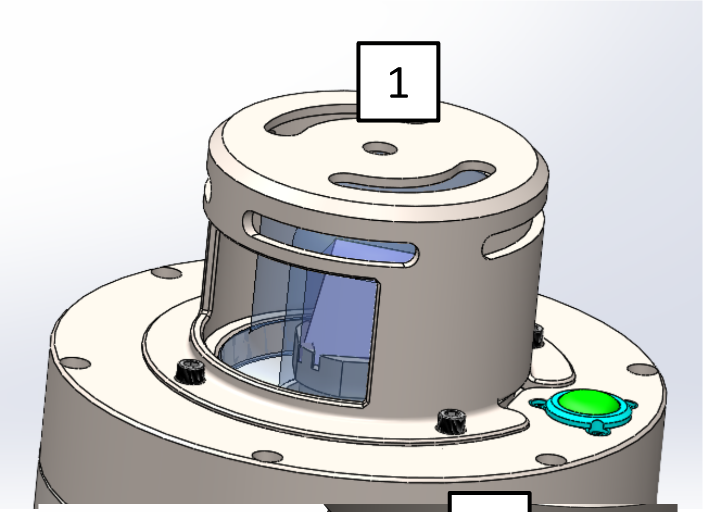
12,227 psi max stress
Max allowable: 23,739 psi

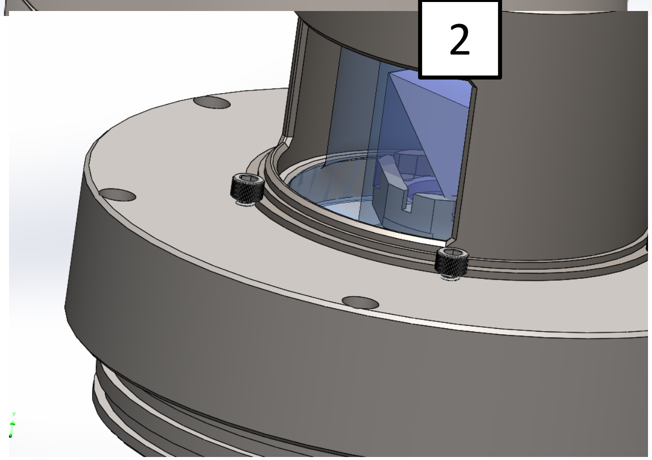


Extreme deformation to show flaring at 23 C

PROTECTIVE SHROUD

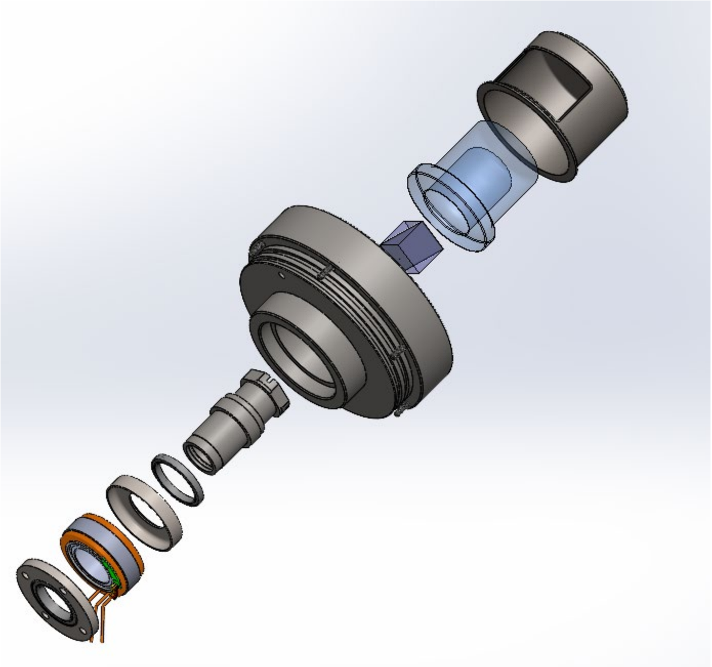
- Two shroud concepts
  - 1
    - More permanent installation
    - Slides into groove in endcap
    - Installs in one orientation
  - 2
    - Can rotate in 360 before clamped down
    - Sits on top of end cap
- Many more configurations / FOV possible
- Slots for bubble venting





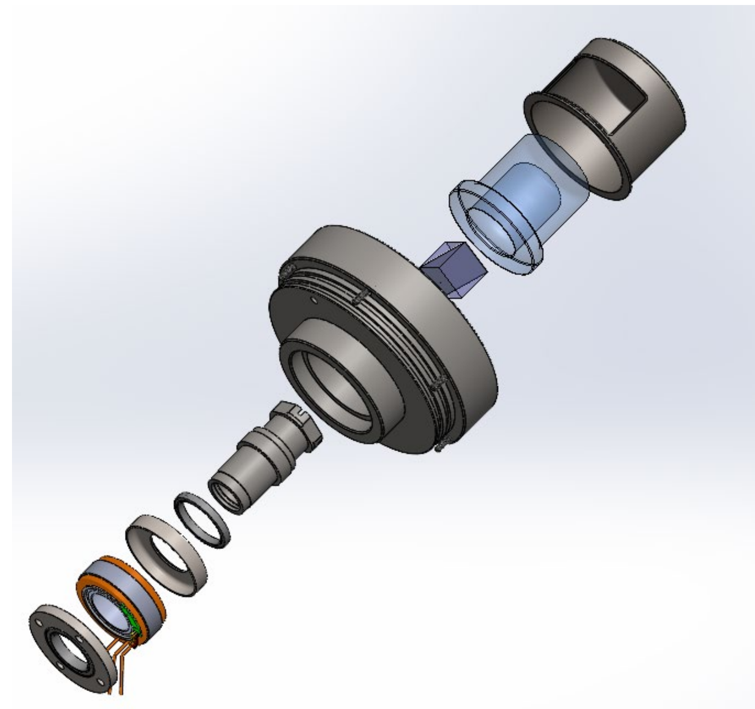
ASSEMBLY

- Window can be bonded to endcap first
- Then all other components can be inserted from the other end
- Shaft can be clamped on to, and all internals can be pulled out if needed



RISK ITEMS

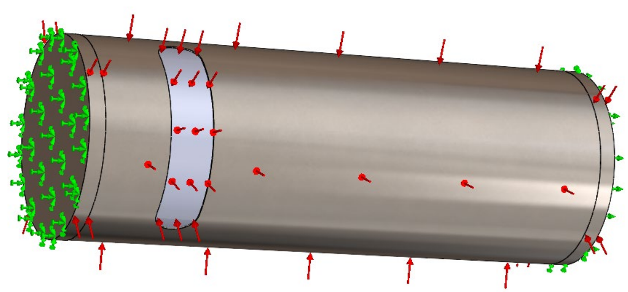
- Shaft rotational balance
- Machined tolerances on shaft
- Bearing lifespan



HOUSING ANALYSIS – STILL VALID FOR THE TUBE

MECHANICAL ANALYSIS AT 4,600M - SUMMARY

- Analysis pressure
  - 4,600m at 6,723 psi (15% margin)
- Tube
  - ID: 5.600”
  - OD: 6.25”
  - Wall thickness: 0.325”
  - Material: TI-6AL-4V Grade 5
  - Tube length = 16.5”
  - Factor of safety of buckling: 1.24
  - Factor of safety of yield: 1.96
  - Minimal diameter improvements result in significantly less resistance to buckling
- Tube deflections are at least as good as SL3 sensor and MBARI WiSSL Gen 1

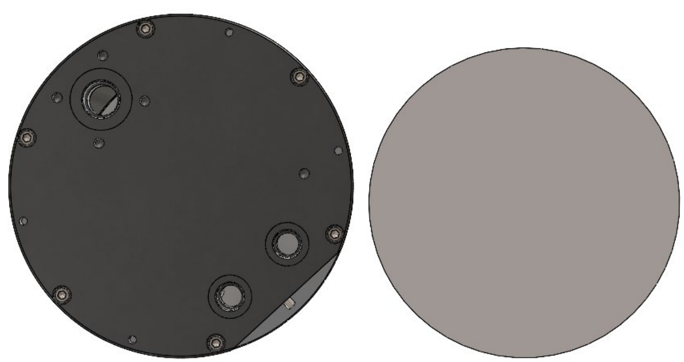


INVESTIGATED MULTIPLE CONFIGURATIONS

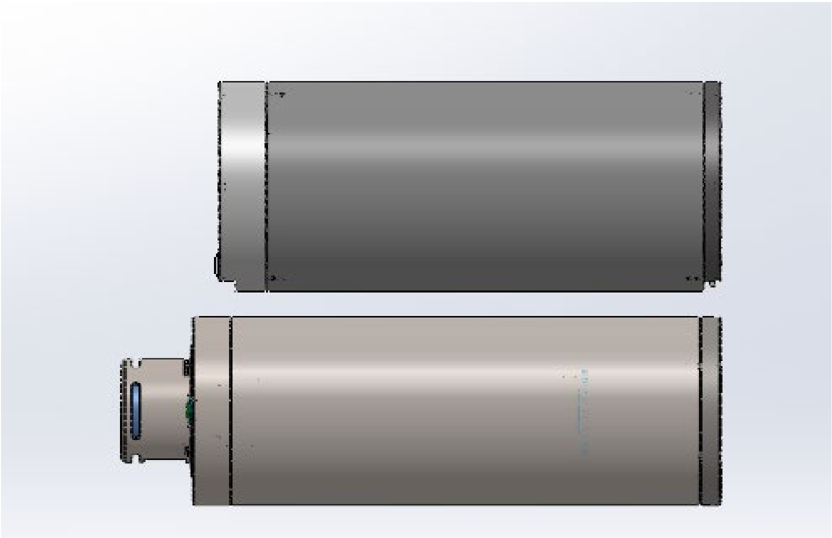
Variable	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	SL3
ID (in)	5.625	5.69	5.625	5.625	5.674	5.625	6.21
OD (in)	6.25	6.25	6.181	6.25	6.25	6.198	6.94
Wall (in)	0.3125	0.280	0.278	0.3125	0.288	0.2865	0.365
Design PSI	6723	6723	6723	6723	6723	6723	6723
Length (in)	15.5"	15.5"	15.5"	16.5"	16.5"	16.5"	14.5"
Material	TI-6AL-4V	TI-6AL-4V	TI-6AL-4V	TI-6AL-4V	TI-6AL-4V	TI-6AL-4V	TI-6AL-4V
Yield (psi)	128,000	128,000	128,000	128,000	128,000	128,000	128,001
Max real stress (psi)	65,440	72,910	72,580	65,400	70,490	71,340	63,000
Max real displacement (mm)	0.293	0.330	0.326	0.287	0.318	0.316	0.305
Buckling failure (psi)	8,901	6,766	6,737	8,344	6,746	6,740	8,429
Yield FOS over design	**1.96**	**1.76**	**1.76**	**1.96**	**1.82**	**1.79**	**2.03**
Buckling FOS over design	**1.324**	**1.006**	**1.002**	**1.241**	**1.003**	**1.003**	**1.254**

COMPARISON TO FIRST MBARI OPTICAL SENSOR

- New sensor estimated to be longer, narrower, and about the same weight
- OD: 6.94” -> 6.25”
- Length: 16.6” -> 20”
- Housing mass approximately the same: 42 → 40 lbs.



Old New

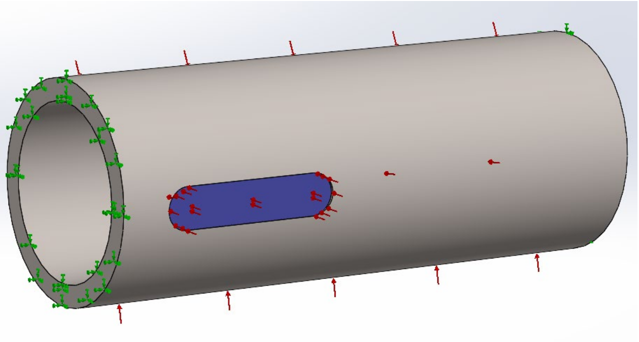


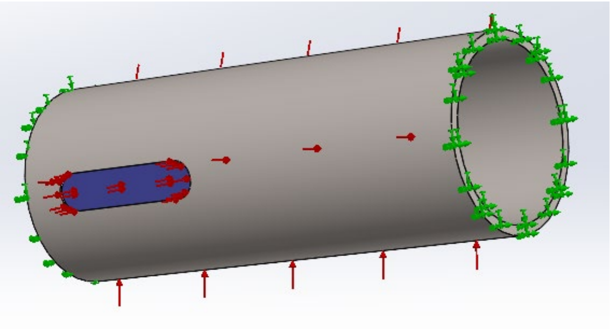
WINDOW AND SCANNER – OLD KEPT FOR COMPLETENESS

FLAT WINDOW

- Advantages:
  - Flat window – ease of manufacturing and AR coating
  - Believe this will require more standard spinning mirror and motor assemblies which reduces cost, lead time, and allows for multiple vendors
  - Stress is more distributed along window

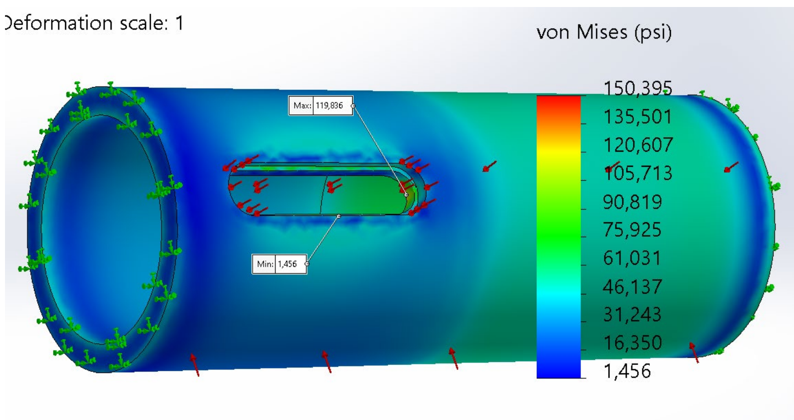
- Window length ~5”
- Window thickness ~6mm

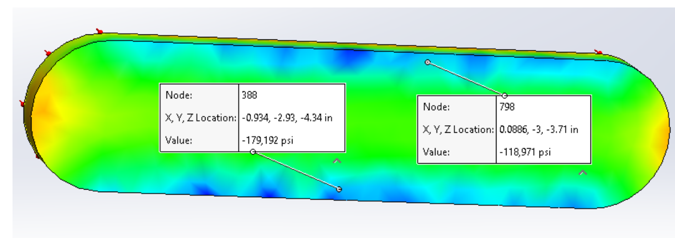




FLAT WINDOW ANALYSIS

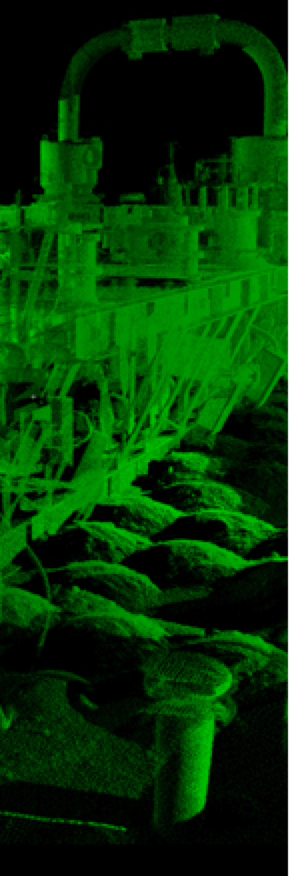
System	Applied Pressure	Window Stress 3rd Principal (Compression)
Flat window	6,723 psi	160 - 180 ksi
Curved window	6,723 psi	80 – 90 ksi





Blue areas indicate higher compression

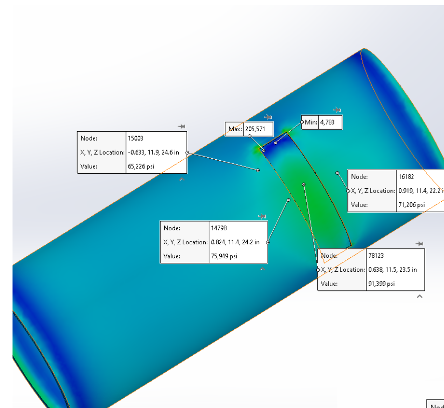
SUMMARY OF FLAT WINDOW

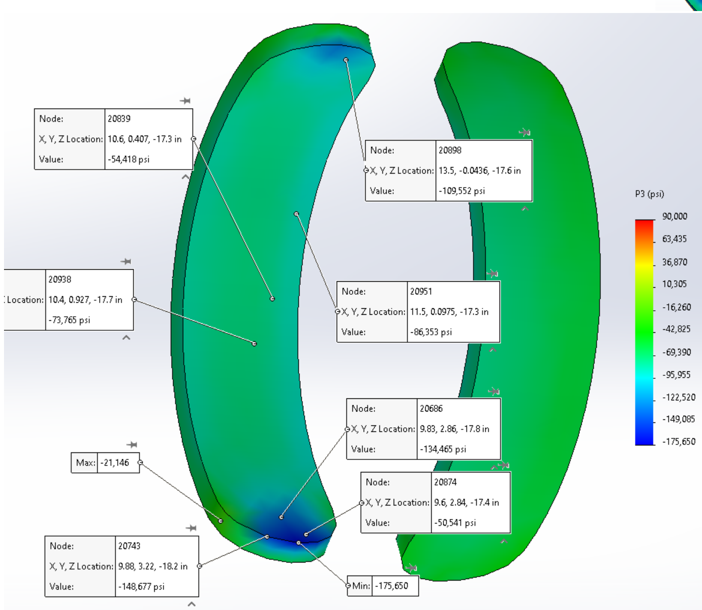


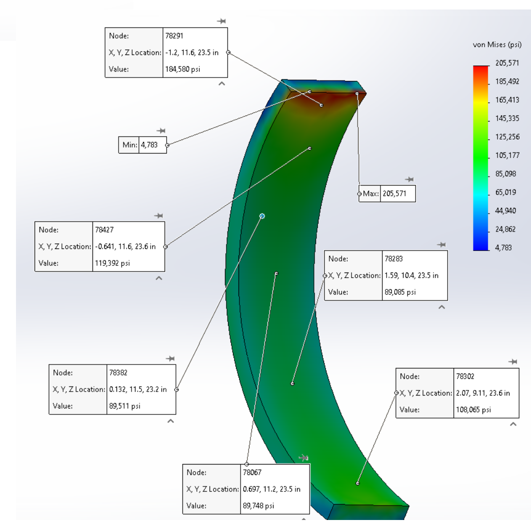
- High compression at end of the curved window shifted to the flat window’s edges
- Window deflection was not improved
- Flat window design did not improve mechanical performance
- Upon further discussions with MBARI, the curved window would be preferred anyone as that allows for a better orientation in a torpedo style AUV
- The flat window design was abandoned at this point.

CURVED WINDOW

- Multiple shapes and configurations were investigated

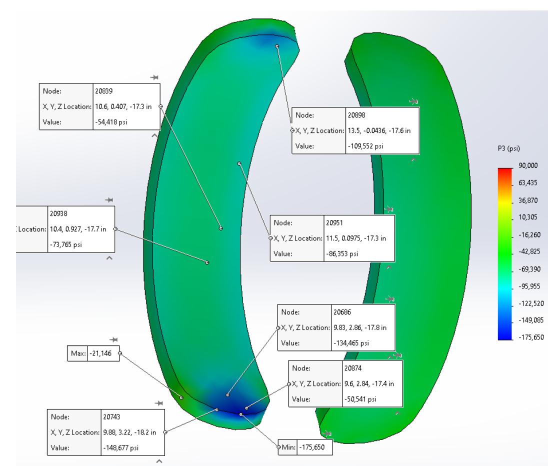






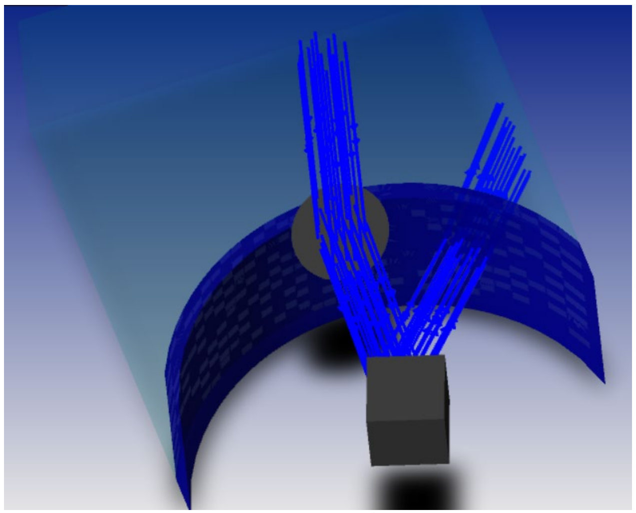
CURVED WINDOW

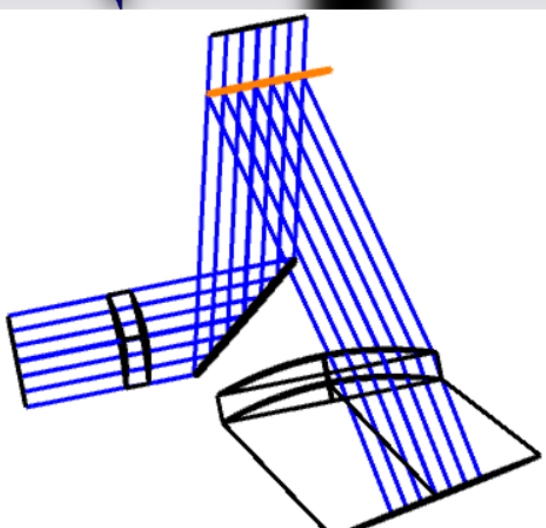
- Multiple configurations were investigated
- Normal flat window vendor unable to provide the curved window
- Normal AR coating vendor unable to AR coat the new window
- Found a new vendor that has built tubes but not a window like this. Are confident they can, but obviously some risk

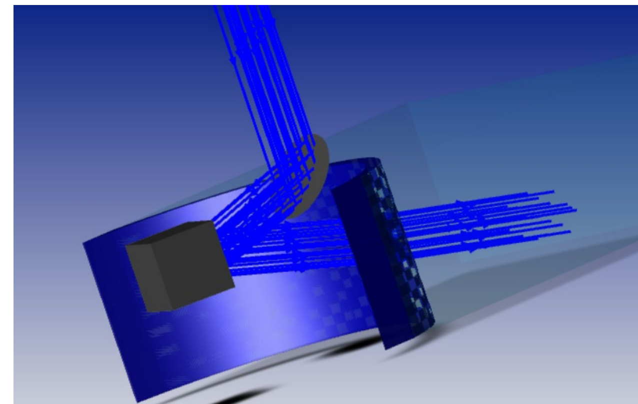


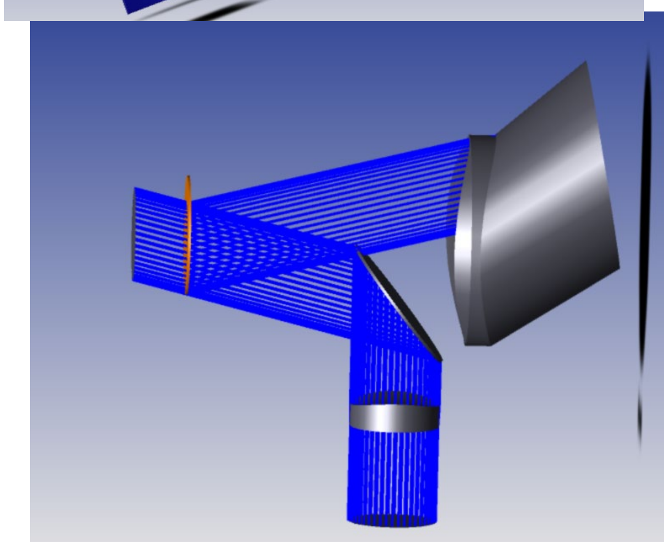
SCANNER OPTION #1

- Had difficulties finding an optimal scanner. Trying to avoid building a custom scanner.
- COTS scanner option #1 below



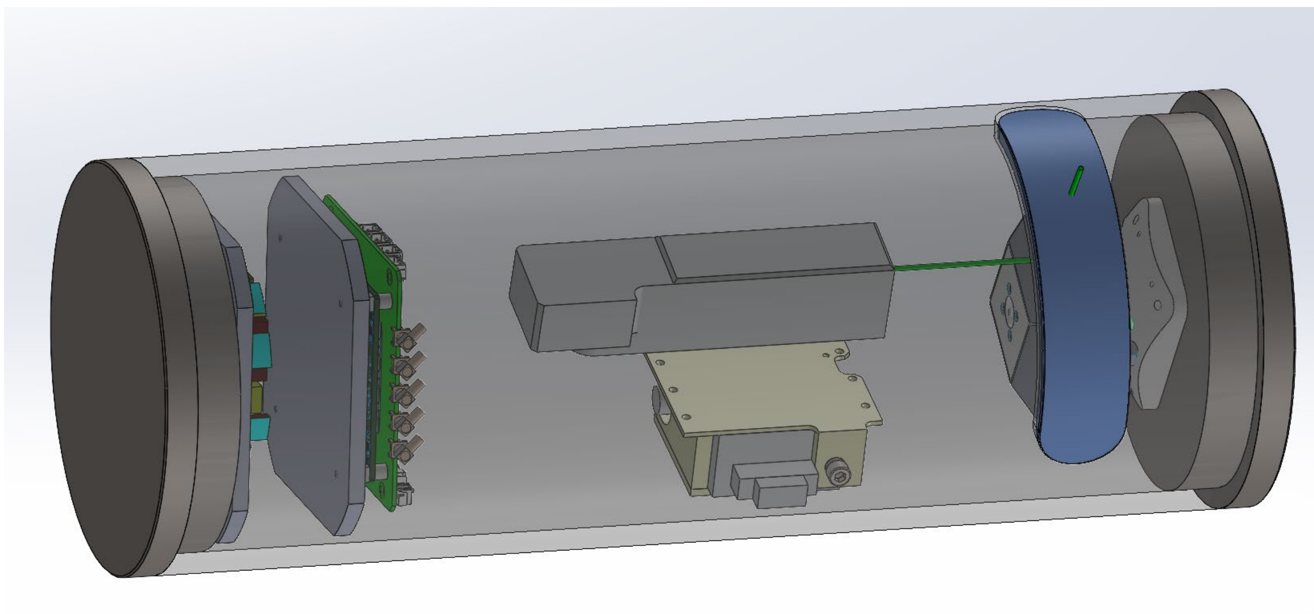






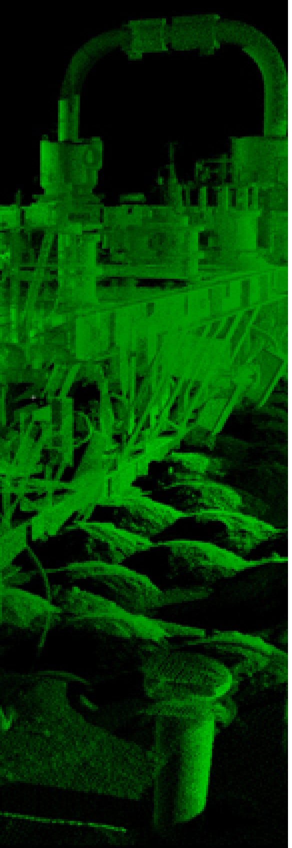
SCANNER OPTION #2

- Last week identified a new COTS scanner that should simplify design.
- Detailed design for scanner and optical bench occurs in Second phase – Detailed Design
- All basic components fit for concept design.



MBARI FEEDBACK & NEXT STEPS

NEXT STEPS – COMPLETED



Proposal

- 3D at Depth – submit proposal to MBARI by July 10th
  - Detailed design – start Jan. 2023
  - Build and FAT at 3D at Depth – estimate
  - Integration / test at MBARI
- Final Phase 1 proposals due July 13th (Dave submits)

Potential Risk Reduction Tasks (2022?)

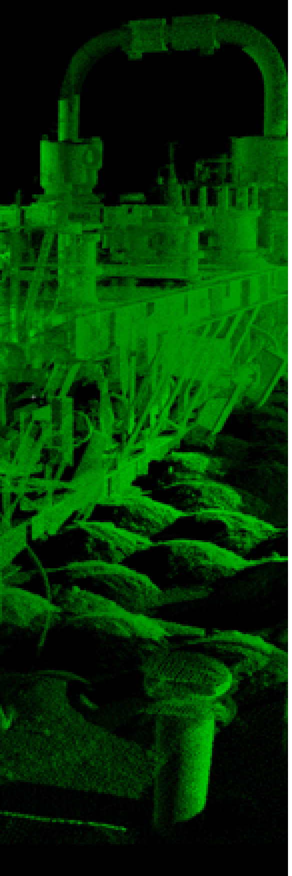
1) Build and pressure test curved window (w/ housing)

2) Lab build and lab test of temperature capability including SW processing path

3) NRE for 350kHz laser (schedule risk reduction)

4) Purchase scanner and lab test (schedule risk reduction)

MBARI FEEDBACK



3D at Depth