Modulating Retro-reflector Lasercom Systems at the Naval Research Laboratory

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Abstract—**Free space optical (FSO) communication has enjoyed a renewal of interest driven by increasing data rate requirements and the crowding of the RF spectrum, affecting both commercial and military sectors. Military communications must also deal with intentional or unintentional jamming, as well as frequency allocation restrictions, neither of which affects FSO. The U.S. Naval Research Laboratory (NRL) has been conducting research on FSO communications since 1998 with an emphasis on tactical applications. NRL's FSO research has covered propagation studies in the maritime domain, component development, and systems demonstrations. NRL has developed both conventional laser communications systems and retro-reflecting systems for small platforms. This paper reviews some of the retro-reflecting work, discusses applications of FSO in the areas of explosive ordnance disposal (EOD) and unmanned aerial vehicles (UAVs), and describes future directions.**

Keywords: lasercom; free-space optical; modulating retro-reflector; LPI/LPD techniques; anti-jamming techniques; Packbot; CREW; frequency allocation; airborne technologies; unmanned aerial vehicles; intelligence, surveillance, and reconnaissance

I. INTRODUCTION

Lasercom, also known as free-space optical communication (FSO), has emerged in recent years as an attractive alternative to conventional RF communication [1, 2, 3]. This is due to the increasing maturity of lasers and compact optical systems as well as unique advantages of lasercom. Setup is relatively low-cost, with no licensing or frequency allocation required.

Lasercom's primary advantages for military applications are covertness, lack of RF interference, immunity to jamming, lack of frequency allocation requirements, and high bandwidth. Lasercom inherently has a low probability of interception and detection (LPI/LPD). This is due to both the tight beams and the wavelength used. For example, over a 16 km link [12], the beam at the remote end had expanded to a diameter of only 2 m. If this relatively small column of light is controlled, interception is highly improbable. In addition, 1550 nm light is completely invisible to standard and "Nightshot" cameras, mid-

and long-wavelength infrared (MWIR and LWIR) sensors, standard night vision equipment, and the human eye.

A modulating retro-reflector (MRR) can allow lasercom communication with platforms that would otherwise not be able to support lasercom communications. Using an MRR lasercom terminal on a UAV [4] shifts most of the weight, power, and pointing requirements to the ground station. The single conventional lasercom terminal is located on the ground or large mobile platform [5—14].

NRL has had a special emphasis on MRR links. In this paper, we describe demonstrations of several MRR links, including on Navy ships at sea, a link to an explosive ordnance disposal (EOD) Packbot in the presence of an active CREW (Counter Radio-controlled improvised explosive device Electronic Warfare) jammer, and a link to a small UAV.

II. MODULATING RETRO-REFLECTORS

The extreme directionality of lasers that give some of lasercom's benefits also creates limits. For long range links, beam divergence is on the order of 100–200 µrad (0.006°–0.012°). If either end is mobile, a gimbal or similar tracking component is required on both ends of the link, adding to size, weight, power, and complexity. A MRR can relieve the size, weight, and pointing requirements on one end of the link.

Retro-reflectors reflect light exactly back along its path of incidence. Retro-reflectors typically have a large field of view (FOV). This allows for a greatly relaxed pointing, typically about +/-15°. An important aspect to note is that although the retro-reflector can have a large FOV, the reflected laser beam will be restricted to a very tight diffraction-limited return beam (typically about 400 µrad), and will thus not be directly detectable from locations away from the interrogating laser. Using standard commercial optical cornercube retro-reflectors, misalignment of the return beam is physically impossible.

MRR transmitters are made by mounting an electro-optic shutter in front of a retro-reflector. A larger platform

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14. ABSTRACT
Free space optical (FSO) communication has enjoyed a renewal of interest driven by increasing data rate requirements and the crowding of the RF spectrum, affecting both commercial and military sectors. Military communications must also deal with intentional or unintentional jamming, as well as frequency allocation restrictions, neither of which affects FSO. The U.S. Naval Research Laboratory (NRL) has been conducting research on FSO communications since 1998 with an emphasis on tactical applications. NRL?s FSO research has covered propagation studies in the maritime domain, component development, and systems demonstrations. NRL has developed both conventional laser communications systems and retro-reflecting systems for small platforms. This paper reviews some of the retro-reflecting work, discusses applications of FSO in the areas of explosive ordnance disposal (EOD) and unmanned aerial vehicles (UAVs) and describes future directions.

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interrogates the MRR with an unmodulated (CW) laser beam, as shown in Fig. 1a. The beam is passively reflected by the MRR back to the large platform. The shutter is turned on and off with an electrical signal carrying the small platform's data. If the interrogation beam is within the retro-reflector's FOV, the beam returns to the interrogator with data impressed on it.
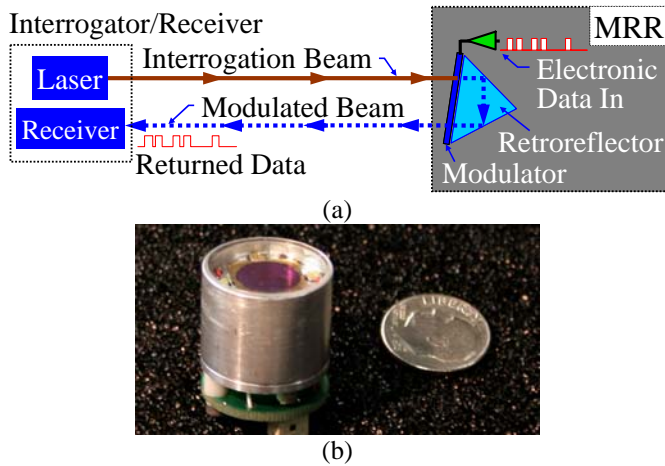

(a)

(b)

Figure 1. (a) Simple MRR system. Electrical signal is impressed onto the incident CW laser beam. (b) NRL MRR transmitter

Optical MRRs were used long before the invention of the laser [15, 16], but were restricted to short distances and low data rates. Recent advances in optoelectronic devices and FSO have greatly increased the capabilities of MRR systems. Such systems can be very light and low-power. Their small size allows the use of arrays [4, 9, 11, 13], further relieving the pointing requirements. MRRs are insensitive to platform jitter. The small platform maintains the covertness and lack of RF interference of a conventional optical communications link, but gains the loose pointing advantage of an RF link.

NRL has been developing MRRs for asymmetrical FSO links since 1998, focusing on multiple quantum well (MQW) modulators. Several different modulator technologies for MRR systems are compared elsewhere [17]. In this discussion, we compare practical considerations of various types of km-range MRRs. Examples of MRR systems using each type are given.

A. Retro-reflector Types

CCRs are the most common type of manmade retro-reflector. Their size, weight, robustness, and wide availability make them attractive for MRRs. Their primary disadvantage is that the modulator must be as large as the CCR aperture. MQW modulators are typically *RC* time limited, so the larger modulators needed for long ranges limit their data rate.

Retro-reflectors can also be made with focusing optics; these are often referred to as "cat's eye" retro-reflectors. Examples are shown in Fig. 2. Cat's eyes come in many forms, all containing a mirrored surface onto which light is focused. Several variations have been described in [18,19]. Cat's eye MRRs can have large optical apertures with small (and thus fast) modulators. The primary disadvantages of cat's eyes are smaller FOV, larger size, and higher cost. Precise alignment is required, thus they are potentially less rugged.

B. Typical MRR Data Rates

For cornercube MRRs used in ~km links, data rates are typically in the MHz range. The NRL MQW MRR shown in Fig. 1b has bandwidths up to 5 Mb/s. When used with the interrogator described later in this paper, it has a range of 4 km and draws 350 mW. NRL has operated cornercube MRRs at >20 Mb/s, however their range is limited to a few hundred meters due to their small apertures.

Figure 2: a) Corner cube MRR array   b) Cat's eye MRR.

Cat's eye MRRs allow longer ranges and/or higher data rate at the cost of increased complexity and size. A 7 km, 45 Mb/s ship-to-shore link was demonstrated with a cat's eye MRR with a 20º FOV [10]. Tradeoffs between cornercube and cat's eye retro-reflectors can be found in [20].

C. Dual Mode Optical Interrogator

Many applications require one or both ends of the link to be mobile. To address this, NRL has worked with Novasol under the Office of Naval Research Dual Mode Optical Interrogator (DMOI) program to develop a tracking laser interrogator [21]. The DMOI works with both retro-reflecting and conventional optical links. It is a bistatic system, which is generally required for MRR links. The current systems use an EDFA to produce maximum output powers from 0.5–2 W. A variety of seed lasers can be used. Divergence is variable, with a minimum of about 200 µrad. Receive and transmit apertures are both 100 mm in diameter. The large transmit aperture allows unaided eye-safe powers up to about 2 W, and has been classified ANSI/IEC Class 1M (eyesafe out of the aperture). Fig 3. shows the DMOI on a tripod. Received light is coupled into a 100 µm diameter multimode fiber so a variety of receivers can be used. The optical head without the gimbal is 305 mm x 305 mm x 254 mm, weighs 16 kg, and draws 100 W.

The DMOI has two internal fast steering mirrors (FSM), one each for the transmit and receive paths. These mirrors do fine, fast steering. The DMOI can be mounted on a gimbal to take out large, slow motions using inertial stabilization. The DMOI head is pointed to within about 1º. In a retro-reflecting link the DMOI FSMs then scan the beam around until it detects a retro-reflected return on its quad cell. It then tracks optically.

DMOIs have been used in several Navy exercises. An early version was used in the 1st high speed lasercom link between ships at sea, in which a 300 Mb/s link was established between the USS Bonhomme Richard (LHD6) and USS Denver (LPD9)

during the Trident Warrior 2006 exercise [22]. A 2nd generation DMOI was used to support a one-way modified Gigabit Ethernet link during Seahawk 2007 [3]. The DMOI has proved to be a flexible system, and versions of it have been used for all the MRR system examples given below.

Figure 3. Dual mode optical interrogator (DMOI) on tripod

D. MRR Modem

The MRR systems described below share a common custom Ethernet modem designed by NRL and SmartLogic for MRR systems. The modem can receive data from any camera which outputs NTSC video. The incoming video stream is digitized and compressed using real-time JPEG 2000 (J2K) compression. Each frame of video is prefixed with metadata based on stored data and/or real-time Pan-Tilt-Zoom (PTZ) feedback to allow geo-rectification and geo-registration of the video image.

The modem includes 4 GB of flash for storage of files or video that can be accessed over the link. In file transfer mode, packets are sent as UDP datagrams with an acknowledgment and retransmission for lost packets across the link.

The J2K compression level and frame rate can be modified from the interrogator without disrupting communication. The remote hardware is reconfigured via commands sent by lasercom uplink. Maximum J2K compressed frame size is 32 kB. In typical operation, J2K frame size is normally 4 kB or less. This is based on a tradeoff between overhead and scintillation effects. Larger packets require less overhead, but due to the highly dynamic link margin, smaller packets have a higher probability of being correctly received. In order to aid in clock recovery, several clock cycles are included as part of the preamble to the packet.

Usable range can be extended by employing multiple sends of each frame, which can also be modified without disruption of video. No forward error correction (FEC) is currently being used, although it remains a possibility for extending range. In the MRR architecture, the use of FEC would require an increase in processing requirements at the remote end, which limits its attractiveness when minimum size, weight, and power are of primary importance. One approach would be to use Reed Solomon FEC. This method, however, does not solve the characteristic FSO deep fade problem. Utilizing an error correction technique such as interleaving is a solid solution for the deep fade FSO problem, but adds much latency to the link, detrimental to live streaming video applications.

III. NRL MRR SYSTEM EXAMPLES

A. Trident Warrior 2008

During Trident Warrior 2008 sea trials, NRL demonstrated a ship-to-ship MRR link in a simulated maritime interdiction operation (MIO) demonstration. The boarding party needs a small, simple terminal that is LPI, anti-jam, and does not require frequency allocation. Only moderate data rates are required. MRR links are well-suited to this type of application.

A DMOI terminal was installed on the USS Comstock, and a MRR array/modem package was carried onto the boarded vessel, the USNS Yukon. The two terminals are shown in Fig. 4. The MRR package consisted of an array of 5 MRRs and 5 photoreceivers. This array has a FOV of 60°, requiring only coarse pointing to establish a link. Re-pointing of the array was only necessary for large course changes. A two-way Ethernet link was established between the MRR and DMOI. The link typically operated at a rate of 2 Mb/s in each direction.
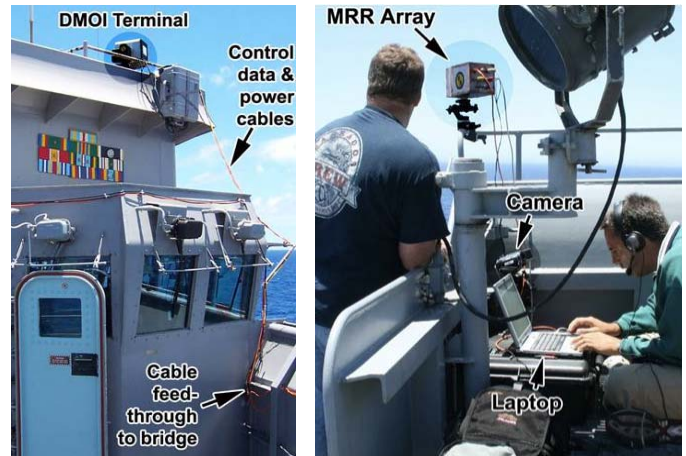

Figure 4. (a) DMOI terminal mounted on the USS Comstock
(b) MRR terminal on the USNS Yukon

Link tests were conducted during transit between San Diego and Hawaii. Over the relatively short (~3 hour) test, a variety of data formats were transmitted including live video and data files. Packet error rates were recorded at all ranges. File transfers using a custom protocol were conducted out to a range of 4.5 km at an effective throughput (file size divided by transfer time) of about 1 Mb/s. More detail is available in [23].

As with Trident Warrior 2006, Trident Warrior 2008 showed that FSO worked well on operational naval vessels. The use of MRRs allows FSO to be extended to much smaller naval platforms with lower bandwidth applications.

B. Packbot Robot

The anti-jam characteristic of lasercom can provide a useful capability to EOD teams. Self-jamming from CREW jammers can be a problem for EOD robots. FSO systems can operate without RF interference due either to other transmitters in the same band or jamming. For these applications, the optical link must transparently replace the RF link.

NRL demonstrated such a link using the Packbot robot [13], which is often used for EOD work. These robots use RF to establish a 1.5 Mb/s Ethernet link to send commands from a control console and receive video streams from the robot. NRL demonstrated that a MRR link could replace the 802.11 link that is normally used for the robot.

The data link required 360° azimuthal coverage on the robot, so an array of retro-reflectors and receivers was used. The Packbot with the MRR array is shown below in Fig. 5.
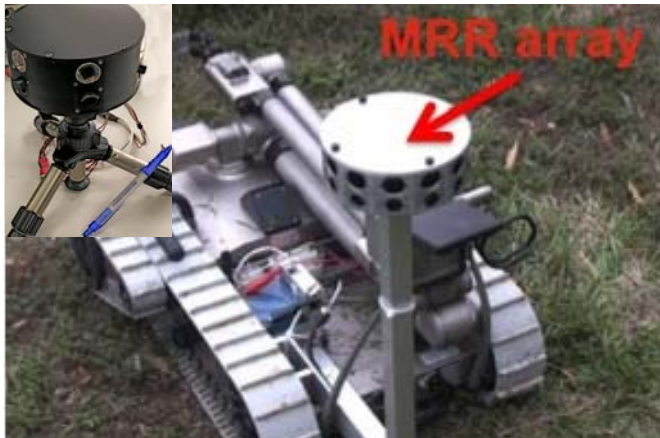

Figure 5. Packbot with MRR/Photoreceiver array. Inset: Packbot-deployable MRR/802.11 terminal for mixed mode FSO/RF serial links.

The interrogator was a DMOI as described above. The MRR modem was plugged into the Packbot's Ethernet port. This allowed the optical link to replace the RF link without any changes to the Packbot hardware.

The optical link worked well out to ranges of about 1 km, limited by line of sight. Scintillation caused some drop-outs in the video feed, but not enough to cause any problem in operating the robot via the lasercom uplink. The Packbot operated using the MRR link next to a small CREW jammer with no affect to the communication link.

RF links do offer one very significant advantage over optical links for this application—they can be non-line-of-sight. One way to gain the advantages of both kinds of links is to combine them serially. The inset in Fig. 5 shows a mixed mode FSO/RF pod designed to be transported and deployed by a robot. In this mode of operation, the FSO system talks to a retro-reflecting pod that can be on the robot or dismounted. The pod communicates with the robot over RF. The optical link then handles the long range, line of sight part of the link, and the RF link handles the shorter-range non line of sight part.

C. Airborne Lasercom System

Lasercom has been previously demonstrated on manned aircraft with Gb/s data rates [24, 25]; however those systems require a high-precision pointing system and correspondingly high-accuracy navigation hardware, both of which are prohibitively heavy for small UAVs. The loose pointing requirements of MRRs open up the use of lasercom to small UAVs which could not otherwise support lasercom. Small, lightweight, low-cost gimbals can be used for pointing. It also allows for low precision navigation hardware to be used,

further decreasing size, weight, power, and cost. The MRR transmitter itself is much smaller, lighter, and uses less power than a traditional laser transmitter. NRL developed an MRR lasercom terminal and applied it to small UAVs. An initial flight test using the Dakota UAV was done [14].

1) Ground Station Laser Interrogator

NRL extended the capabilities of the DMOI described above to allow it to track aircraft. Using GPS information, a gimbal provides coarse pointing, putting the aircraft into the FOV of the DMOI's fine steering mirrors, which then optically track the lasercom transceiver.

2) Airborne MRR Lasercom Transceivers

Two basic architectures have been used to allow an MRR system to have hemispherical coverage:

a) Arrayed MRR Transmitters and Photoreceivers: Most airborne MRR systems as well as the robot system described above have used arrays of devices to enable coverage of wide angles. The primary advantage of such systems is the lack of moving parts. However, the longest ranges and highest data rates can only be obtained with cat's eye MRRs described above. These do not lend themselves well to arraying due to their smaller FOVs and larger sizes. Photoreceiver arrrays have additional complications. In order to obtain photoreceiver FOVs that match the MRR FOVs, compromises must be made in the photoreceiver optical design that limit the optical gain, and thus range and/or data rate.

b) Pointed MRR Transmitters and Photoreceivers: An alternative to arrays is using a transmitter and receiver in a gimbal. A single MRR has a FOV large enough to allow the use of a low quality inertial navigation system (INS) and gimbal. This not only allows a very lightweight, low-cost MRR lasercom system, but it also provides a natural progression to longer range and higher data rate systems. This pointing architecture also virtually eliminates the possibility of the sun directly illuminating the photoreceiver.

The intended development path begins with the lightweight cornercube MRR system described here for very small UAVs. With a more accurate INS and gimbal, range and/or data rate can be increased by using a narrow FOV cat's eye MRR. The next step would further increase the pointing accuracy and replace the narrow FOV cat's eye MRR with a second laser, giving further gains in range and data rate. Each increased level of pointing accuracy increases size, weight, and cost.

3) Dakota Wingpod Lasercom System:

MRR transmitters and photoreceivers were installed in modified low-cost, lightweight gimbals. Two wingpods were prepared, each containing an MRR gimbal, a photoreceiver gimbal, a stabilized camera, and electronics. Navigation hardware providing GPS position, inertial sensing, and heading to calculate the pod's pointing were included in each wingpod. The wingpods were duplicates with the exception of a GPS beacon and an RF modem in one wingpod. An on-board processor maintained pointing to the laser ground station. Fig. 6 shows the wingpods on a Dakota UAV.

Navigation information source configuration changes could be made while in-flight for testing purposes. The final weights

of the pods are 3.6 kg and 3.1 kg, including gimbaled lasercom transmitter and receiver, stabilized camera, video compressor/modem, navigation data sources, antennas, pod structure, and mounting hardware. The combined power draws and weights of the pointing and communication components are 6 W and 1 kg per wingpod. To the best of our knowledge, this is approximately two orders of magnitude lighter than any other airborne lasercom terminal reported. The pods are self-contained, requiring only power and an optional GPS antenna feed from the Dakota. The pods were designed to allow for easy adaptation to other similar-sized UAVs.

Figure 6. Dakota UAV with MRR lasercom wingpods

4) Flight Tests:

NRL successfully completed flight tests on a Dakota at Dugway Proving Ground, Utah from June 15-19, 2009. Two pods were carried on the Dakota. The pods operated independently, allowing various configurations to be tested on the same flight. Maximum range was 2.5 km. The data rate on all links was 2 Mb/s. Three types of links were demonstrated:

1) Live video was transmitted to the ground using the lasercom downlink, while pointing and zoom commands were sent to the camera via the lasercom uplink. A frame captured from a 15 frame/second video stream is shown in Fig. 7.

Figure 7. Frame captured from 15 frames/second video stream

2) Video was stored on-board while the aircraft was out of range, followed by download of the video files over the lasercom link when it came back in range.

3) An Ethernet link was established and used for 2-way file transfer and communication with the aircraft.

D. Atmospheric scintillation measurements:

The returned optical power was recorded at a later date during two flights so as to give a measure of the atmospheric turbulence along the double-passage, slanted path of the beam. The scintillation index σ_I^2 was derived from measured variances of the signal recorded over 30 second intervals using the 100 mm diameter aperture of the DMOI and fiber-coupled to a 4 kHz bandwidth photodiode detector. The airborne retro-reflector aperture was 12.5 mm.

For comparison, measurements were also taken along a 0.5 km horizontal path one meter above the ground immediately after the flight using a 30 mm aperture receiver and a 10 mm retro-reflector. A typical probability spectral density (PSD) of the ground link is shown in Fig. 8. As can be seen, the scintillation index, σ_I^2, is moderate at 0.49, and the frequency knee of the PSD is at about 30 Hz.
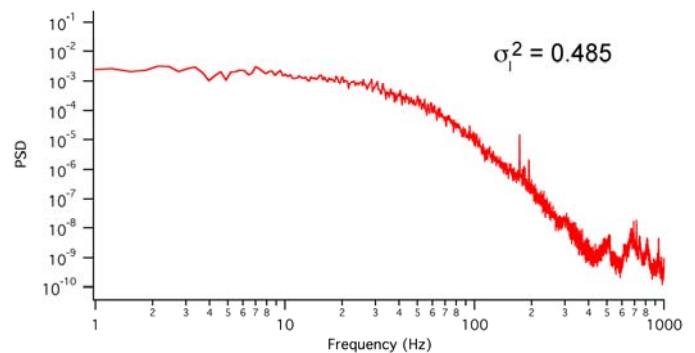

Figure 8. PSD of scintillation for a ground based link at a 500 m range using a 10 mm retro-reflector and a 30 mm receive aperture.

Scintillation data was then taken of the retro-reflector in flight on the UAV with the 100 mm receive aperture tracking terminal. Fig. 9 shows the PSD at a range of 4.3 km. Despite a range that is ten times longer, the scintillation index, σ_I^2, at 0.37, is about the same as for the 500 m ground based link. Aperture averaging due to the larger receiver may play some part here, but the bulk of the effect comes from the higher elevation of the link. The frequency knee of the airborne link is about 300 Hz, ten times higher than the ground based link.
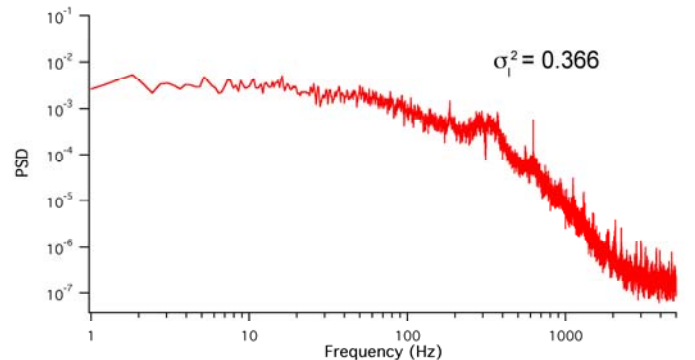

Figure 9. PSD of scintillation of airborne retro-reflector at a 4.3 km range with a 12.5 mm retro-reflector and a 100 mm receive aperture.

Fig. 10 shows the scintillation index values σ_I^2 measured as a function of range as the UAV flew towards the ground station at an attitude of about 2,500 ft. As expected, the scintillation

index drops as the range decreases. The in-flight values of σ_I^2 are low when compared with the $\sigma_I^2 = 0.49$ measured at ground level immediately after the flight, which is also as expected.
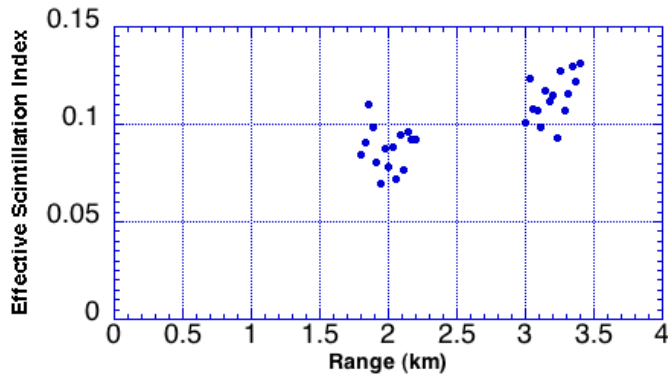

Figure 10. Scintillation index vs. range using 100 mm receive aperture.

This data shows some of the unique challenges faced by airborne links as opposed to ground based links. In general, though the depth of scintillation fades should be less for airborne links, their frequency should be much faster. This may require different choices of protocols for efficient transfer of data and will certainly impact pointing and tracking systems.

IV. CONCLUSION

Free space optical MRR links have many possible applications for military systems. MRR lasercom can be useful in asymmetric situations such as boarding parties, small robots, and UAV platforms which are much too small to carry a conventional lasercom terminal. They offer smaller, simpler, cheaper systems at the cost of range and data rate. MRR systems retain most of the attractive features of FSO, including immunity to jamming, lack of interference with existing RF systems, as well as being LPI/LPD. While NRL has focused on the science and technology of lasercom, we have also emphasized real-world demonstrations. These demonstrations have often illuminated issues that did not show up in lab tests. Demonstrations also show to users that lasercom is a viable technology for their applications. Given the ever-present need for secure communication, the increasing need for higher bandwidth, and the decreasing available RF spectrum, it seems to be a question of when, not if, free space optical links will be used in many military applications.

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