# Modulating Retro-reflector Links for High Bandwidth Free-Space Lasercomm

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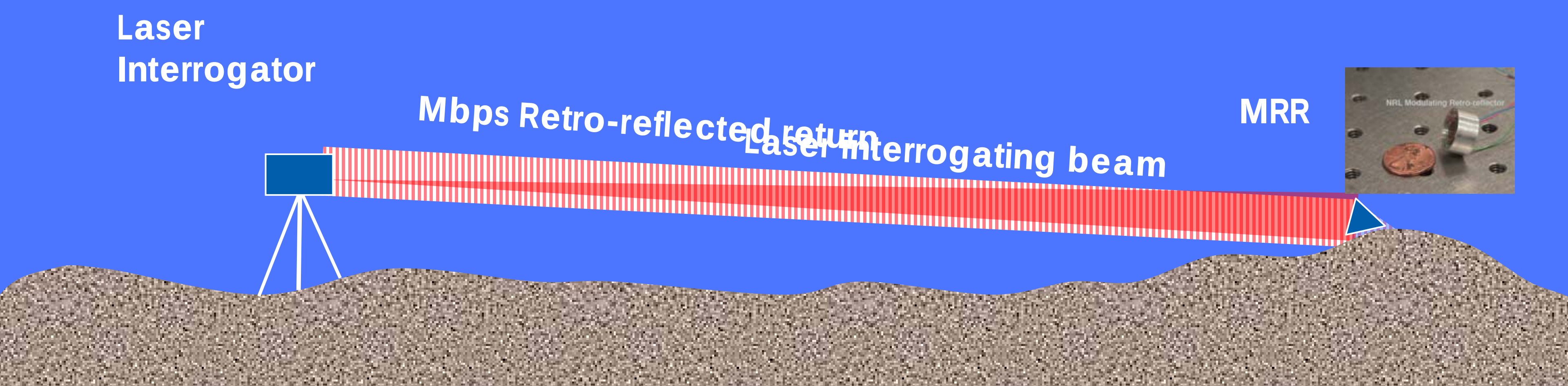
# MRRs in ONR BAA 09-18

- **Product 2 – Modulating retro-reflector (MRR) communications terminals The MRR terminal contains in very general terms:**
  - 1. A multiple quantum well (MQW) based MRR (transmitter) and a photodetector (receiver) for two-way communications
  - 2. MRR driver electronics
  - 3. Modem for communication between the lasercomm link and USN/USMC network

**Items 1 & 2 in Product 2 will be supplied as government furnished equipment (GFE) for integration into lasercomm systems developed in this program. Item 3 will be developed as part of this program.**

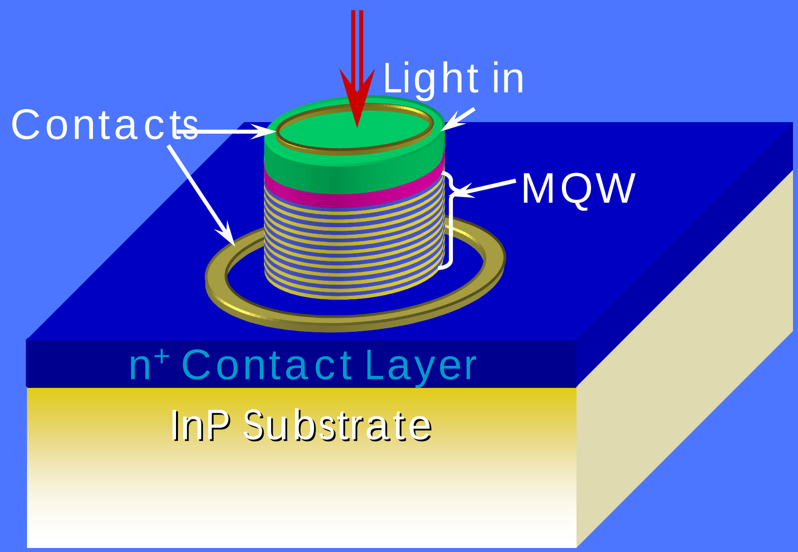
# Modulating retro-reflector links

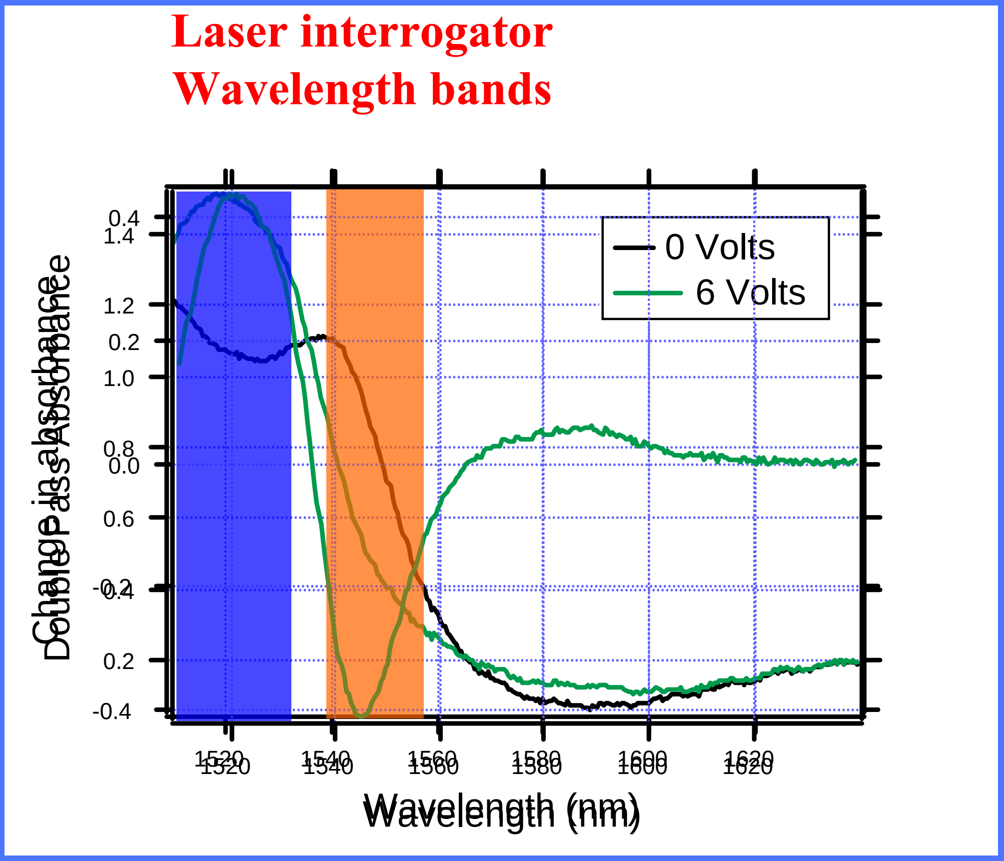
- Uses transmitter optics, laser, pointing and tracking, receive optics at <u>one</u> end of the link
- Uses a passive retro-reflector with modulator at the other end
- Asymmetric comms
  - –Good when very little power/weight capability at one end of the link
  - –Appropriate for unattended sensors or disadvantaged users
  - –Link falls off as $1/R^4$
  - –Ranges of a few kilometers to tens of kilometers depending on link
  - –Data rates of up to 10 Mbps (corner cube) or 10’s Mbps (cat’s eye)



# Multiple Quantum Well Modulators

- Coupled quantum well structure requires ~ 5V drive
- Approximately 3 dB extinction
- Capacitance of 5 nF/cm$^2$, Sheet resistance of 5-10 Ohms
- Power consumption ~ CV$^2$f, where f is the drive frequency
- Absorption of light changes when voltage is applied
- NRL GFE devices operate in telecom c-band
- **Data rates limited by RC time**

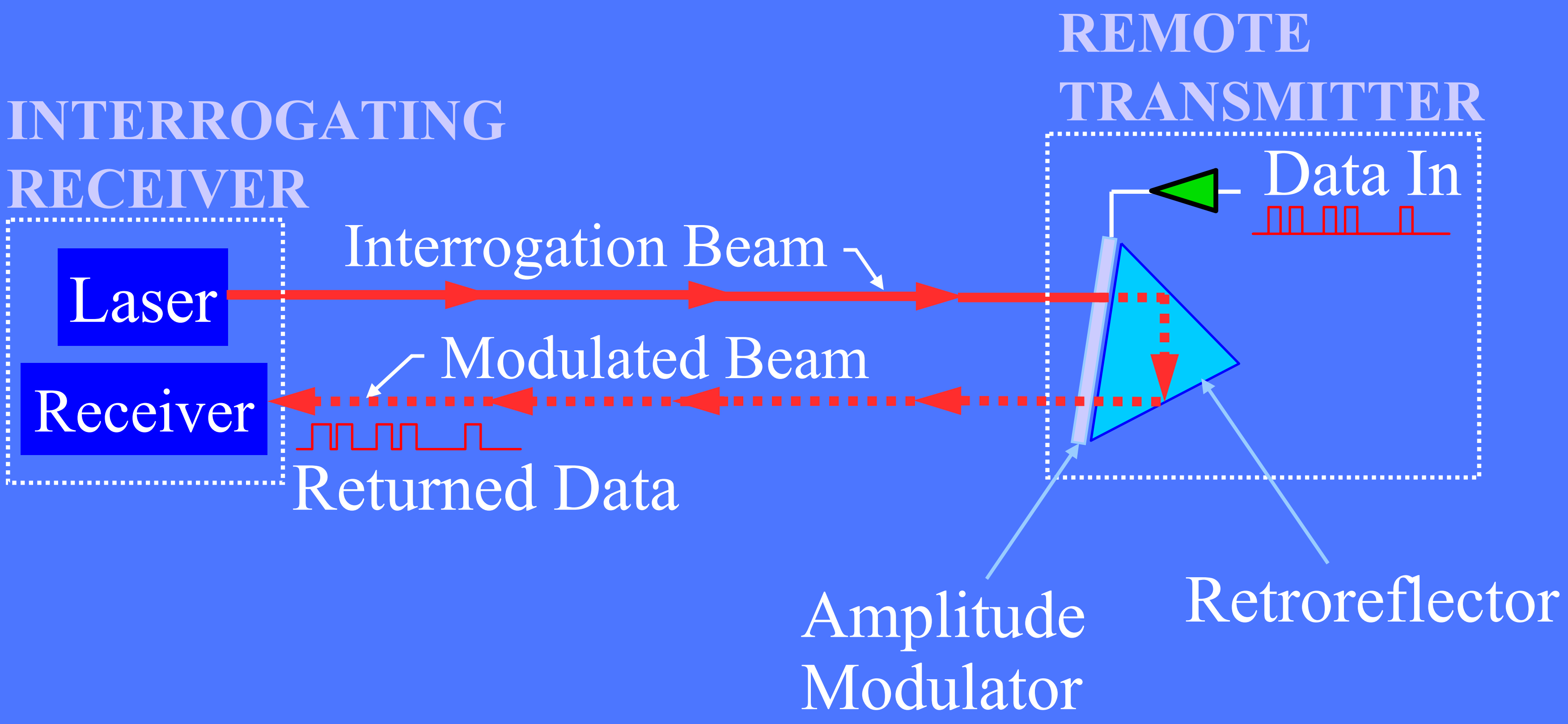


# Retroreflector Types

- Corner cubes: prisms
- Cat’s eyes: optical systems using lenses and mirrors

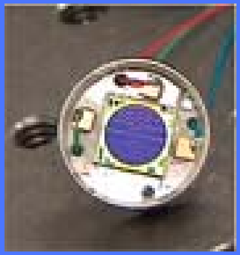
# Corner Cube MRRs




**Data rate determined by modulator switching rate**

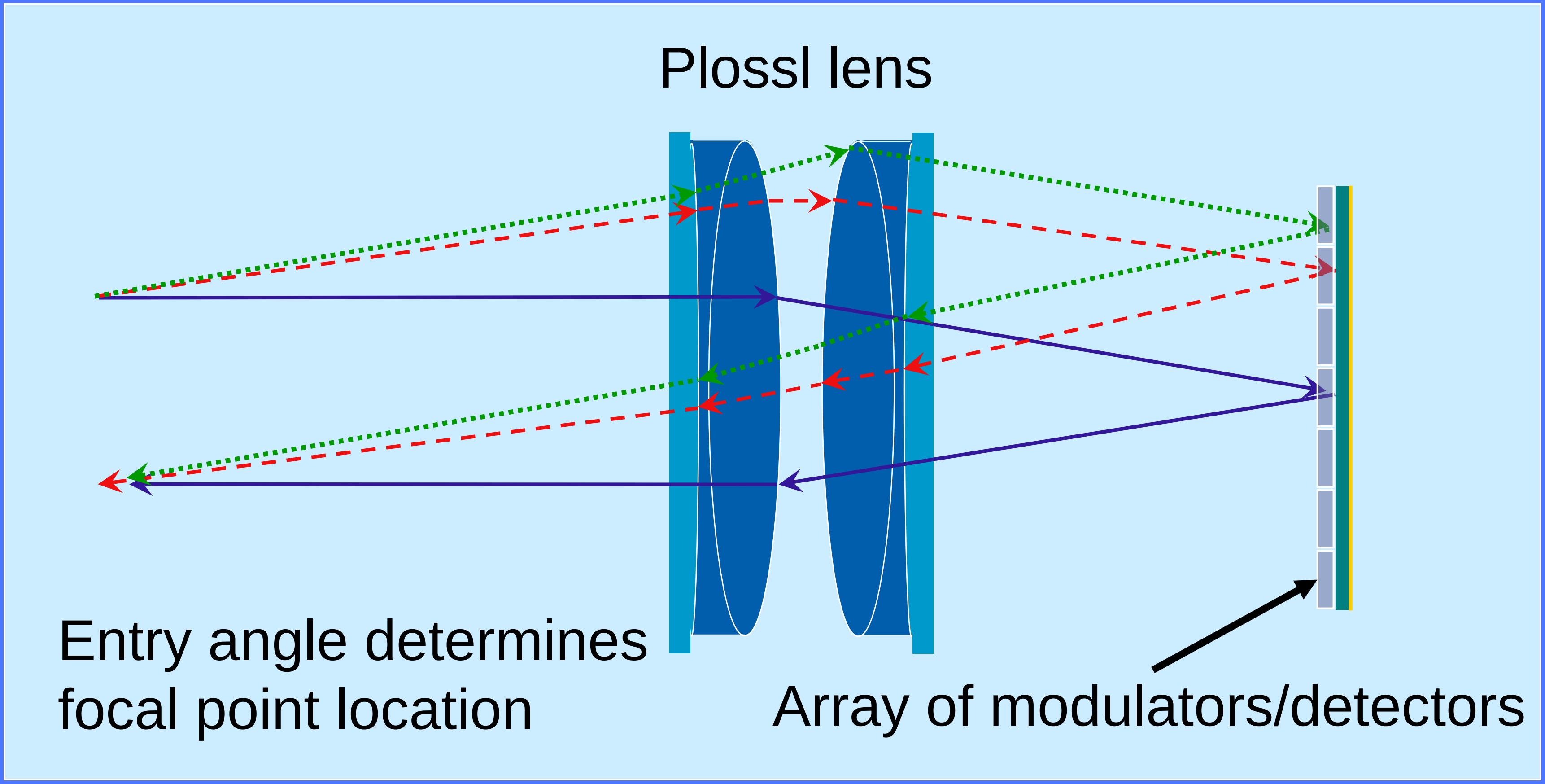
# Corner Cube Retro-reflectors (CCR)

- Simple, rugged, inexpensive
  - Single component, no possibility of misalignment
- $\boldsymbol{D_{modulator} \approx D_{aperture}}$
  - Bandwidths<10 MHz
- Only design parameter is index of refraction
  - High index materials $\Rightarrow$ larger field of view (FOV)



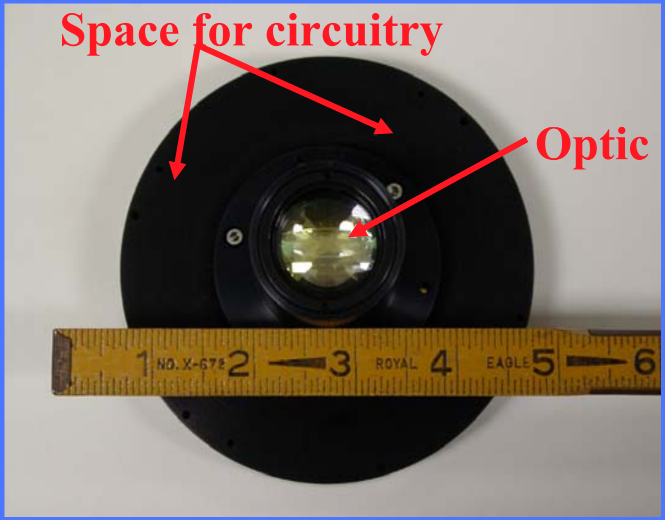
# Cat's Eye Retroreflectors (CER)

- Light focused onto a mirrored surface



# Cat's Eye Retro-reflectors (CER)

- Complex, custom optical design
  - Requires multiple optical elements for practical MRRs
  - Can achieve bandwidths of 10's of MHz
  - Field of view: 5°-20°
- $D_{modulator} \ll D_{aperture}$
  - Allows small (fast) modulators in long links



# LINK BUDGETS

# MRR Link Budgets

**MRR Antenna Gain:** $G_{MRR} = \left[\frac{\pi D_{retro}}{\lambda}\right]^4 S$

**Interrogator Laser Power** · **Laser collimation and pointing** · **Interrogator receive aperture**

$$P_{sig} = P_{Las} L_{Tx} G_{Tx} L_R T_{atm} G_{MRR} L_{MRR} M L_R T_{atm} G_{Rx} L_{Rx}$$

$L_R$: $\frac{1}{R^2}$ **Weather losses** ($T_{atm}$) $L_R$: $\frac{1}{R^2}$

$$\frac{1}{R^4}$$

**Geometric propagation losses**


W. S. Rabinovich, et al, "Free-space optical communications link at 1550 nm using multiple quantum well modulating retro-reflectors in a marine environment," *Optical Engineering, 44(5), (2005)*

*W.S. Rabinovich et al., "45-Mbit/s cat's-eye modulating retroreflectors", Optical Engineering, 46(10) (2007)*

# MRR Link Budgets Detail

$$P_{sig} = P_{Las} L_{Tx} G_{Tx} L_R T_{atm} G_{MRR} L_{MRR} M L_R T_{atm} G_{Rx} L_{Rx}$$

| Term | Formula |
|---|---|
| **$P_{Las}$, Transmit Power** | Measured |
| **$L_{Tx}$, Transmitter loss** | Measured |
| **$G_{Tx}$, Transmitter antenna gain** | $\frac{32}{\theta_{div}^2}$ |
| **$L_R$ , Range loss** | $\left[\frac{\lambda}{4\pi R}\right]^2$ |
| **$T_{Atm}$, Atmospheric transmission** | Measured |
| **M, MRR Modulation efficiency,** | ~ 0.25 |
| **$L_{MRR}$, MRR loss** | Measured |
| **$G_{MRR}$, MRR Antenna gain** | $\left[\frac{\pi D_{retro}}{\lambda}\right]^4 S$ |
| **$G_{Rx}$, Receiver antenna gain** | $\left[\frac{\pi D_{Rx}}{\lambda}\right]^2$ |
| **$L_{Rx}$, Receiver loss** | Measured |

**Definitions:**

$\theta_{div}$:Tx divergence (1/e$^2$ full)

$\lambda$: laser wavelength

R: range

$D_{retro}$: MRR diameter

S: MRR Strehl ratio

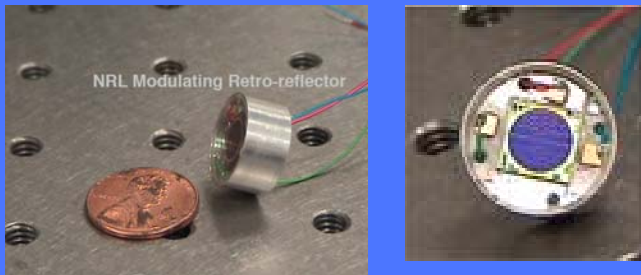
$D_{Rx}$: Receiver diameter

# Example Link Budget

| Term | Parameter | Formula | dB |
|---|---|---|---|
| Transmit Power | 5 Watts | Measured | 37 dBm |
| Transmitter loss | | Measured | -1.0 |
| Transmitter antenna gain | Full angle $e^{-2}$ divergence<br>$\theta_{div}$=300 microradians | $\frac{32}{\theta_{div}^2}$<br>Gaussian beam underfilling transmit aperture | 85.5 dB |
| Range loss (interrogator) | Range, R=7 Km<br>$\lambda$= 1550 nm | $\left[\frac{\lambda}{4\pi R}\right]^2$ | -215 |
| Atmospheric transmission | 16 Km visibility | | -1.5 |
| MRR Modulation efficiency, M | Coupled-well modulator | $e^{-\alpha_{Off}} \cdot \left[C_{MQW} - 1\right]$ | -7.0 |
| MRR loss | Loss due to anti-reflection | Measured | -0.7 |
| MRR T/R Antenna gain, $G_{retro}$ | $D_{retro}$ =1.6 cm<br>S=0.4 | $\left[\frac{\pi D_{retro}}{\lambda}\right]^4 S$ | 177 |
| Range loss (retro return) | 7 Km | $\left[\frac{\lambda}{4\pi R}\right]^2$ | -215 |
| Atmospheric transmission | 16 Km visibility | | -1.5 |
| Receiver antenna gain | $D_{rec}$=15 cm | $\left[\frac{\pi D_{rec}}{\lambda}\right]^2$ | 108 |
| Receiver loss | Fiber coupling loss | | -1 |
| Predicted received power | 0.28 µW | | -35.0 dBm |
| Actual received power | 0.4 µW | | -34 dBm |

# GFE MRR Options

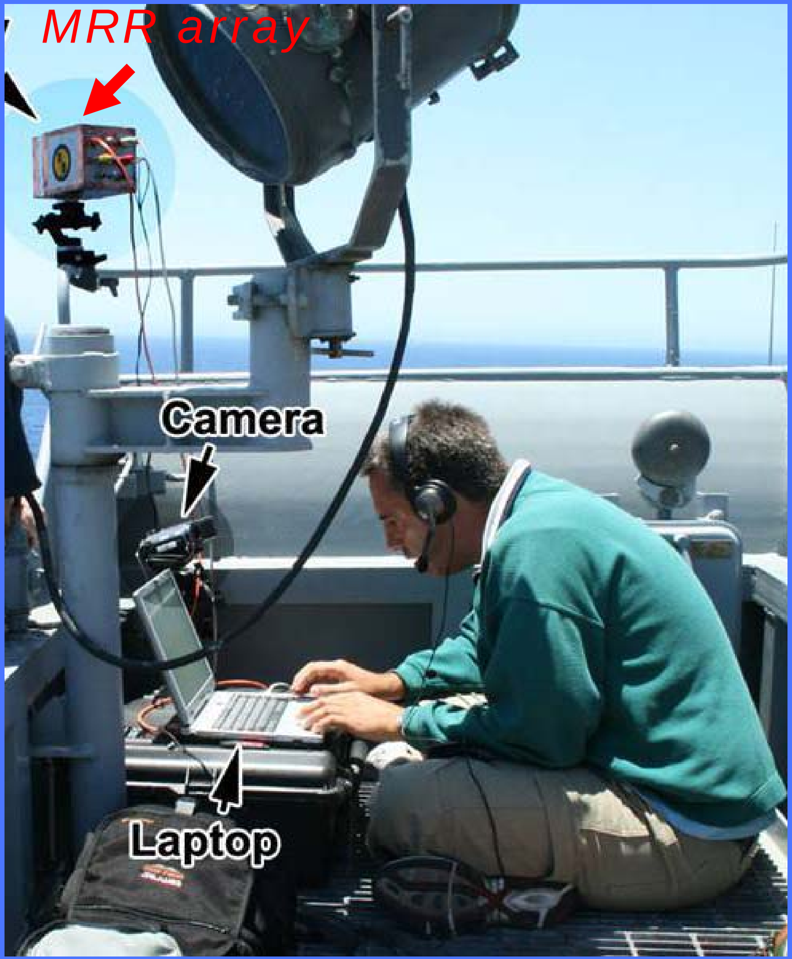
# Some MRR Configurations




Single Corner cube MRR
30º FOV, 5 Mbps, 8.5 g

Corner cube MRR array
60º FOV, ~5 Mb/s
86 g,
including drive electronics

Cat’s eye MRR
1.6 cm aperture
20º FOV optic, 45 Mb/s
410 g,
including drive electronics




Corner cube MRR array
Tested on USNS Yukon

# GFE MRR

| Design | Aperture | $G_{retro}$ | FOV (degrees) | Bandwidth |
|---|---|---|---|---|
| CCR | 0.63 cm | 163 dB | 26-70 | 10 MHz |
| CCR | 1 cm | 171 dB | 26 | 5 MHz |
| CER | 1 cm | 171 dB | 20 | 5-45 MHz |
| CER | 1.6 cm | 179 dB | 20 | 5-20 MHz |
| CER | 2.8 cm | 189 dB | 5 | 5-45 MHz |

Notes:
Field of view for single elements; MRR arrays can broaden FOV
CCR field of view depends on corner cube material: glass vs silicon

Electrical input to all MRRs: 5V TTL, power consumption < 1 Watt

# Wide FOV MRR Photodetectors

- The MRR terminal photodetector must match the field of view of the MRR

- GFE design: PIN photodetector with 5 mm lens 35° FOV
  - Sensitivity at 5 MHz bandwidth~ -30 dBm

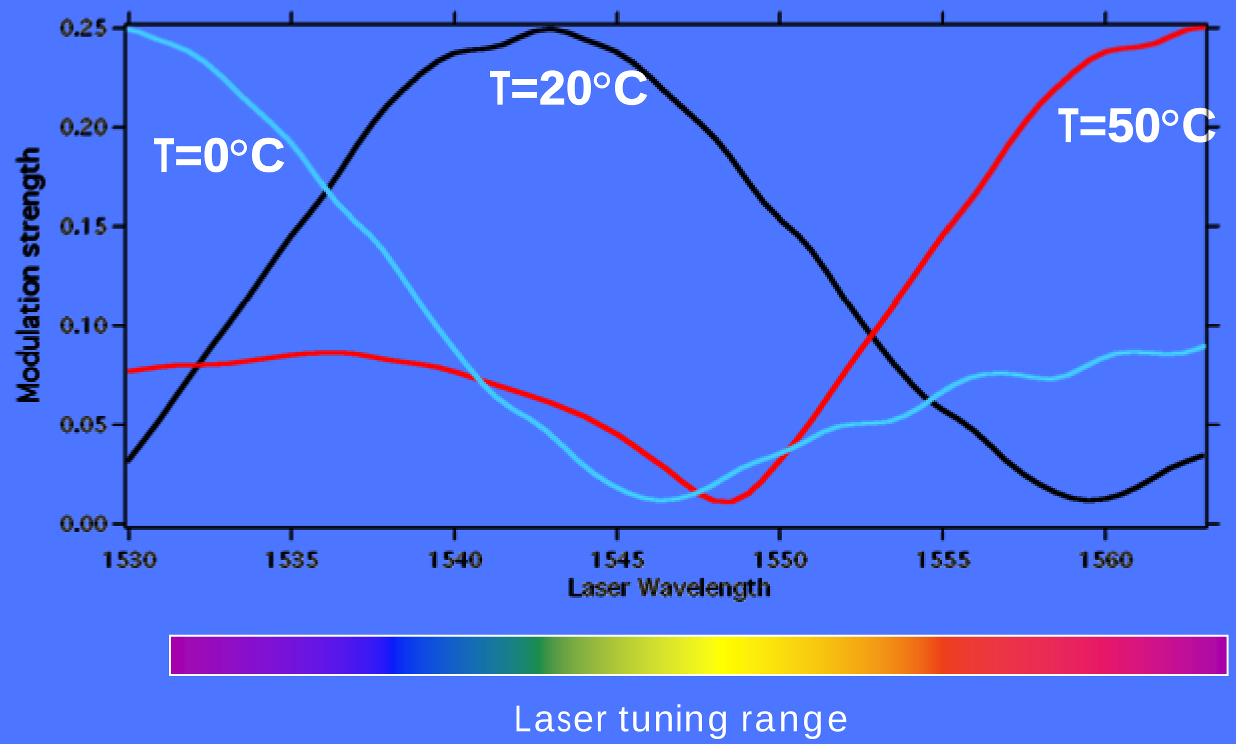
- Other variants are possible

- Note: optical fluence on the MRR terminal is much higher than on the interrogator ($1/R^2$ vs $1/R^4$)

# Other Design Considerations

# MQW Temperature Dependence

- The response of the MQW modulator shifts with temperature
  - the optimal laser wavelength shifts by 0.67 nm/°C
  - Changes of less than ±10°C have a small effect
- Can use a tunable laser to compensate: more complex interrogator
- Can thermally control the MRR: more complex MRR terminal



# Interrogator Considerations

- Optical power levels
  - Typical MRR links will return ~ -50 dBm to the interrogator
  - Your system must be able to track on these levels
- MQW modulator has about 3 dB extinction
  - Needs to be considered in interrogator receiver design
- Tx/Rx isolation
  - Typical Tx powers will be on the order of +30 dBm
  - => 80 dB of Tx/Rx isolation needed
  - Return beam is at same wavelength as Tx beam => No spectral isolation
- Optical scintillation is higher in a retro-reflected link
  - Modem designs must deal with deep and frequent fades

# Conclusions

- MRRs can be used in your designs for asymmetric links
- Corner cube vs cat's eye MRRs offer different advantages
  - Corner Cubes:
    - Simple and rugged
    - Easy to array for wide field of view
  - Cat's eye:
    - Larger aperture yields high antenna gain
    - Capable of higher bandwidth
- MRR links can use the same interrogator as direct links, but have special requirements