Radiometric simulation of LADAR imaging for underwater environments

UPC – MSc Photonics
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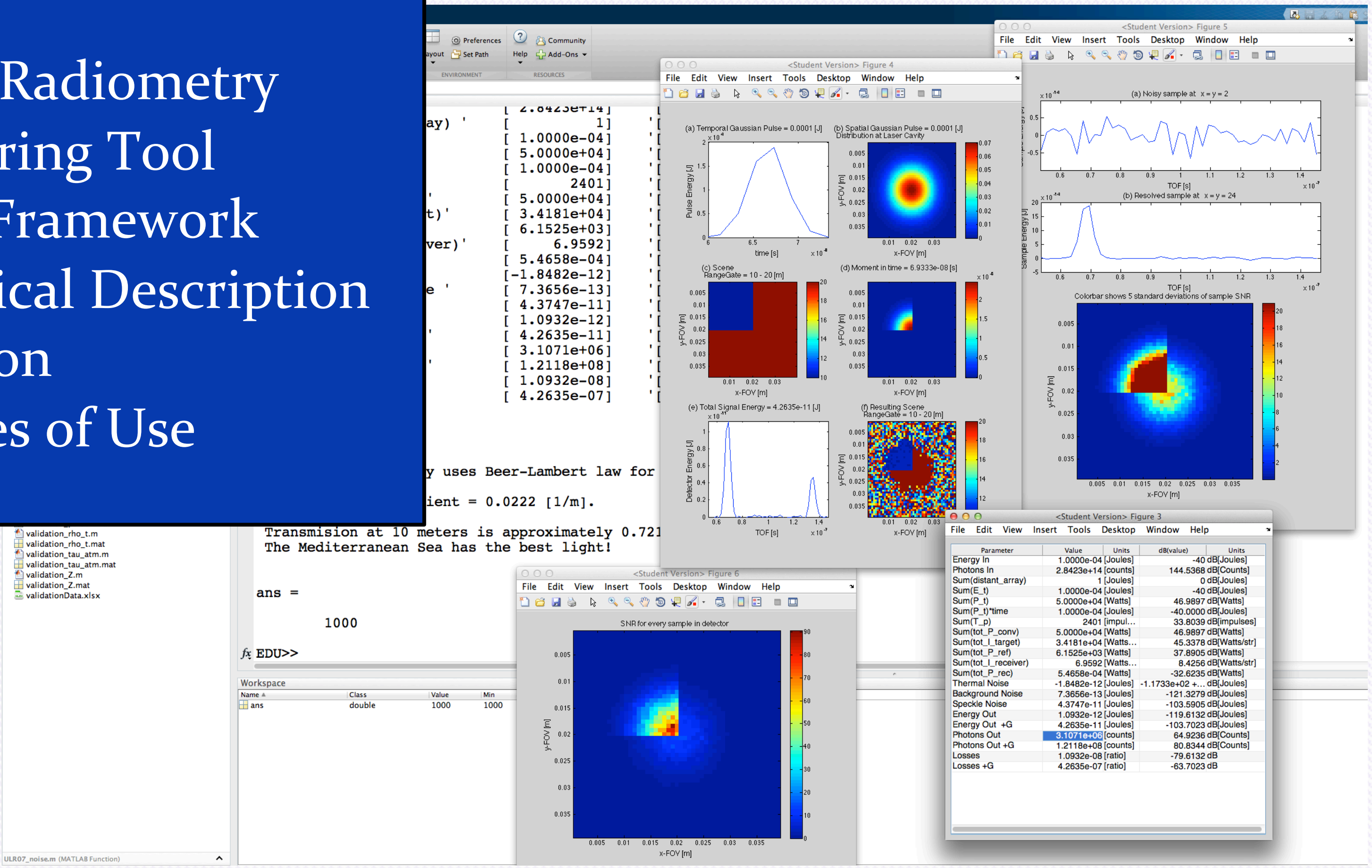
Abstract

- LADAR Radiometry
- Engineering Tool
- Matlab Framework
- Theoretical Description
- Validation
- Examples of Use



Outline

- Motivation
  - -Description of LADAR systems
  - -Design need in underwater environments
- Theoretical Discussion
  - -Range equation
  - -Spatial energy distribution
  - -Temporal energy distribution
  - -Attenuation in ambient media
- Validation
  - -Example LADAR system
  - -Analytical vs. numerical calculation
- Results
  - -Radiometric outcome of using the example system in three different environments

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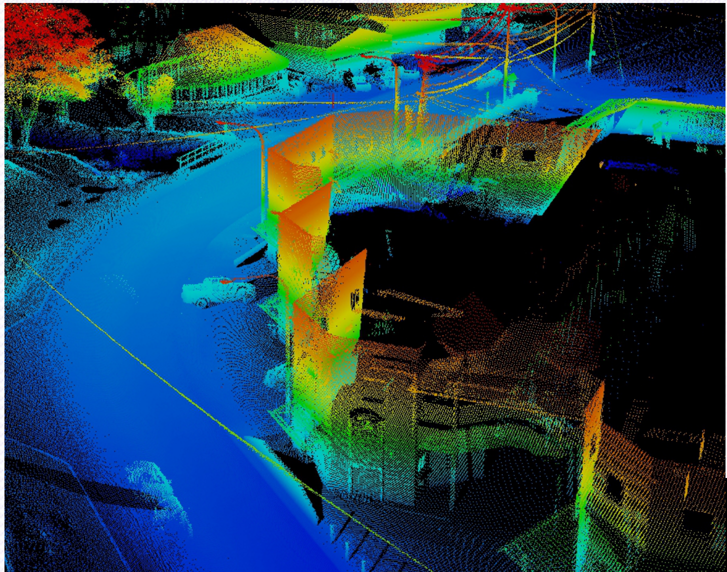
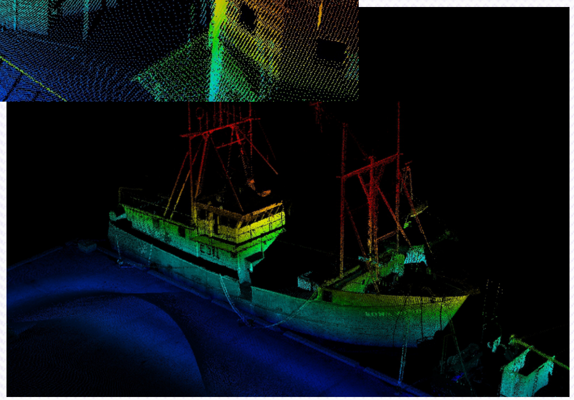
What is LADAR?

Laser Detection and Ranging (LADAR) is method of rendering 3D spatial information using the time-of-flight (TOF) that it takes a pulse of laser light to travel from the laser, reflect off a target, and return to a detector.





Time-of-Flight (TOF) $\boxed{t = 2R / c}$

Single Point

- Single laser and photodetector

Imaging

- Single point system that scans
- Photodetector array with single laser (with and without scanning)
- Multiple laser and detectors

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Underwater LADAR Radiometry (ULR)

Engineering Motivation

- Radiometry of LADAR
- Tool for use during the design process

Educational Motivation

- Specialty in rising technology
- Radiometric aspect of remote sensing
- Experience in Matlab environment
- Using numerical methods for discrete calculations

ULR - Theoretical

Range equation

- Optical transmission
- Ambient media transmission
- Aperture diameter
- Reflectivity
- Area of FOV
- Pulse power
- Distance of surface
- Divergence

$$P_{det}\left(m,n,k\right)=\frac{\tau_o\tau_a^2D_R^2\rho_t\left(dA\right)P_t\left(m,n,k\right)}{R^2\theta_R\left(\theta_tR\right)^2}$$

ULR - Theoretical

Spatial Distribution

- Laser cavity Gaussian
- Fundamental mode – TEM00
- Spatial sampling in the photodetector array at m, n
- Beam waist
- Beam width function for distance z < Rayleigh length

$$g_{LC}\left(x_m, y_n\right) = A_g e^{\frac{-\left(x_m^2 + y_n^2\right)}{\omega_0^2}}$$

$$\omega\left(z\right) = \omega_0 \sqrt{1 + \left(\frac{z\lambda}{\pi\omega_0^2}\right)^2}$$

ULR - Theoretical

$$P_t(t) = \frac{E_t}{\sigma_w \sqrt{2\pi}} e^{\frac{-t^2}{2\sigma_w^2}}$$

Temporal Distribution

- Gaussian Distribution
- Sampling 'dt' is set to the temporal standard deviation of the laser pulse, Sigma_w
- The **Range Gate** is the expected range of distances where the scene will be located
- The range gate corresponds to the start and stop time of the signal observation

$$R_{gate} = (T_{\max} - T_{\min})\, c/2$$

ULR - Transmission

Attenuation - the loss of signal caused by absorption and scattering of particles found in the ambient media.

Attenuation in ocean water

- Particulates
- Colored decaying organic matter
- Absorption of water

$$\boxed{a = a_p + a_{CDOM} + a_w}$$

The optimal window for transmission in most oceans is around 550 nm

Transmission of light is the fraction of the light that returns to the detector due to losses attenuation losses in the ambient media. Given by the Beer-Lambert law.

$$\boxed{I = I_o e^{-az}}$$

ULR – Example LADAR System

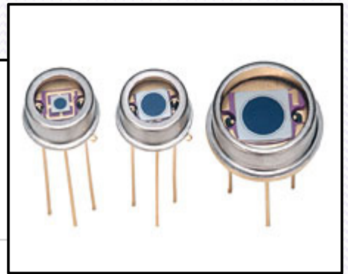
Fiber laser module:

- Currently in use at CD6
- Downconvert to 550 nm
- Pulse energy 0.0001 J

3sgroup.com

MLT-PL-R-OEM20 Series

Avalanche Photodiode Array



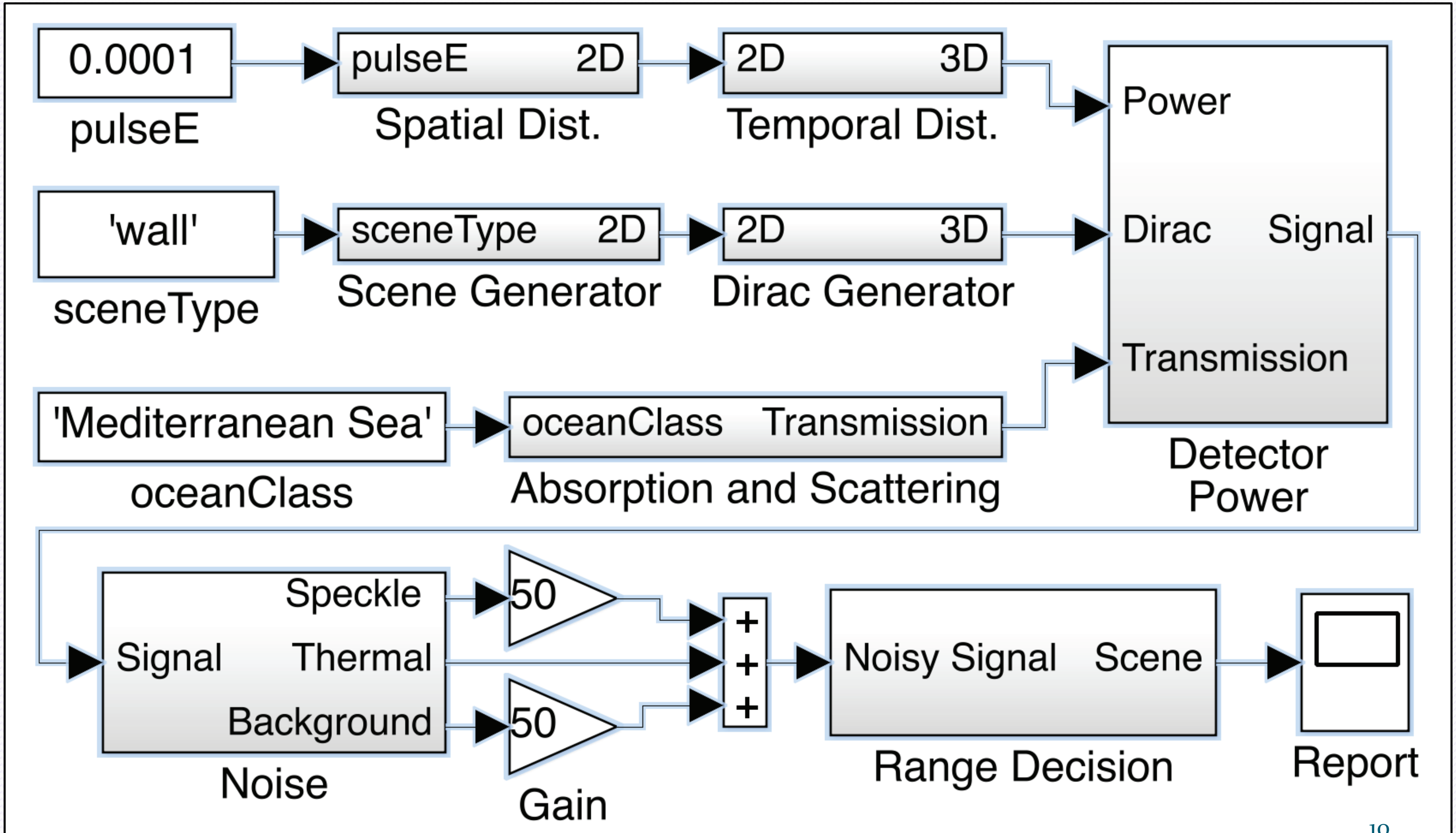
5.0mm UV-VIS (200-1000nm), Si APD

Stock **#58-263** Specifications and Downloads

Active Area Diameter (mm)	5.00
Spectral Response (nm)	200-1000
Photosensitivity S (A/W) @ λ_p	0.42
Quantum Efficiency QE (%) @ λ_p	80.00
Breakdown Voltage BDV, I_d=100μA (V)	150/200 (Typical/Maximum)
Temperature Coefficient of BDV (V/°C)	0.14
Dark Current I_d (nA)	3.00/100.00 (Typical/Maximum)
Response Time (ns) R_L=50Ω	43.75
Gain (M)	50.00
Terminal Capacitance (pF)	320.00
Mount	TO-8
Operating Temperature (°C)	-20 to 60

edmundoptics.com

ULR – Structure of Code



ULR – Spatial Distribution

Creates Gaussian distribution of laser energy in the 2D "distant_array" that is normalized and then scaled to the input energy, "pulseE"

1.00E-4 J

<Student Version> Figure 3

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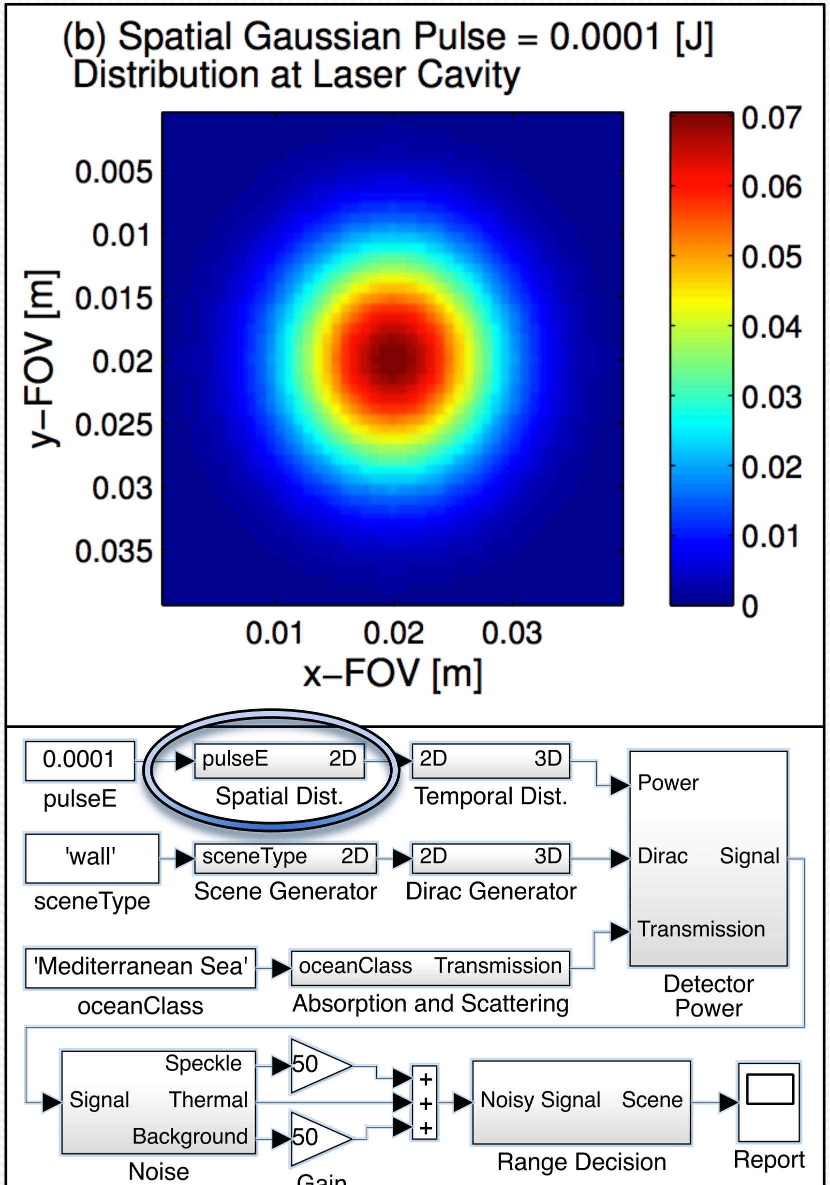
Parameter	Value	Units	log10(value)	Units
Energy In	1.0000e-04	[Joules]	-4	B[Joules]
Photons In	2.8423e+14	[counts]	14.4537	B[Counts]
Sum(distant_array)	1	[Joules]	0	B[Joules]
Sum(E_t)	1.0000e-04	[Joules]	-4	B[Joules]
Sum(P_t)	[illegible]	[Watts]	4.6990	B[Watts]
Sum(P_t)*time	1.0000e-04	[Joules]	-4.0000	B[Joules]
Sum(T_p)	2401	[impul…	3.3804	B[impulses]
Sum(tot_P_conv)	5.0000e+04	[Watts]	4.6990	B[Watts]
Sum(tot_I_target)	2.9564e+04	[Watts…	4.4708	B[Watts/str]
Sum(tot_P_ref)	5.3215e+03	[Watts]	3.7260	B[Watts]
Sum(tot_I_receiver)	5.4878	[Watts…	0.7394	B[Watts/str]
Sum(tot_P_rec)	4.3101e-04	[Watts]	-3.3655	B[Watts]
Thermal Noise	9.2317e-13	[Joules]	-12.0347	B[Joules]
Background Noise	1.2648e-12	[Joules]	-11.8980	B[Joules]
Speckle Noise	3.4501e-11	[Joules]	-10.4622	B[Joules]
Energy Out	8.6202e-13	[Joules]	-12.0645	B[Joules]
Energy Out +G	3.6689e-11	[Joules]	-10.4355	B[Joules]
Photons Out	2.4501e+06	[counts]	6.3892	B[Counts]
Photons Out +G	1.0428e+08	[counts]	8.0182	B[Counts]
Losses	8.6202e-09	[ratio]	-8.0645	B
Losses +G	3.6689e-07	[ratio]	-6.4355	B

Radiometry Table



ULR – Temporal Distribution

Temporally expands the pulse energy contained in the 2D distant_array resulting in a 3D matrix of the pulse power.

Total Power

5.00e+4 W

1.00e-4 J

Total Energy

<Student Version> Figure 3

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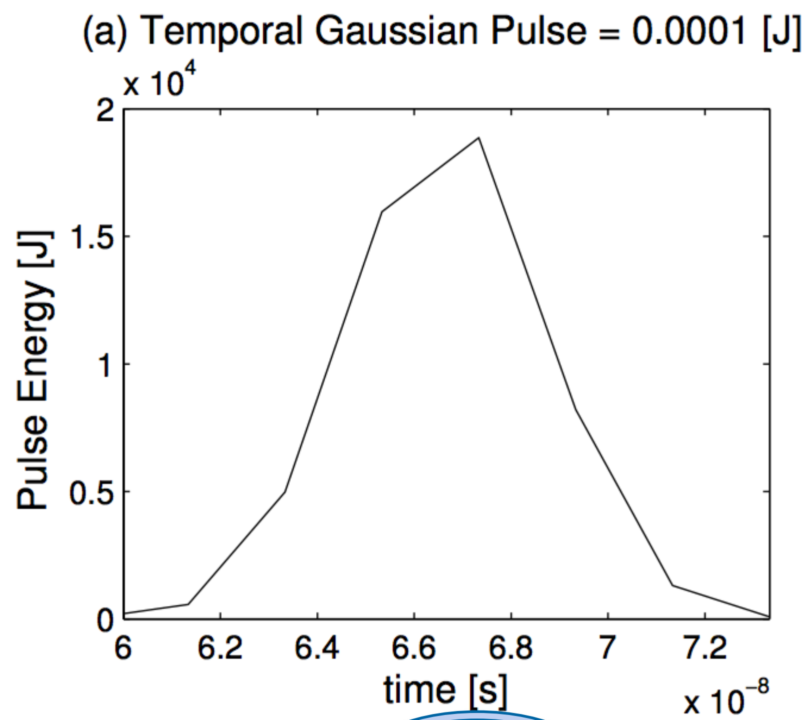
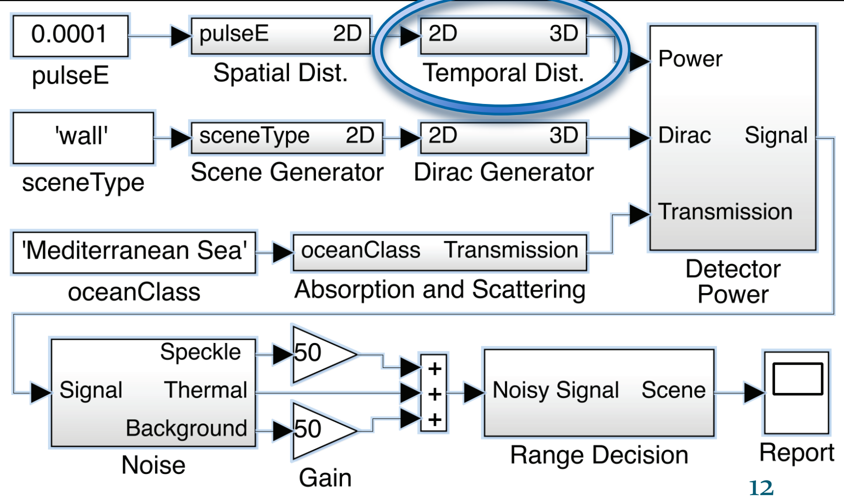
Radiometry Table

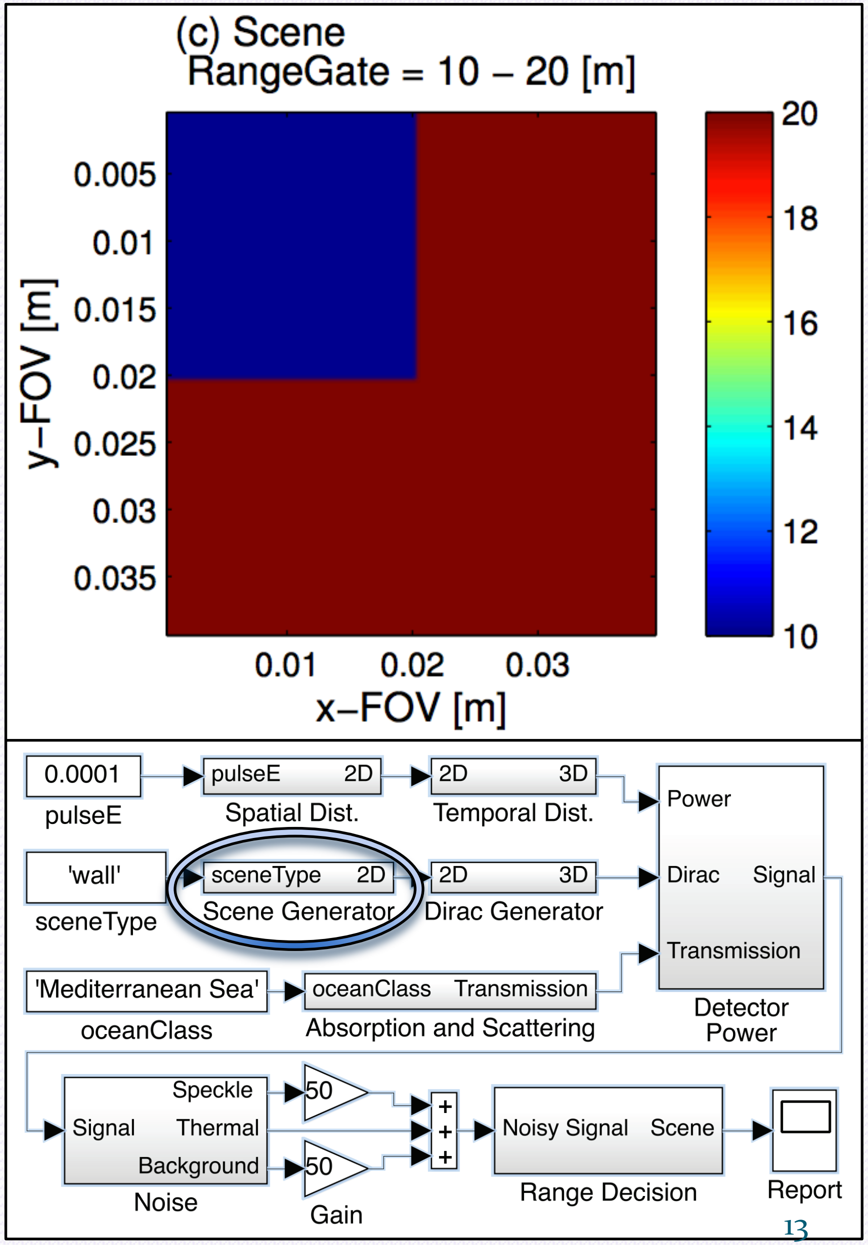




ULR – Scene generation

The observation scene is defined by one of several commands including wall, corner, square, slope, bars, cone, cone4th, etc.

It generates a normalized 2D array that is scaled by a user input and placed at a distance "Z" from the detector.



ULR - Dirac

- In LADAR simulations, the Dirac function is called the **Target Profile.**
- A 3D matrix of zeros is created, and the 2D scene array is used to assign Dirac impulses as the proper indices are set to one.
- The number of impulses contained in the target profile is given in the radiometry table.

2401

<Student Version> Figure 3

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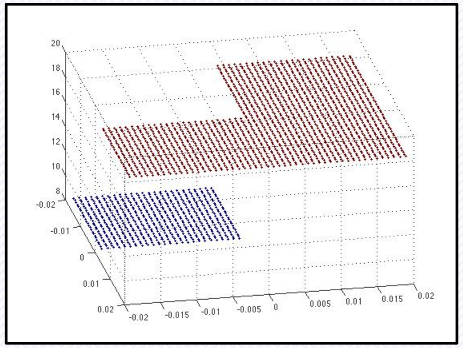
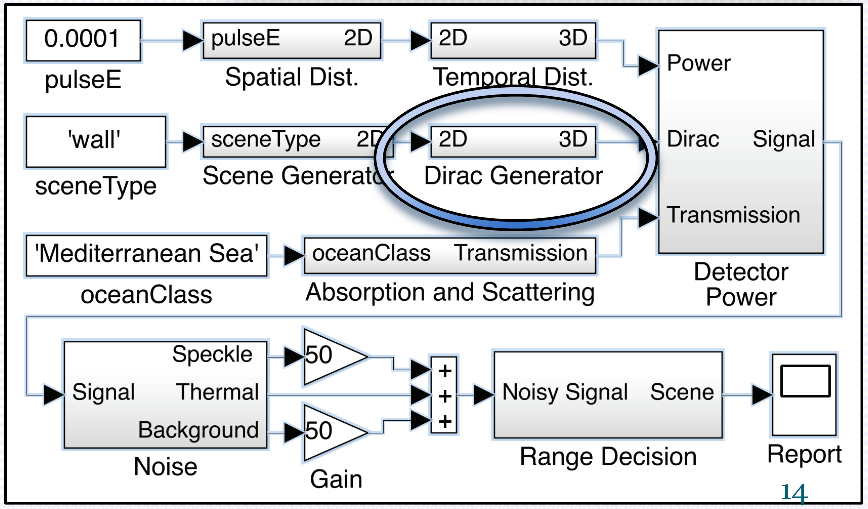
Radiometry Table



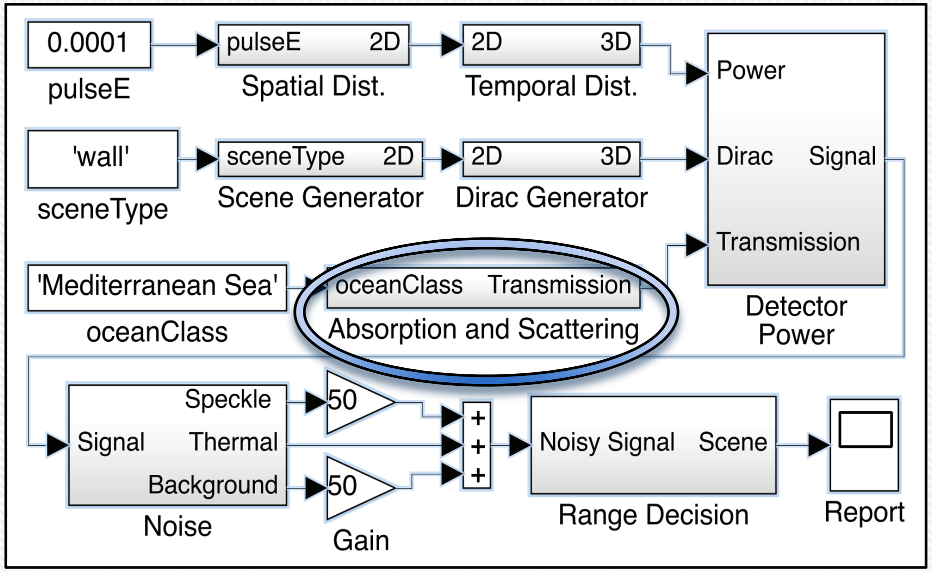


ULR - Transmission

- The transmission function selects a known attenuation coefficient for the specified body of water.

- It then applies the Beer-Lambert law to calculate the transmission values for each sample in the range gate.

- Output is a vector with the same dimensions as the range gate.



ULR - Range Equation

The power contained in the laser pulse is then convolved with the Dirac target profile to obtain the final temporal distribution of the laser energy.

The **received power** at the detector is then calculated using a for-loop to apply the range equation for each temporal sample of the photodetector array.

4.31e-4 W

<Student Version> Figure 3

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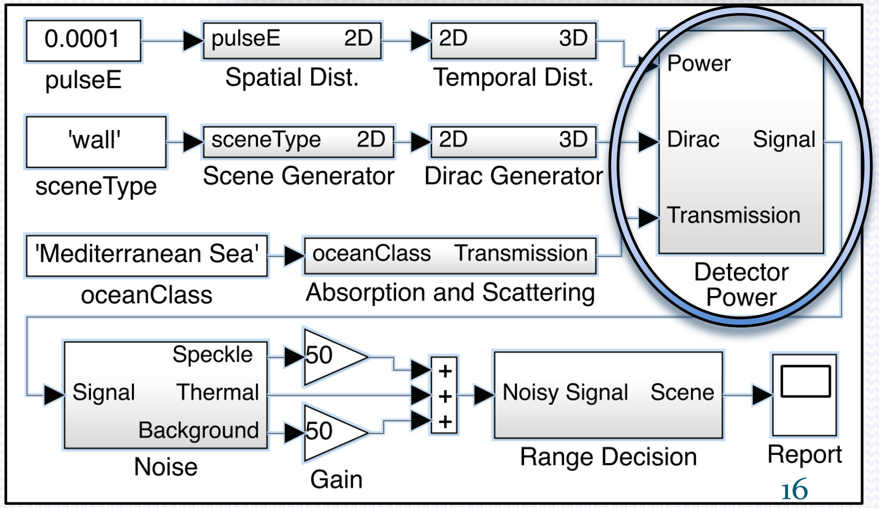


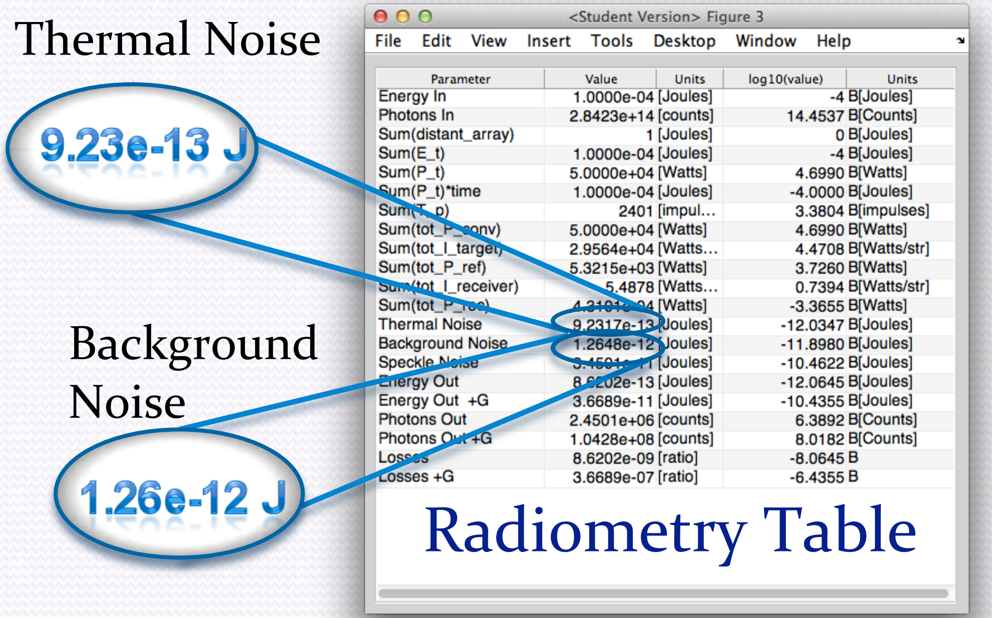
Noise and Gain

Background noise is calculated according to the detector specifications and the solar irradiance of the environment.

Thermal noise is calculated based on the temperature of the detector.

Signal is contained by the speckle data. Since speckle can be compensated by time averaging techniques, it is adequate to run the simulation as incoherent light for radiometric purposes.

Gain is applied to the signal and background noise before all three are added together.



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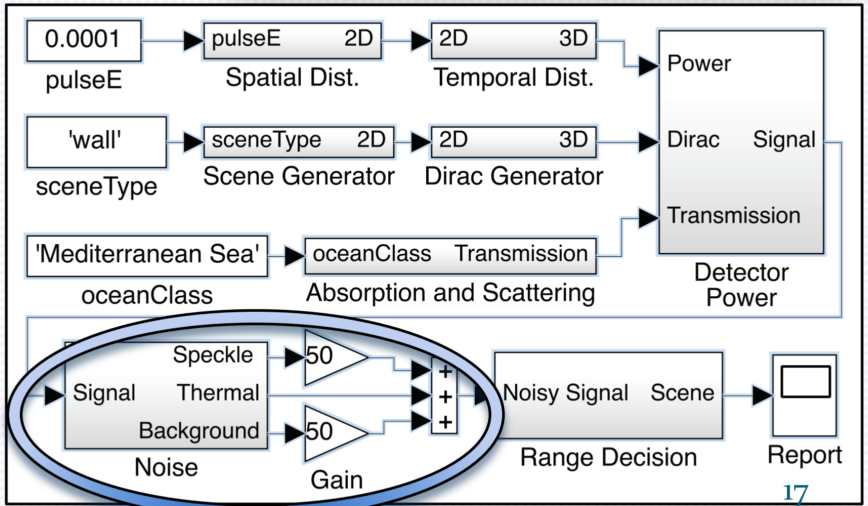
Radiometry Table



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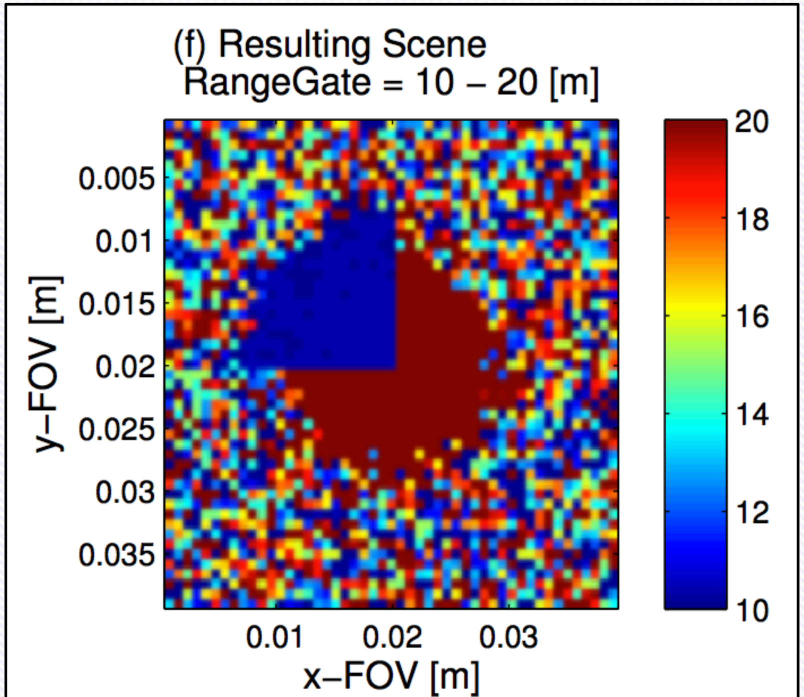
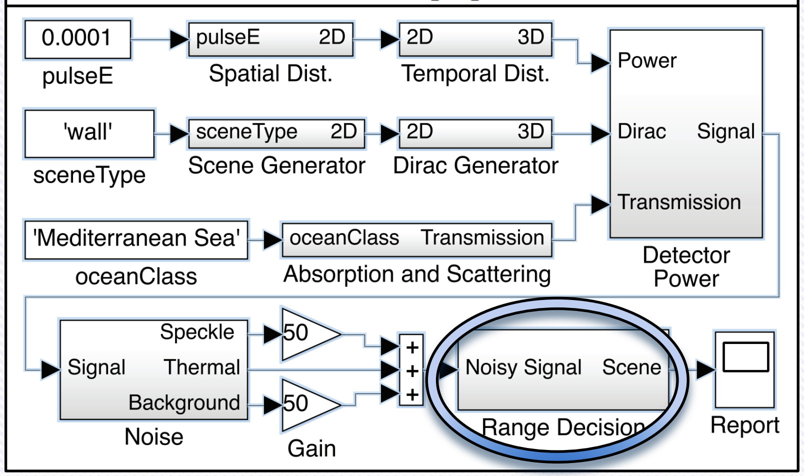
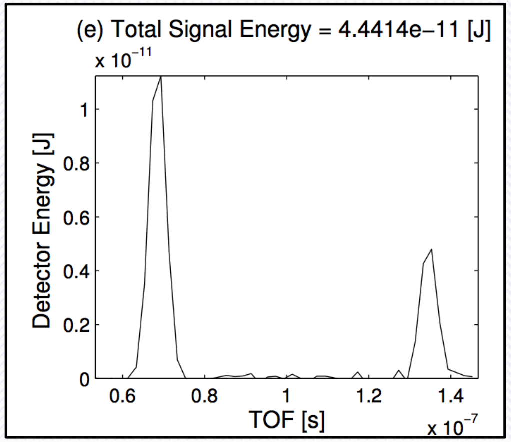
ULR – Scene Construction

The TOF for the maximum value in each time varying sample of the array is chosen for determining the range during scene reconstruction.

The integrated array energy vs. time is also useful radiometric tool.







ULR - Validation

- Matlab results were compared with the expected analytical values for both input variables
- Spatial and Temporal Gaussian distributions were tested at the FWM(1/2), FWM(2/3)

Table 1. Validation of simulation with expected values.

Test Variables and Outputs		Test 1	Test 2	Test 3
Test of range 'Z'	[m]	20	1000	10000
Expected Distant Beam Width	[m]	9.00E-03	2.17E-02	2.00E-01
Matlab Distant Beam Width	[m]	9.00E-03	2.17E-02	2.00E-01
Expected Energy	[J]	6.25E-12	2.50E-15	2.50E-17
Matlab Energy	[J]	6.13E-12	2.50E-15	2.50E-17
Test of pulse energy 'pulseE'	[J]	0.001	0.0005	0.00005
Expected Energy	[J]	1.11E-10	5.56E-11	5.56E-12
Matlab Energy	[J]	1.08E-10	5.42E-11	5.42E-12
Test of transmission 'tau_atm'		0.8	0.5	0.2
Expected Energy	[J]	7.11E-12	2.78E-12	4.44E-13
Matlab Energy	[J]	6.89E-12	2.78E-12	4.17E-13
Test of reflectivity 'rho_t'		0.5	0.18	0.1
Expected Energy	[J]	5.56E-12	2.00E-12	1.11E-13
Matlab Energy	[J]	5.42E-12	1.95E-12	1.08E-13
Test of aperture 'ap_diameter'	[m]	0.008	0.004	0.001
Expected Energy	[J]	7.11E-12	1.78E-12	1.11E-13
Matlab Energy	[J]	6.93E-12	1.73E-12	1.08E-13

Table 2. Validation of Gaussian power distributions.

	Spatial Validation		Temporal Validation	
Gaussian Position	FWM(2/3)	FWM(1/2)	FWM(2/3)	FWM(1/2)
Expected Value	0.0162[m]	0.0212[m]	3.6021E-09[s]	4.7096E-09[s]
Matlab Result	0.0159[m]	0.0223[m]	3.6000E-09[s]	4.8000E-09[s]

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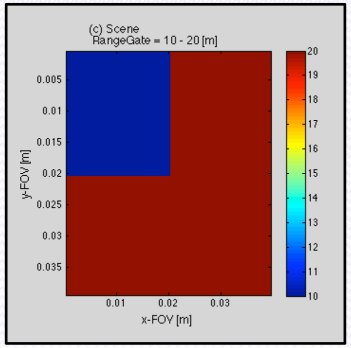
ULR – Thesis Scenario

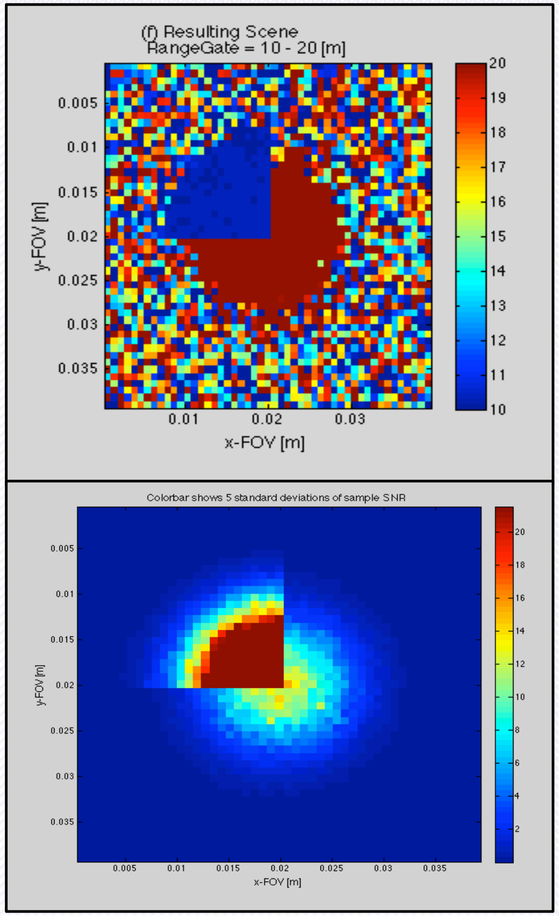
- The loss do to attenuation in the first scenario is -2.6dB = 45%
- The additional loss when doubling the distance of the walls in the scene is -8.32dB = 84%



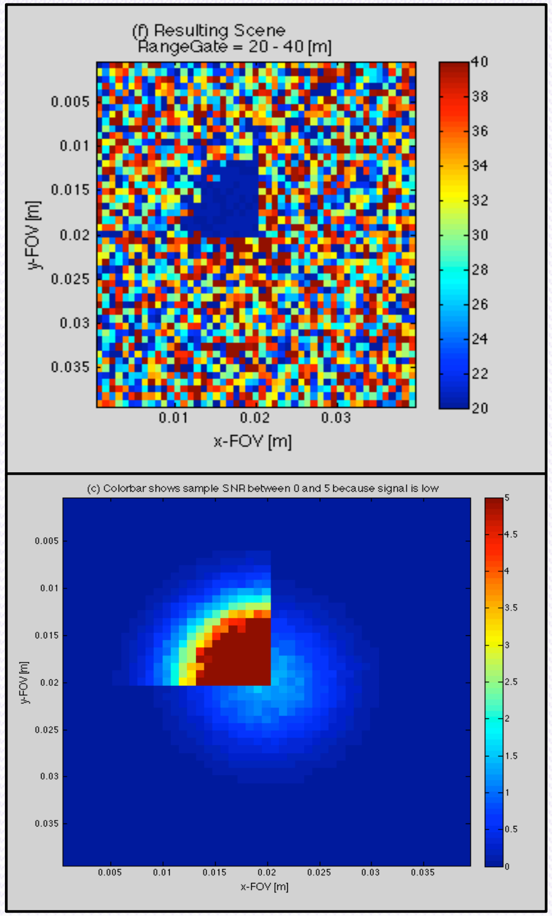
‘Corner’ Scene Type

- Same LADAR system as example

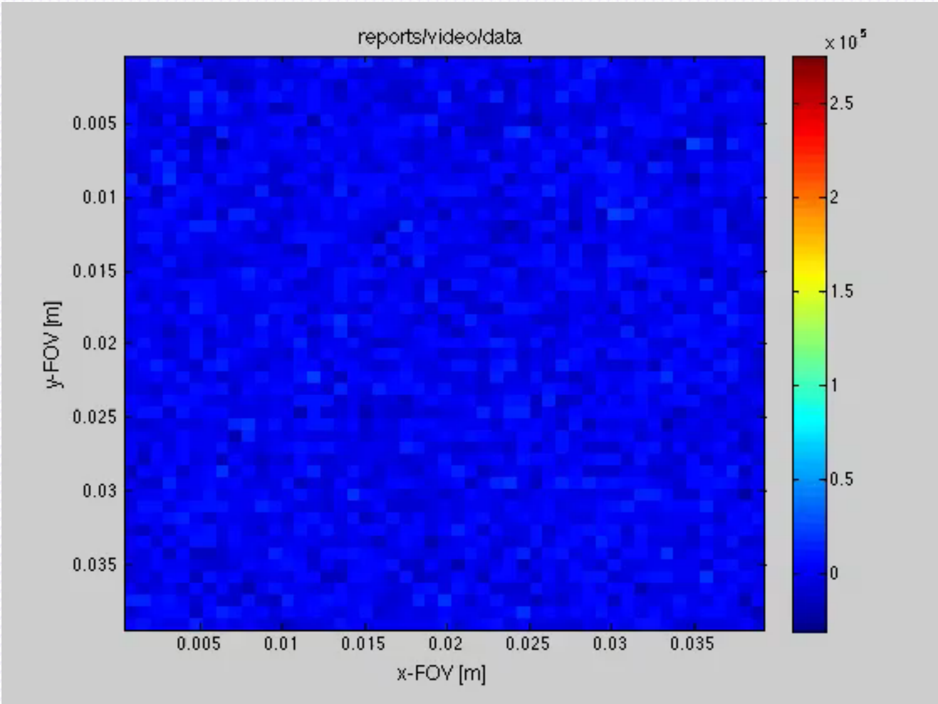
(a) 10 & 20 meters

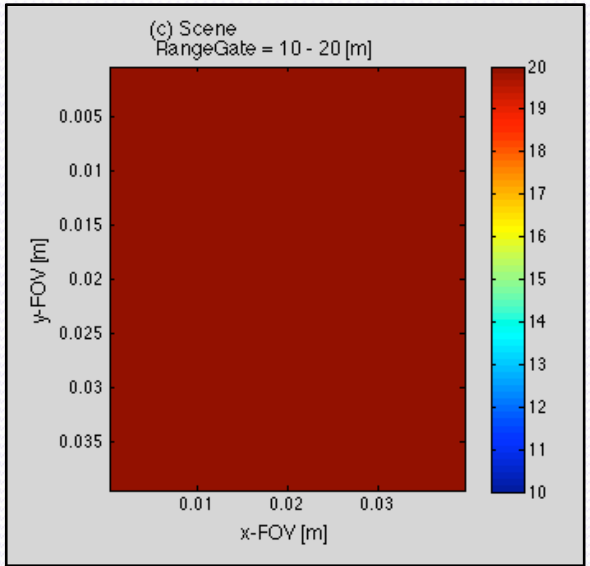


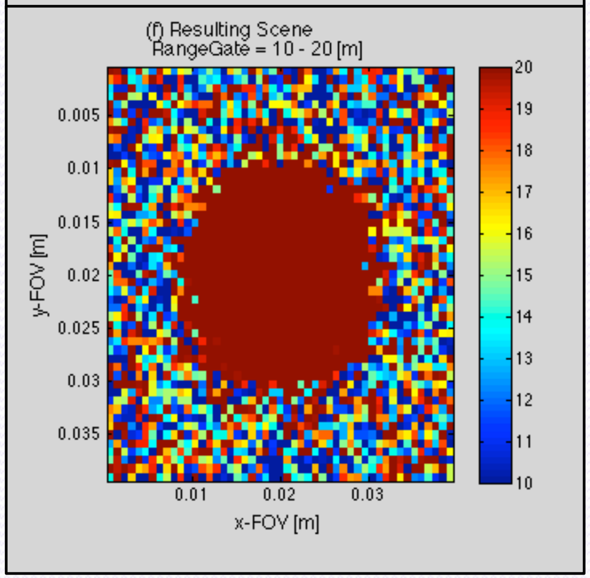
(b) 20 & 40 meters



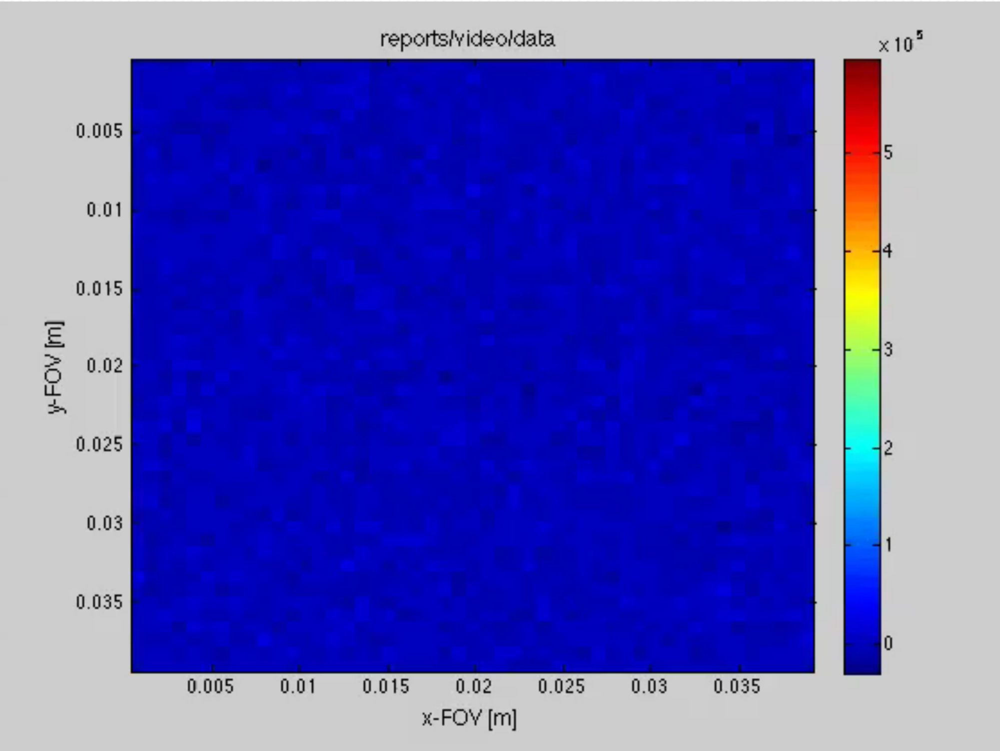
ULR – 'Wall' Scene Type

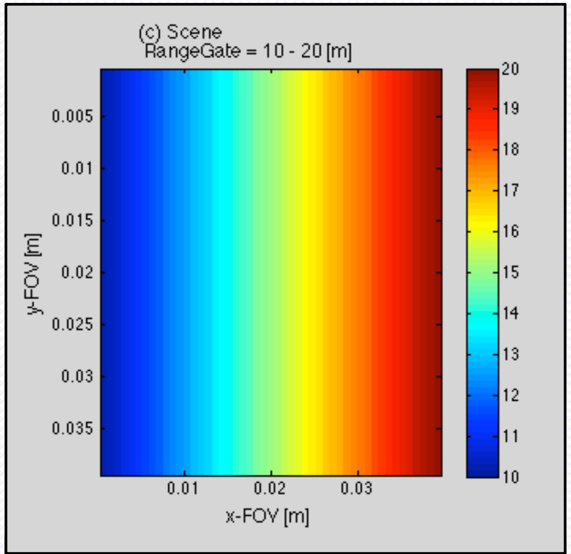


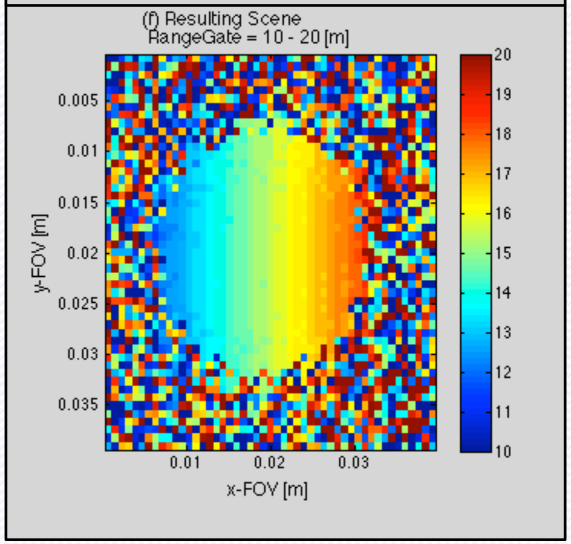




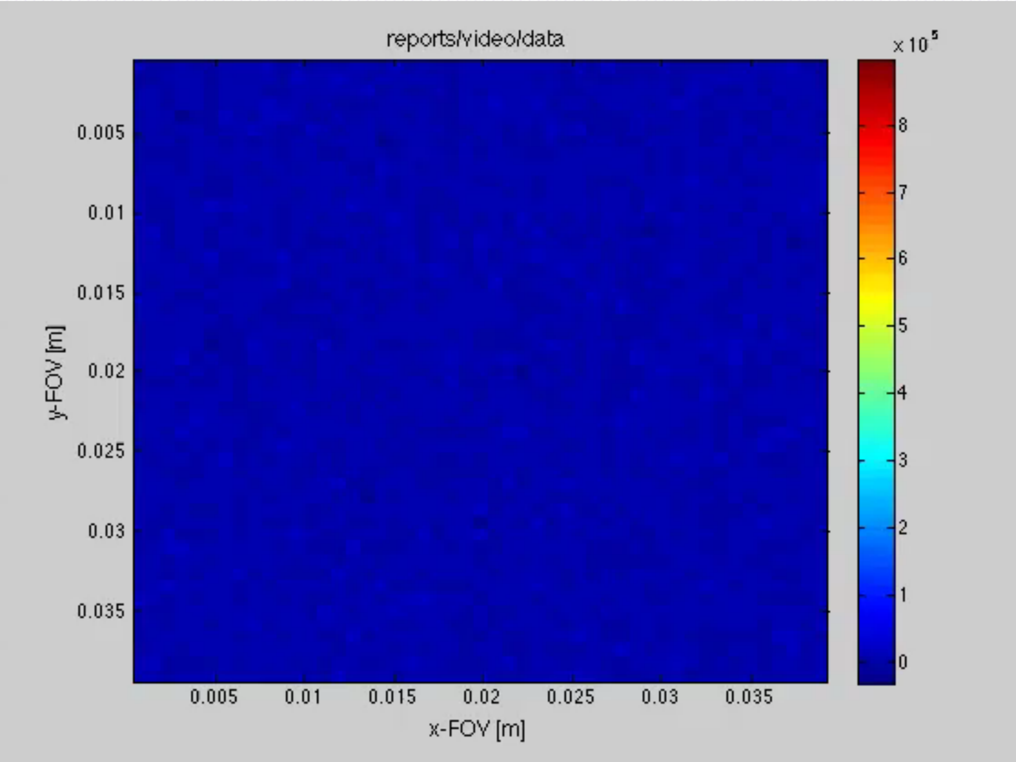
ULR – 'Slope' Scene Type

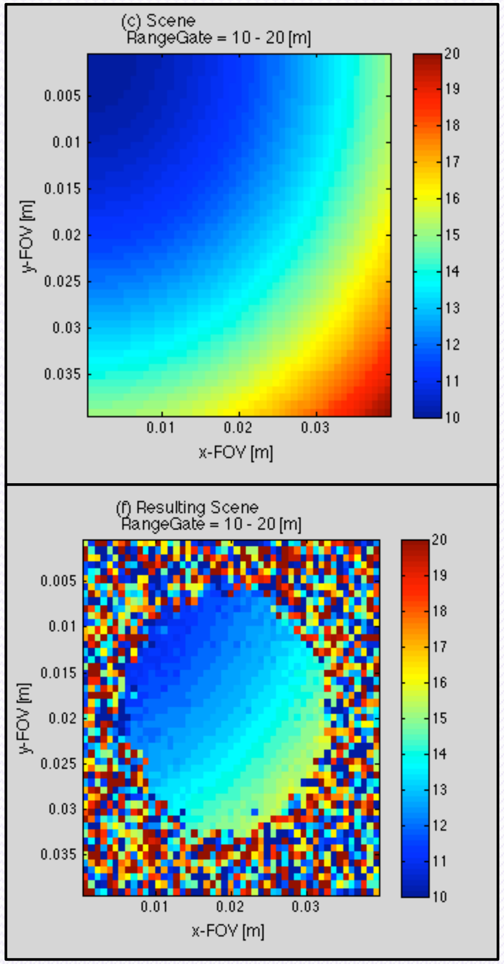






ULR – Cone4th Scene example





ULR - Conclusions

- Radiometric Analysis
- Engineering Tool
- Matlab Framework
- Useful for predicting LADAR behavior in underwater environments
- Structure of Code
- Validation
- Examples of use

THANK YOU!