Free Space Optical Communications: Coming of Age

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INTRODUCTION

Information superiority, where for the military or business, is the decisive advantage of the 21st Century. While business enjoys the information advantage of robust, high-bandwidth fiber optic connectivity that heavily leverages installed commercial infrastructure and service providers, mobile military forces need the wireless equivalent to leverage that advantage. In other words, an ability to deploy anywhere on the globe and maintain a robust, reliable communications and connectivity infrastructure, equivalent to that enjoyed by a CONUS commercial user, will provide US forces with information superiority. Assured high-data-rate connectivity to the tactical user is the biggest gap in developing and truly exploiting the potential of the information superiority weapon. Though information superiority is much discussed and its potential is well understood, a robust communications network available to the lowest military echelons is not yet an integral part of the force structure, although high data rate RF communications relays, e.g., Tactical Common Data Link, and low data SATCOM, e.g, Ku Spread Spectrum, are deployed and used by the military. This may change with recent advances in laser communications technologies created by the fiber optic communications revolution. This paper will provide a high level overview of the various laser communications programs conducted over the last 30 plus years, and proposed efforts to get these systems finally deployed.

BACKGROUND

The concept of Free Space Optical (FSO) communications has been around since the late 1960's. Lasers offered the potential for small transmitters and receivers with very high antenna gain (that is, small transmitter spot sizes). Specifically, FSO communication system could be much more efficient and could provide orders of magnitude gains in data rate compared to an RF system of the same size. Unfortunately in the 1970s and 1980s, much of the potential gain in efficiency was lost because of poor electrical-to-optical efficiency, poor optical detector efficiency, and the increased transmitter spot sizes necessitated by

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transmitter pointing error limitations. Also, the lifetime of laser transmitters and some key subsystems available at the time were not good enough for a practical space system. So when all the dust cleared during those decades, the advantages of FSO communications over RF communications were never realized and the latter became the technology of choice for over 40 years. Then the fiber optic communications revolution came.

Although this paper will not address fiber optics communications, free space laser communication has benefited greatly from the solid state lasers and wideband detectors developed for fiber optic communications. For instance, the development of optical detectors with bandwidths on the order of 100 Gbps allows 100 times greater data rate than in the late 1960's. Diode-pumped solid state lasers, with 100 watts of output power, were a big improvement over the few watts of flash-lamp pumped laser power available in the 1960's. Unfortunately, fiber optic systems do not require pointing and tracking, and this area did not benefit from the any research investment by this industry. The result, with the exception of the adaptive optics compensation funded by the high energy laser community, is that not much of the pointing and tracking hardware proposed for FSO systems has changed in last 40 years.

In spite of this last point, FSO communication systems concepts have been developed for a plethora of military and commercial applications. These range from SETI links to extra-terrestrial, links to deep space probes, links to submarines under the arctic ice cap, links between secret agents, and systems with every possible permutation of aircraft, ship, satellite, and ground station links.

The two major military applications that have received the majority of the funding over the last 40 years are the Air Force high data rate backbone networking and Navy Submarine Laser Communication (SLC). These two systems alone have received on the order of a billion of today's dollars, although most of this was spent during the 1980's. Yet, even with this large financial investment, there is not now, nor has there ever been, an operational military optical communication system implemented.

AIR FORCE HIGH DATA RATE FSO COMMUNICATIONS

Starting in the late 1960's, the Air Force (AF) initiated efforts to develop FSO networks for high bandwidth ISR information dissemination. The first big effort was their 405B program, which was intended to provide gigabit data rate optical communications between high orbit satellites like those deployed as part of the Defense Support Program (DSP). Field tests of FSO links between a high flying aircraft and a ground based receiver were conducted over ranges on the order of 100 Km. The downlink used a doubled Nd:YAG laser operating (532 nm) at 1 Gbps, and the uplink used a Nd:YAG laser (1.06μm) operating at was 20 Kbps. The former laser used a two-bit per pulse, short pulse, modulation format, which allowed a gigabit from a 500 Mega-Pulse per Second laser. These successful field tests let the Air Force to begin an optical satellite transreceiver development, intended to be flown on a high altitude satellite. Unfortunately, the development program failed miserably for numerous reasons. The prime contractor was inexperienced in optical satellite systems development and the technology available in the 1980 was not up to what was required, as noted above. This set space based, high data rate optical communications system development back at least 20 years. Alternately, the AF turned to airborne laser communications.

What follows is a brief synopsis of several laser communications tests conducted by AFRL and is predecessor organizations starting in the early 1980's [References 1-5]. In addition, a summary of laser communications tests and associated technical papers was written by Major Anne Hocutt and is available as Wright Laboratory Technical Memorandum, WL-TM-93-109, entitled "Summary of Wright Laboratory Airborne Laser Communications Efforts" published 30 July 1993.

HAVE LACE (Laser Airborne Communications Experiment)

This effort began in 1983 with the objective of determining the feasibility of air-to-air laser communications between two aircraft utilizing small, solid state optical communication transceivers for low and medium data rates (Ref. 1). The communication terminals consisted of two gyro-stabilized gimbals with a cassegrain-type receive telescope with an effective aperture of 5 inches and transmit optics with an effective aperture of 1.5 inches, Figure 1. Range requirements were 100 miles at 30,000 feet. Objective data rates were 19.2 to 1.2 Kb/s with a bit error rate of 10^{-6}. The system consisted of a 2 m electronics rack and gimbal; see Figure 2. If one looks closely at Figure 2; the edge of the gimbal yoke can be seen between the rack and aircraft window. The terminals consisted of a laser transmitter powered by a 100 watt peak-power diode array operating at the infrared wavelength of 904 nanometers (Ref. 2). Flight testing of the HAVE LACE system occurred in late 1985 and early 1986 in which the equipment was installed in two C-135 aircraft. The gimbals and operator stations were installed in close proximity of each other with the gimbals mounted behind large windows on each aircraft. Initial acquisition was done manually, operators had to enter coordinates for the other end of the link and the gimbals would begin a search for the other end. HAVE LACE was successful in meeting its technology objectives and demonstrated that air-to-air laser communications was possible using small off-the-shelf components [Reference 1].

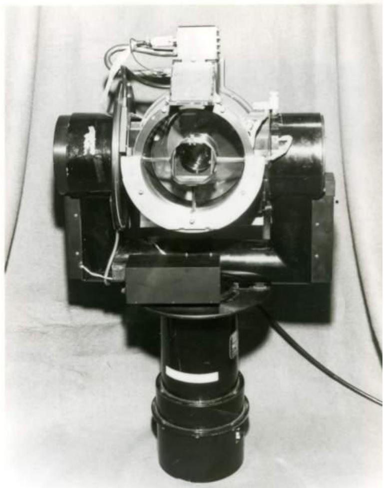

Figure 1, HAVE LACE Gimbal

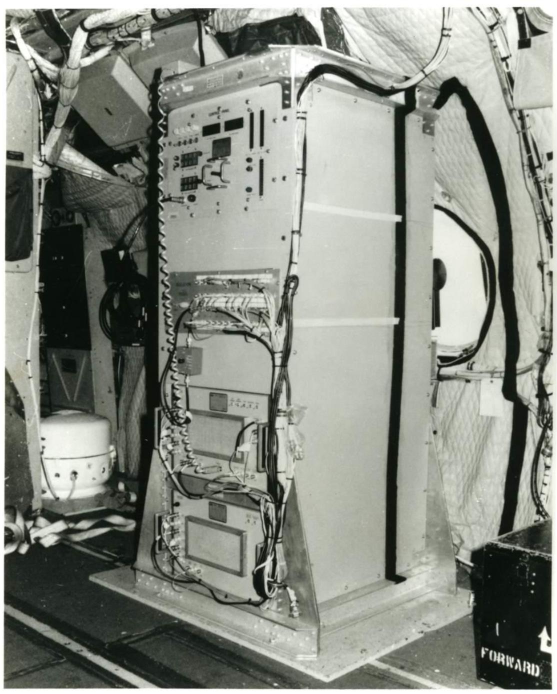

Figure 2, HAVE LACE Electronics

Following the success of HAVE LACE, AFRL/SN conducted a limited test using equipment from the Ballistic Missile Defense Organizations (BMDO) Innovative Science and Technology Office to evaluate two slightly modified terminals designed for space applications. This test utilized terminals sighted on Haleakala and at Mauna Loa located 150 kilometers away. One terminal was mounted on a six post motion table to emulate aircraft vibration and displacements that could be experienced in flight. The terminals used in this test were capable of 1.1Gbps full duplex communications and utilized an RF channel to begin the acquisition process. The hardware demonstrated in this test formed the foundation for what became a follow on program to develop a suitable air-to-air system (Ref. 3).

Recc-Intel Cross Link (RILC)

This effort began in late 1995 as an AFRL/SN program to develop an air-to-air crosslink system capable of communicating between two aircraft operating at 40,000ft with separation ranges of 50 to 500km. Objective data rates were 1Gbps with a bit error rate (BER) of 10-6. The time to acquire and establish the communications link was 10seconds from initiation by a master control aircraft (Ref 3). The RILC terminal was a clean sheet design and consisted of an optical bench containing transmit and receive optics mounted on a two axis limited displacement gimbal ring. The limited displacement gimbal ring was capable of ±6 degree fine azimuth and elevation steering. This limited gimbal/optical bench assembly then sat inside a large field of regard two axis gimbal shell that accomplished coarse steering for the whole assembly and protected the inner gimbal from wind loads Figure 3. The RILC units operated in a master slave arrangement in which a radio system transmitted terminal coordinates between systems to initiate the acquisition cycle. The system then utilized a coarse/fine beacon arrangement in which the coarse system brought the system into initial fine track region and the fine beacon then brought the system into final track. RILC utilized CCD arrays for its tracking system instead of position sensing detectors (Ref. 4).

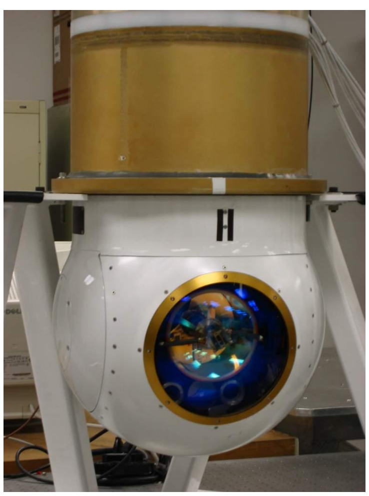

Figure 3, Recce/Intel Laser Crosslink Turret

Unfortunately, because of programmatic and technical issues the RILC effort ran into development problems and only limited ground testing occurred with the system at White Sands Missile Range in 2004 and at Wright-Patterson AFB in 2005. Several issues resulted in the lack of interest in further developing the RILC system. The system utilized 810nm and 850nm based components and had fewer suppliers since commercial telecom components had shifted to

1550nm. Another problem with the RILC system was the excessive size and weight of the gimbal system. The turret assembly alone for the RILC weighed approximately 150lbs. Therefore development of RILC was halted in 2005.

A different approach to laser communications terminal development was undertaken in 2003 by AFRL/SN. This approach would attempt to leverage as much commercial off the shelf hardware as possible to avoid the obsolescence that occurred in RILC. It would also attempt to utilize commercial gimbals that were now available in the market to leverage existing pointing and stabilization systems. This effort became the Ultra-Wideband Laser Communications for Intelligence, Surveillance and Reconnaissance effort. The objective of this effort was to integrate a 1550nm based laser communication system into a L-3/Wescam MX-12 gimbal that was capable of 2.5Gbps full-duplex and a BER of 10-6 and operate at 40,000ft and at ranges of 100km (Ref. 5). Limited ground testing of these terminals occurred at Wright-Patterson AFB and uncovered deficiencies in the optical train that had to be rectified. Upgrades are in progress with a flight test of the turrets now slated for late summer 2008, Figure 4.

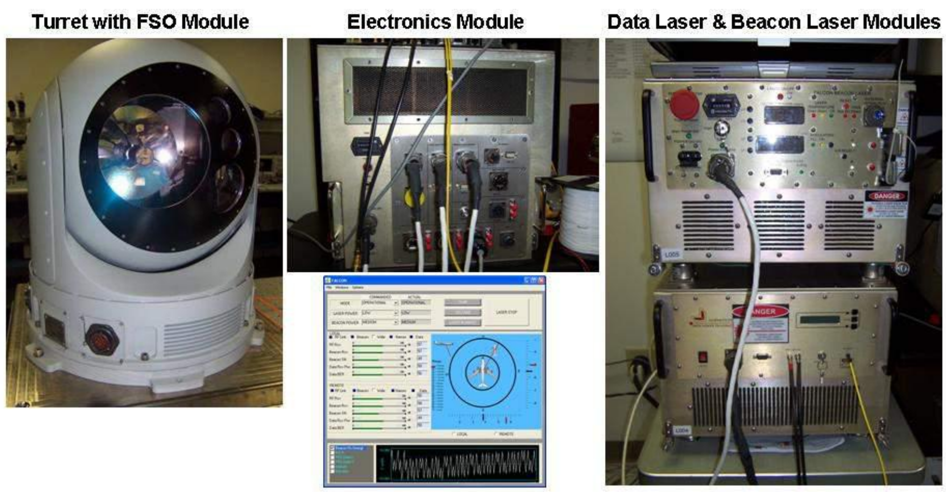

Figure 4, Laser Communications System utilizing MX-12 Turret

The maturity of technologies available for AFRL to build lasercom turrets using COTS equipment has not been lost on the acquisition community. The Airborne Lasercom Terminal (ALT) program executed by the MILSATCOM Terminals (ESC/MC) Systems Program Office was conducted to assess the Technology Readiness Levels of airborne lasercom terminals that could communicate with the Transformational Communications Satellite (TCS) system from high flying aircraft such as the U-2 or RQ-4 Global Hawk. The initial program phase let four contracts to construct and test optical heads in order to determine Technology Readiness Levels and assess compatibility issues with the Family of Beyond Line of Site Terminals (FAB-T) architecture. The goal was to have a terminal ready by the initial Transformational Satellite IOC date in FY09. However, due to slips in the TCS program the follow on ALT effort to the initial four demonstration contracts was delayed. However, the results of the initial study did show that the maturity of the components critical to acquisition, tracking, and pointing technology was sufficiently mature to address the air-to-satellite tracking problem.

The one issue that does keep arising in all the above programs is the impact of aero-optics disturbances on the performance of the laser communications terminal. This is a problem that does not lend itself well to analytical analysis since computational fluid dynamics (CFD) codes require fine grids in order to capture the turbulence scales of interest and generally are not designed then to hand off a solution to calculate index of refraction variations along a particular path. Though there has been much work done to do just this, the anchoring of the CFD and optical path codes to actual tests is just now getting underway. Wind Tunnel testing also is being conducted but much of this work is focusing more on High Energy Laser applications and results have not been widely disseminated. The real problem is that aero-optics impacts really can't be addressed until actual flight test due the impacts of location and installation on the airflow over the aperture. Therefore, the real test of laser communications will come not from ground demonstrations but when terminals are finally installed on aircraft and performance assessments made in flight.

EUROPEAN & JOINT HIGH DATA RATE FSO COMMUNICATIONS

European and joint U.S.-European satellite laser communication systems are also in development. In 2006 a 5.5gbps, 142 Km, optical link between two mountain tops in Spain was tested. This system is unique in that it uses coherent (Homodyne) optical detection, which is seldom used in U.S. systems. The hardware used was identical to that being integrated as a secondary payload on the German government's TerraSAR-X radar Earth observation satellite and the U.S. Missile Defense Agency's Near Field Infrared Experiment (NFIRE) NFIRE was launched in April 2007, and TerraSAR-X was launched in June 2007.

The laser communications packages are not related to either satellite's prime mission. TerraSAR-X is designed as an operational Earth observation system for use by the German government and commercial industry. NFIRE is intended to develop the means to distinguish the body of missiles in their boost phase from their exhaust plume. Once in orbit, the two laser terminals will attempt to communicate with each other in the more laser-friendly environment of low Earth orbit.

The use of laser optics for communications has yet to fulfill its European backers' long-held hopes for military or commercial space applications. But several European governments, notably Germany and France, continue to invest in it, mainly for its potential to speed communications between low-orbiting satellites and their ground controllers, even when they are on opposite sides of the Earth; between satellites located in low-Earth and the higher geostationary orbit; and between unmanned vehicles or aircraft and geostationary-orbiting satellites.

SUBMARINE LASER COMMUNICATIONS

The laser communication systems concept discussed above were almost all chosen because of the reduction in λ/D that they allowed. Reducing λ/D would allow both increased data rate for the same laser power, and would make the links more covert.

Starting in the late 1960's, the Navy became interested in developing a communication system that would send EAMs (Emergency Action Messages) to all our ballistic missile submarines (SSBM) at depth in a few minutes. The existing VLF/ELF communications systems at that time required the SSBMs to come near the surface and drag a long antenna which could make them detectable by the enemy. Although it is possible to use VLF/ELF links to communicate with submarines at depth and speed, the data rates were very low and the transmitters requires a very large antenna, e.g., the Navy's ELF facility in Michigan used a 159 mile long antenna. For these and other reasons, this RF approach fell into disfavor and alternatives to VLF/ELF were encouraged by the Congress.

In 1976, the Navy and DARPA established a program to look at the other part of the spectrum that penetrated ocean water, the blue-green portion of the visible light spectrum. This was the birth of Blue-Green Laser Communications, aka, SLC. The SLC system is different than nearly all of the other laser communication systems because it does not require small transmitter spot sizes. An SLC downlink spot size might be on the order of 1000m rather than the few meter spot sizes used for high data rate laser links. Two observations made this concept even more attractive, in addition to the light being in an optimum water transmission band.

The first was that on a cloudiest day, the light attenuation for plane waves is not greater than about 12 dB. Hence, if one could use scatter light to transmit information, one would have significantly lower link losses over the use of the unscattered direct beam, and communications at depth and speed was possible.

Second, the attenuation of optical plane waves in ocean water did not follow the equation $\exp(-KD \csc \Theta)$, where $K \equiv$ Diffuse Attenuation Coefficient, D

≡ Depth; csc ≡ cosecant and Θ ≡ angle of propagation relative to Nadir. Rather, it followed the relation, $F_w(\Theta)\ \exp(-KD)$ where

$$F_w(\Theta) = 1-9.72\times10^{-4}(\Theta) - 4.28\times10^{-4}(\Theta^2) + 6.04\times10^{-6}(\Theta^3) - 4.28\times10^{-8}(\Theta^4)$$

This relates to the well known "man-hole effect" in diving and accounted for the much lower loss seen at depth for sunlight, no matter whether the sun was rising, somewhere in the sky or setting. For some situations, the reduced loss is on the order of 30-40 dB. Once again, one would have significantly lower link losses than expected, and communications at depth and speed was possible. Figure 5 compares this equation with experimental data recorded at depth.

During its 15 year life, the SLC program had many names (Submarine Laser Comp, Satellite Laser Com, TALC, SLCAIR, Project V, Blue Green, etc) and did a number of field demonstrations over the years [Reference 6-12]. It demonstrated communication over the full range of submarine depths (using small transmitter spots). It communicated through clouds, turbid water, ice, snow, etc. It demonstrated duplex communications, although uplink covertness remains an issue. One of these programs, TALC, created the critical enabling technologies to make this concept exciting to the Navy and is the basis for the rekindled enthusiasm for SLC today [References 13-19].

TACTICAL AIRBORNE LASER COMMUNICATIONS

In October 1989, the Congress directed that DARPA conduct expeditious demonstration of a two-way optical communications link using a specific high-altitude, long endurance (HALE) aircraft and Advanced Development Model (ADM) blue-green laser technology. It was felt that an airborne communications capability would be more affordable than a satellite-based one. The program was called Tactical Airborne Laser Communications (TALC). The goals of the TALC program were to establish the utility of a TALC system for sensor link communications, and to demonstrate example that are potentially lightweight, prime-power efficient and affordable. The Congress suggested that a High Altitude, Long Endurance (HALE) aircraft, such as the Boeing CONDOR, be used by the Navy for tactical operations and may be a lower cost alternative to Space-based SLC.

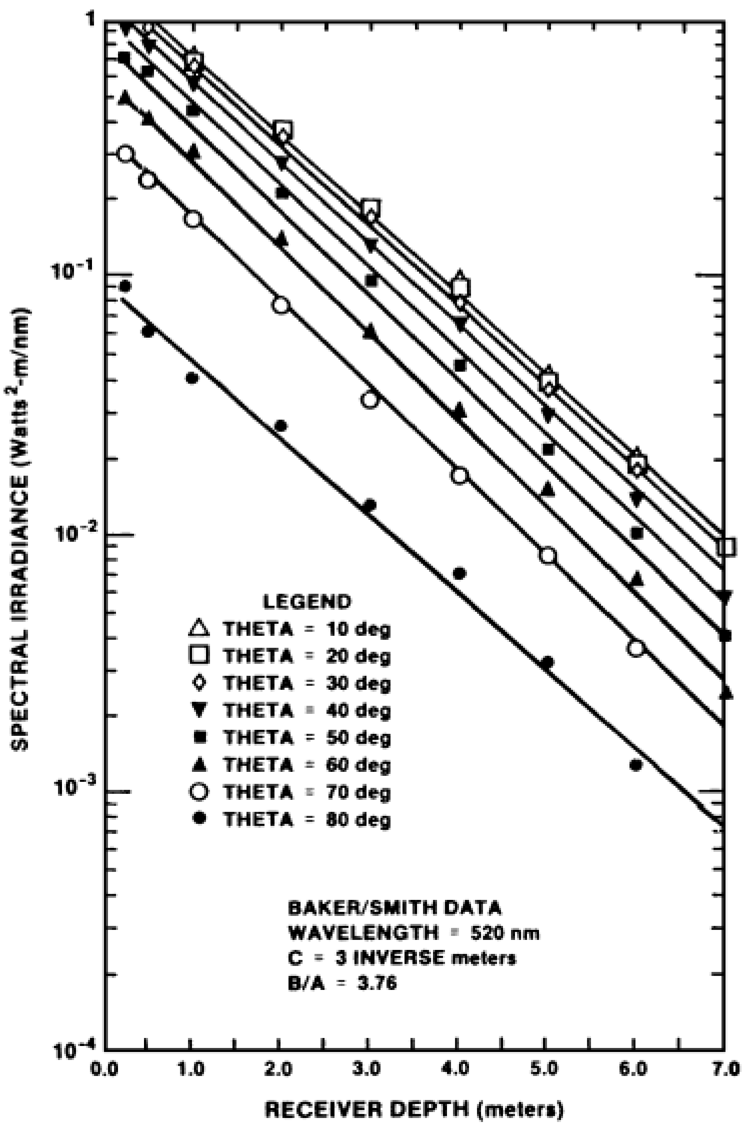

Figure 5, Comparison of $F_w(\Theta)$ and Experimental Data

Per the Congressional language, TALC was required to address the four major concerns about laser communications, whether airborne or space-based:

- Affordability
- Technology maturity for immediate application
- Reasonable data transfer rate
- Uplink vulnerability to the submarine

Based on a first-order analysis of TALC and its utility, DARPA initiated an aggressive 18 month program to meet the Congressional guidance. Experiments were conducted between a P-3 and the USS Dolphin off San Clemente Island, PMRF. Sea States varied from 4 to 6, and cloud conditions were standard

Southern California Stratus Clouds/layer. The following TALC objectives were achieved in the 1991 experiments[1]:

Achieved	Objectives to be Demonstrated
✓	Duplex Laser Communications
✓	Uplink-Initiated Communications
	Downlink-Initiated Communications [1]
✓	Acquisition and Tracking
✓	Nadir angles greater than 60°
✓	Nadir angles greater than 70°
✓	Operation of diode-pumped green laser in field
✓	Operation of blue laser in field
✓	Operation of Deep-Red Hybrid PMTs in field
✓	Pulse-summing to explore LPI techniques
✓	Scattered light measurements to study LPI issues
✓	Verification of system models
✓	Measurements of optical communications properties of night
✓	Duplex communications, not interweaved
✓	Scalability to space borne systems
✓	Scale ability to HALE systems
✓	Scalability for utility analysis of operational systems

Figure 6 shows one of the authors viewing TALC airborne hardware and the first diode-pumped solid state laser, which was quite controversial at the time.

TALC's pioneering achievements were:

- Uplink laser communications from a submarine
- Duplex laser communications between a submarine and an airborne platform
- Field use of a sub-safe certified, optical hull penetrator in a submarine
- Use of error correction coding in submarine laser communications
- High nadir angle, extended duration laser communications to a submarine
- LPI-Related measurements made during submarine laser communications
- Field use of diode-pumped solid state laser with space potential (Over 33 million shots without laser degradation)
- Field use of solid-state blue laser operated inside the submarine
- Measurement of ocean optical communications performance from submarine both day and night

[1] Downlink initiated communications was not achieved because of schedule delay imposed by bad water pump on USS DOLPHIN

0.5J @ 20 Hz, 532 nm center wavelength, and ~2.5% wallplug efficiency

Figure 6, TALC Airborne Hardware Installed on CV-580.

During FY1989-1991, the DARPA TALC and Advanced Space Technology Programs developed and demonstrated the following key SLC components:

- Diode-pumped, Solid State Lasers (High Electrical Efficiency)
- Improved Cesium Atomic Line Filters (High Light-to-Light Conversion)
- Deep-Red Photo Multiplier Tubes (PMTs) (Efficient photo-detector)
- Infrared to water transmission optimized blue light

The combined improvement in SLC performance from these achievements has the potential for a large net prime power! This would allow the size, weight and volume of a SLC satellite to be significantly reduced. With reduced size, weight and volume, the estimated cost of any SLC system will be dramatically less (satellite costs were approximately $55,000 per lb in FY1991).

In a subsequent meeting to review TALC results with one of the authors and Dr. Gary Denman, the DARPA Director at the time, the Honorable Gerald Cann, the Assistant Secretary of the Navy for Research, Engineering and Systems [ASN(RES)], established a $113M Advanced Technology Demonstration (ATD) for a Geosynchronous Green Laser SLC payload development and demonstration. Unfortunately, with the demise of the Soviet threat shortly thereafter, the Chief of Naval Research and Space and Naval

Warfare Command cancelled the ATD and all SLC technologies were “put on the shelf.” Given new submarine threats to the fleet, the Navy has resurrected the TALC concept and is funding efforts to redevelop the key technology components shelved over 15 years ago, i.e., PMW-770’s Optical Laser Communications (OLC) program.

SLC downlinks require large FOV submarine receivers with very narrow optical bandwidths. Although there are receiver issues, the main problem with SLC systems was always a wall-plug efficient solid state laser. A wise man once said “do not start a laser communication program if you do not have a laser”. In recent years there have been advances in both green and blue laser technology, and DARPA is presently funding solid state blue laser development, optimized for both water transmission and Cesium Atomic Line Filter. Results from this effort are promising, and support the prime power reduction number established in TALC.

SUMMARY

Information superiority, where for the military or business, is the decisive advantage of the 21st Century. While business enjoys the information advantage of robust, high-bandwidth fiber optic connectivity that heavily leverages installed commercial infrastructure and service providers, mobile military forces need the wireless equivalent to leverage that advantage. This paper providef a high level overview of the various laser communications programs conducted over the last 30 plus years, and proposed efforts to get these systems finally deployed.

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