This is an electro-optical analysis of the UCMS (underwater camera mapping system) designed for TerraSystems.

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For simplicity the SNR of only one 50nm wide channel near 500nm is determined. The normal 60 fps mode (1/125s exposure) is used with an F/1.3 lens. Pixel size is 9.9um on a side, so assume a capacity of about 80,000 electrons. Frame grabber is 10 bits, CCD quantum efficiency is about 0.44, and assume optics transmissivity of the lens to be about 80%.

$\lambda_{filter} := 50$ $\quad \rho_{floor} := 1$ $\quad F := 1.3$ $\quad x_{pixel} := 9.9 \cdot 10^{-6}$ $\quad y_{pixel} := 9.9 \cdot 10^{-6}$

$\tau_{optics} := 0.8$ $\quad q_e := 0.44$ $\quad t_{sample} := 0.008$ $\quad e_{full} := 80 \cdot 10^{3}$ $\quad N := 10$

$z := 0, 1 .. 100$ $\quad \lambda := 500 \cdot 10^{-9}$ $\quad h := 6.63 \cdot 10^{-34}$ $\quad c := 3 \cdot 10^{8}$ $\quad d := 0$

First we need to determine the noise of the camera. Dark current is specified as 2mV with a full scale output of 500mV at an ambient temperature of 60C. Since dark current doubles about every 7 degrees the noise at 40C ambient will be about 8 times less.

$$e_{dark} := \left(\frac{2 \cdot e_{full}}{500 \cdot 8} \right) \qquad e_{dark} = 40$$ electrons per frame

SNR of the camera is specified as 60dB. Ignoring dark current the read noise is simply

$$e_{read} := \frac{e_{full}}{1000} \qquad e_{read} = 80$$ electrons

Jerlov water characteristics are given by two coefficients, one for attenuation, and one for backscatter. The Jerlov 1B water type is clear coastal or better.

$a := 0.052$ $\quad b := 0.011$ $\quad K_d := a + b$ $\quad n := 1.33$

Transmission of light through water is exponential as a function of depth.

$$\tau(z) := e^{(-K_d \cdot z)}$$

Light from the sun is lost through the air-water interface (assuming zero angle) by

$$\tau_{surface} := \frac{4 \cdot n}{(1+n)^2} \qquad \tau_{surface} = 0.98$$

The backscattered light is a complex function of angle and depth. Using a simple model from Mobley that treats it as a lumped bulk component given by

$$\rho_{ocean} := \frac{0.33 \cdot b}{a} \qquad \rho_{ocean} = 0.07$$

Solar illumination of a bright sunny day at sea level is given as 1.5 watts per meter squared per nm. With a 50nm filter the illumination power per area is

$$E_{sun} := 1.5 \cdot \lambda_{filter}$$

The sterance (radiance) reflected off an object of maximum albedo (reflectance = 1) at depth is given by

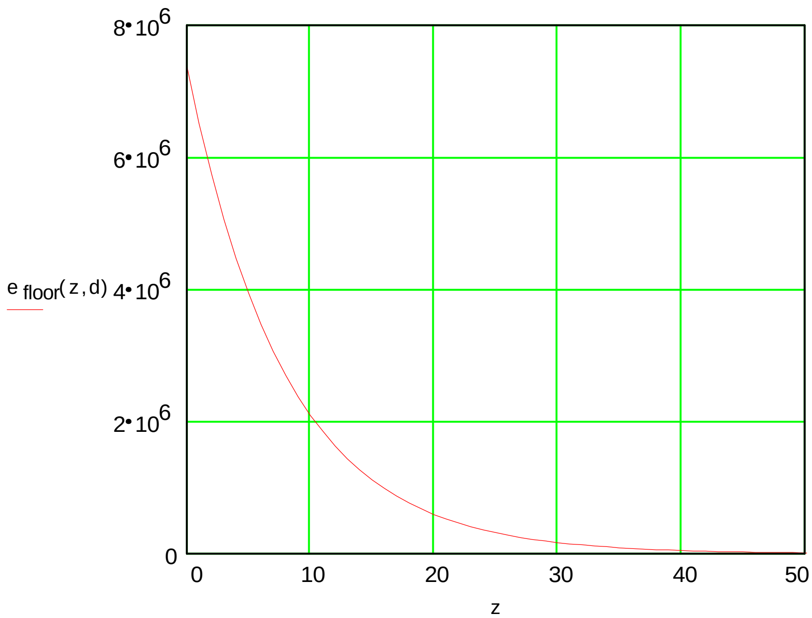
$$L_{floor}(z) := \frac{E_{sun} \cdot \rho_{floor} \cdot \tau_{surface} \cdot \tau(z)}{\pi}$$

And the light power received by the detector at any given sled depth is

$$\Phi_{floor}(z, d) := \frac{L_{floor}(z) \cdot \pi \cdot x_{pixel} \cdot y_{pixel} \cdot \tau_{optics} \cdot \tau_{surface} \cdot \tau(z-d)}{4 \cdot F^2}$$

Converting to CCD electrons per pixel per frame we get

$$e_{floor}(z, d) := \frac{\Phi_{floor}(z, d) \cdot \lambda \cdot t_{sample} \cdot q_e}{h \cdot c} \qquad e_{floor}(30, 0) = 1.687 \cdot 10^5$$



This is a lot of electrons and will saturate the detector if not stopped down. Nominally the sled is at a depth (d) of near zero, just under the surface. The backscattered light is then approximated as a function of depth by

$$L_{ocean}(z) := \frac{E_{sun} \cdot \rho_{ocean} \cdot (1 - \tau(z))}{\pi}$$

Backscatter noise collected by the detector is

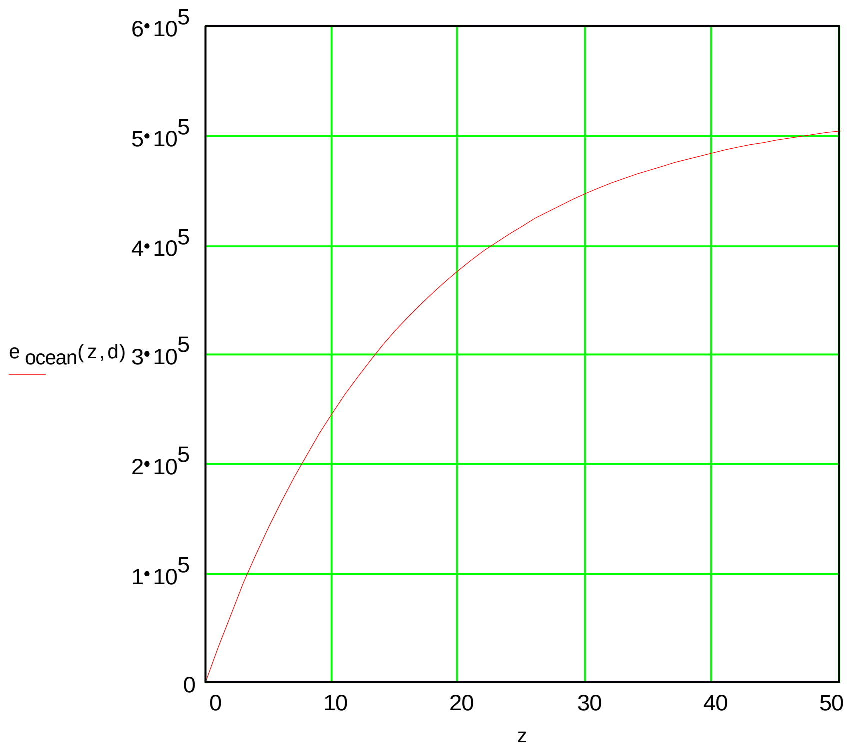
$$\Phi_{ocean}(z, d) := \frac{L_{ocean}(z) \cdot \pi \cdot x_{pixel} \cdot y_{pixel} \cdot \tau_{optics} \cdot \tau_{surface} \cdot \tau(d)}{4 \cdot F^2}$$

This converts to CCD electrons by

$$e_{ocean}(z, d) := \frac{\Phi_{ocean}(z, d) \cdot \lambda \cdot t_{sample} \cdot q_e}{h \cdot c}$$

$$e_{ocean}(30, 0) = 4.47 \cdot 10^5$$

At depths of 30m to 40m there is very little backscatter noise.



The total number of electrons is the sum of signal, backscatter, and dark electrons. The aperture must be set such that the total does not saturate a pixel.

$$e_{total}(z, d) := e_{floor}(z, d) + e_{ocean}(z, d) + e_{dark}$$

Aperture is calculated for a given camera depth as

$$\alpha(d) := \frac{e_{full}}{e_{total}(\infty, d)} \qquad \alpha(0) = 0.152$$

So at zero camera depth the worst case requires stopping down the lens by a factor of more than 6. At a depth of 20m the lens can be set wide open. This prevents pixel saturation. SNR is calculated taking into account aperture by

$$\mathrm{SNR}(z,d) := \frac{\alpha(d)\cdot e_{floor}(z,d)}{\sqrt{\alpha(d)\cdot\left(e_{floor}(z,d)+e_{ocean}(z,d)\right)+e_{dark}+e_{read}^{2}+\left(\frac{e_{full}}{2^{N}\cdot\sqrt{12}}\right)^{2}}}$$

This formula assumes post processing to subtract out solar backscatter and dark signals. Thus, only the fluxuations of these noise sources remain. SNRs at various depths are plotted in the following graph for an object reflectivity of 1. In real life the reflectivies will be much lower.