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Review Article

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High Speed Laser Based Intersatellite Link Systems for Harsh Environment of Space

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Abstract

This paper will focus on the trends for the space-based lasers, optics and terminals used in the intersatellite networks. Reviewed and evaluate the recent development in the space-based laser technologies and the critical parameters that are employed for successful high-speed intersatellite communications systems.

Fiber optics and photonics technology including lasers increasingly being used in aerospace applications and many challenges are involved, since designing for aerospace is very different than for the earth environment. Satellites are much more challenging and for their intersatellite solutions have to contemplate more specific requirements such as space radiation attacks, operation in harsh environment of space and achieving weight, power requirements and reliability for space are few to consider. Therefore it is important to design a system to defend against the radiation from ionizing, gamma, and other attacks. There are numerous methods to protect them from radiation, including shielding, error correction, and using radiation resistance shielding and radiation hardening.

Building laser for high speed communications network for the harsh environment of space using optical links in space has proven to be complicated task and many such schemes were tried without success in the past. Space-based optical communications using satellites in low earth orbit (LEO) and Geo-synchronous orbits (GEO) hold great promise for the proposed Internet in the Sky network of the future. However in the last few years, there has been impressive progress made to bring the concept of laser-based intersatellite systems to fruition in civilian and government-non classified projects. Laser communications offer a viable alternative to established RF communications for inter-satellite links and other applications where high performance links are a necessity. High data rate, small antenna size, narrow beam divergence, and a narrow field of view are characteristics of laser-based systems and they are just few numbers of potential advantages for system design over radio frequency communication.

Introduction

For the harsh environment of space application building a high speed communications network using optical links in space has proven to be an extremely complicated task and many such schemes were tried without success in the past. A typical mission scenario is a communication return link between a LEO (low earth orbit) and a GEO (geostationary earth orbit) satellite at 45,000 km distance, 500 Mb/s data rate, and 10 bit error rate. Space-based optical communications using satellites in low earth orbit and geo-synchronous orbits hold great promise for the leading edge internet in the sky network of the future. In the last few years, there has been impressive progress made to bring the advanced laser communication to commercial and government agencies. The successful trial tests in space conducted by NASA, the European space agency and Japanese space agency are few examples of these achievements. Their experiments showed the time for successful deployment of this technology is in the realm of reality. The US military has a lot of interest in such systems for building the next generation Transformational Satellite Systems commonly known as (TSAT). To-day's market for space based laser communications is primarily Inter-Satellite Links which are the main focus of this paper. There is also a need for high data rate (Multi-gigabit) space-earth links, although the propagation effects due to atmosphere and weather make it a more difficult link to implement in spite of the many advance made in Adaptive optics technology and Signal Processing algorithms.

The emerging development of observation for orbiting satellites are LEO–LEO or GEO–GEO, and other low earth orbit satellites capable of greatly enhanced high volume data acquisition capabilities is expected to increase the need for high-speed data transmission. This need is compounded by the limited time window available for direct communication between a LEO satellite and a ground-based antenna and the resulting requirement for high-volume data transmission. In addition, the size of the RF communication terminal increases with the transmission speed.

While the optical links in space can boast to an incredible number of high technology achievements as is the evidenced in the optical terrestrial networks, however there still remains formidable challenge to test, qualify and successfully integrate in real world full scale deployment. This paper examines the various aspect of the optical intersatellite development. Figures 1 and 2 shows communication by laser beam between a LEO satellite and a data relay satellite in geostationary orbit GEO [1-2].

Figure 1: Intersatellite Laser Communication Systems

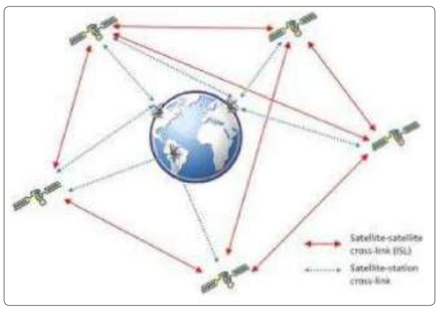

Figure 2: Space Based Laser System for Inter-Satellite Communication

Development of Laser Communication

The development of laser communication began at McDonnell Douglas Electronic System Company MDC (currently the Boeing Co.) in late 1960s under both U.S. Air force and MDC's internal R&D funding. Laser communication at short wavelengths theoretically holds great advantages over the best achievable communication in the RF spectrum. The extremely low beam divergence minimizes signal loss and narrow receiver (field of view) made it extremely difficult to jam.

- In 1981, McDonnell Douglas Electronic System Company (currently the Boeing Co.) was selected by the U.S. government to bring laser communication into production by developing a satellite-to-satellite crosslink. The system was installed on an already existing satellite. In order to minimize any impact to the satellite, the laser crosslink needed to be a stand-alone, bolt-on package, which provided terminal control and could operate from raw spacecraft power. One of the key advantages of this system over other communication was due to the high directivity of laser for the accurate directional nature of lasercom which made it difficult to intercept and jam communication, resulted from the short wavelengths of visible and nearly infrared energy. Their system had the following key features [3]:
- Low probability of data intercept and error,
- Survivability as results of the narrow beam width,
- Jam resistance,
- Reduction of reliance on foreign ground stations.

Another feature was the use of lasers in transmitting optical data that took the advantage of its small wavelength and low beam divergence to send highly directed signal over significant distances with controlled losses in intensity. Furthermore, the high directivity of the laser helped in resistance to jamming communication between satellites, or between satellites and ground stations [3]. Figure 3 shows MDC satellite development during 1980s.

Lasers have been considered as light sources for a large number of space applications since their realization in 1960. In future global telecommunication scenarios, optical space-to-space communication links are considered as a viable means of transferring data at high rates between satellites. Among the various types of lasers available, semiconductor lasers are especially attractive for harsh environment of space applications since they provide small size, high efficiency and long lifetime.

Figure 3: Shows, McDonnell Douglas Electronic System Company MDC (currently the Boeing Co.) satellite development in 1980s

Previously laser application was restrained due to poor spatial and spectral beam quality and low output power. Today after all, laser have reached such a high standard of performance that they are seriously are considered as a light source in space borne systems.

Figure 4 illustrates the block diagrams of the essential features of a space-to-space laser optical communication system using GaAlAs lasers in a transmitter and receiver. The incoming signal is mixed with a local oscillator (LO) laser and the transmitter uses the signal with the information to be transmitted to modulate a transmitter-laser; at the receiver, the resultant IF signal is processed to recover the original signal much as a radio frequency (RF) signal is recovered. Mixing the very weak signal and the strong LO at the receiver raises the signal level well above the noise level of subsequent electronics [4].

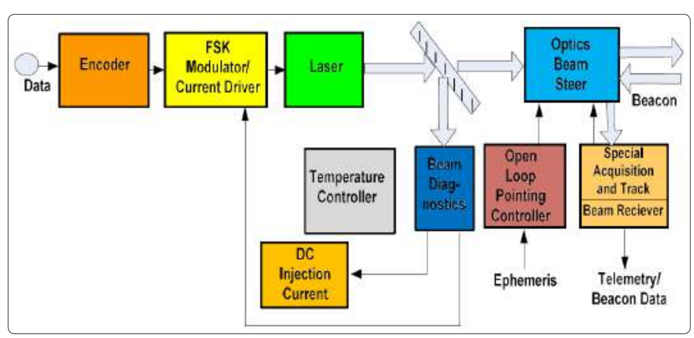

Figure 4: Block diagram of transmitter and receivers of intersatellite optical communication [4]

European Intersatellite Communication Systems

In summer of 1977, the European Space Agency (ESA) placed a technological research contract for the assessment of a high data rate laser links in space. When ESA considered optics for inter-satellite communications, virtually no component technology was available to support space-system development.

By end of 1970's, semiconductor diode lasers operating at room temperature became available, providing a very promising transmitter source for optical inter-satellite links. This resulted for the French National Space Study Center (NES) to look into a laser-diode-based optical data-relay system, which began the development of Semiconductor-laser Inter-satellite Link Experiment (SILEX). In 2001, ESA performed the world's 1st SILEX. After having invested into SILEX and its success the European industry developed laser communication terminal (LCT) for the commercial market [5].

Experiment SILEX between Advanced Relay and Technology MISsion Satellite (ARTEMIS) and the Earth observation satellite SPOT-4, shows that optical communications technologies and reliably of these satellites in the harsh environment of space. As early 1989 European Space Agency has placed strong emphasis on the development of Nd-YAG laser-based coherent communication system technologies. Since then, hundreds of laser communication links have been established which prove that the extremely demanding pointing, acquisition and tracking requirements associated with optical wavelength can be reliably mastered and that laser communication technologies are a viable alternative to radio communications in space. Figure 5 (a) shows the SILEX inter-satellite link between two satellites SPOT-4 and AREMIS and Figure 5 (b) shows the first image of transmitted by the SILEX [5-6].

Figure 5 (a): Schematic depiction of SILEX inter-satellite link between SPOT-4 and ARTEMIS. (b). First image transmitted by the SILEX optical data-relay system, shows part of the island of Lanzarote, Canary Islands, and Spain [6].

The fact that data-relay scenario has emerged as the most important application for optical communication technology, since it is the only way to retrieve the data generated by today's Earth observation satellites operating with synthetic aperture radar or multispectral imagers, German Space Agency (DLR) seized the opportunity to embark on ESA's latest telecommunication satellite Alphasat, which consists of a Ka-band terminal for space to ground links and laser communication link (LCT) for the intersatellite links. This satellite has an updated version of the ones flown on TeraSAR-X and NFIRE with increased telescope diameter and transmits laser power. This increased LEO-GEO intersatellite distance to 45,000 km with net data rate of 2.8 Gb/s and on the satellite to ground link it will support K-band terminal of 600 Mb/s. It has an impressive 11 m diameter L-band reflector. See Figure 6 [6].

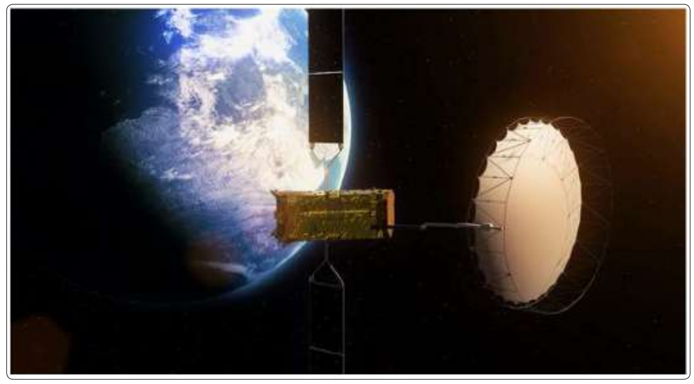

Figure 6: Alphasat spacecraft showing its large 11 m diameter L-band reflector [6]

In summary 30 years of technology endeavor, sponsored by European space agencies and ESA, has put them among a leading position in the domain of space laser communications. SILEX is one of the most visible results of their effort.

USA and Europe Advanced Optical Intersatellite Laser Communication for Harsh Environment of Space

Advanced laser technology enables high-speed data links in space for intersatellite communication. Due to extremely harsh environment of space the laser communication terminal (LCT) was developed to withstand the high acceleration forces and vibrations during launch. In 2007 teams from USA and Germany have succeeded in setting up a laser-optical data link between two satellites. The Near Field Infrared Experiment (NFIRE) satellite (USA) and TerrSAR-X satellite (Germany) (see Figure 7) [7].

These two satellites located 5,000 kilometers apart, and maintaining an error-free connection at transmission rate of 5.5 Gb/s. This is equivalent of transmitting 200,000 pages of text per second or the content of 400 DVDs in a single hour. Their laser subassemblies were tested under extremely tough conditions on ground with temperature range of -35°C to 60°C, acceleration forces 1,300 g (1,300 times Earth's gravity) with constant bombardment with gamma rays. The laser terminals require less than 130 watts of power to operate, just little more than a light bulb. The US satellite NFIRE and TerraSAR-X pass each other several times a day in low Earth orbit (LEO). At each pass, a laser link can be established for up to 20 minutes. One of the most challenging tasks is pointing the laser beam precisely in the direction of the partner satellite at speed of 25,000 km/h and up to 5,000 km away [7].

Laser communication terminal (LCT) high reliability and low mass, size and power consumption is also designed for easy handling, integration and test in order to simplify the LCT's integration on its host spacecraft. Consequently, the LCT consist of a single unit only, See Figure 8 [8]. For more technical information on LCTs for spacecraft described in this paper see Table 1 [6].

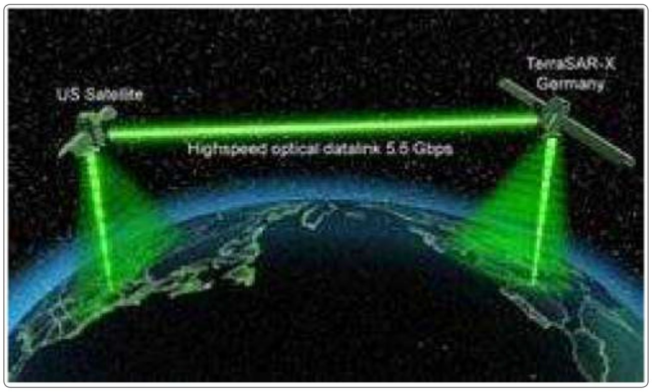

Figure 7: Intersatellite links between US Satellite and European Satellite using high speed laser [7]

Another recent development of Tesat Laser Communication Terminals (LCT's) has been used on LEO, LEO-to-LEO, LEO-to-ground, and LEO-to-GEO and UAV-to-GEO links. This satellite is based on homodyne binary phase shift keying (BPSK), a highly robust and sun light immune modulation scheme, the LCT's offer a full duplex data rate of 5.625 Gb/s at a high rate lower than 10-9 bit error rate. LCT used a frequency stable Nd:YAG laser on a wavelength of 1,064 nm with robust and reliable operation. This satellite has been developed for very harsh environment of space. See Figure 9 [8].

In comparison to LEO-GEO scenario, the LEO-LEO constellation allows to verify the performance under more demanding dynamic constraints: larger tracking angles, varying link distance, Doppler shifts to be compensated, and larger point-ahead angles to be adjusted. The LCT performance were verified under realistic environmental conditions over several years in regard to link quality, bit error rate, acquisition and allowed the evaluation of link budgets and the models used for tracking errors, atmospheric channel to verify basis link budget assumptions with measured empirical data [8].

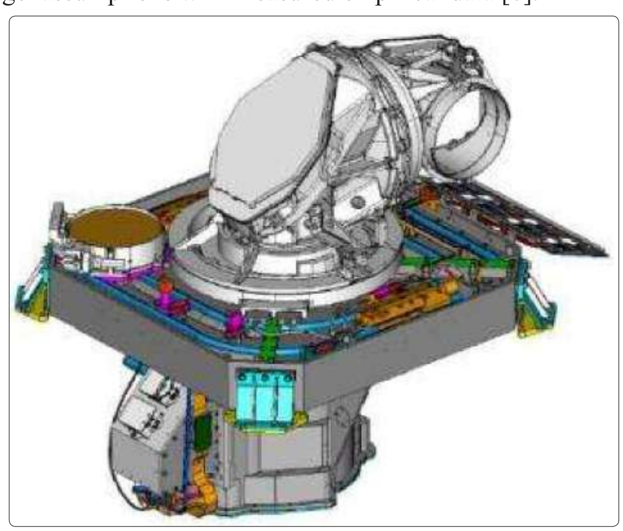

Figure 8: Tesat-lasercom communication terminal developed for very harsh environment of space and has been used on LEO-to-LEO, LEO-to-GEO and other intersatellite links [8]

Further cooperation between USA and Germany demonstrates the verification of these satellites. For LEO-to-ground the communication links based on homodyne BPSK have been established from NFIRE to Hawaii (mount Haleakala) with a receive telescope of 60 mm diameter in the optical ground station (OGS). Figure 9 illustrates the location of the first intersatellite link between the two satellites. The green color shows the link trajectories which vary between 3,700 km and 4,700 km [8].

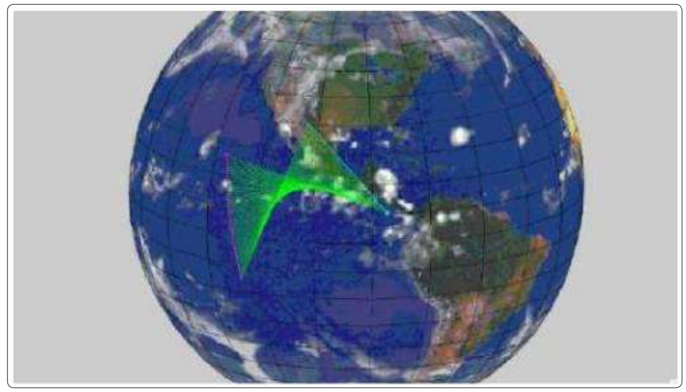

Figure 9: Location of first NFIRE and Terra SAR-X intersatellite link [8]

Japanese Intersatellite Communication Systems

The Japanese's Optical Inter-orbit Communication Engineering Test Satellite (OICETS) system shown in Figure 10 is the result of JAXA optical inter-orbit and the ESA geostationary (ARTEMIS) which was made by European. The development verified the importance of large volume optical communications between satellites, and the crucial capability for future space activities, including global-scale data acquisition from Earth observation satellites and stable communications for manned space missions. In their design the following important experiments were considered [9]:

1. Evaluating on-board equipments capabilities under space environment
2. Acquisition and tracking mechanism using stars and planets
3. Inter-orbit optical communications analysis
4. Evaluate the effect to communication link
5. Measurement of micro vibration of satellite
6. Orbit determination by laser ranging
7. Evaluation of inter-satellite optical communication equipment on the ground, tracking performance
8. Measurement of data accusation of the atmosphere fluctuation for low orbit satellite at communication wavelength

The OICETS is controlled via S-band inter-orbit link with ARTEMIS and DRTS or S-band direct links with tracking communication stations using conventional radio frequency signals to transmit and receive telemetry, command and mission data. The satellite carries an optical communication terminal called the laser utilizing communications equipment (LUCE) and functions in orbit. The mass of this equipment is 146 kg and its power consumption is 226 W during operation. It consists of two units: LUCE-O which is the mobile part and LUCE-E. The LUCE-O has the following equipment: Optical antenna, internal optics, and two-axis gimbals mechanism call coarse-pointing mechanism. The internal optics consists mainly of laser transmitter, laser communication receiver, fine and coarse pointing and sensors. The optical antenna is a center-feed Cassegrain mirror-type telescope with the primary mirror of 26 cm diameter. In order to maintain a highly accurate alignment and to ensure high performance of the optical devices, the temperature of optical bench is carefully controlled by a thermal control system. Figure 10 illustrates free-Space laser communication, the Japanese experience of OICETS Satellite system [9].

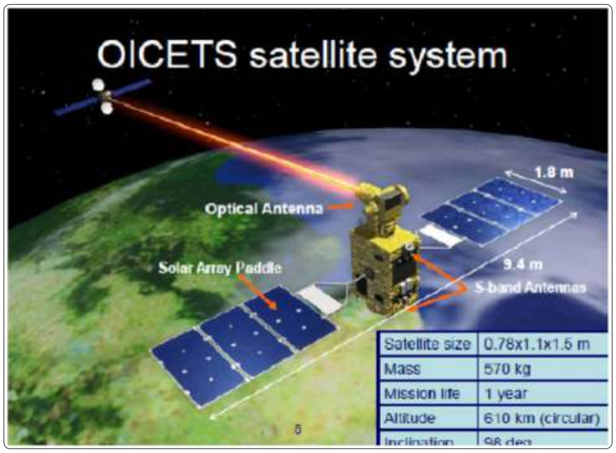

Figure 10: Free-Space laser communication, Japanese experience of OICETS Satellite System [9]

Table 1: Technical Data of Laser Communication Terminal for Spacecraft Described in this paper [6]

	ARTEMIS	SPOT-4, OICETS	TerraSARX, NFIRE	Alphasat
Rx diameter	250 mm	250 mm, 260 mm	125 mm	135 mm
Rx data rate	50 Mb/s	None, 2Mb/s	5.6 Gb/s	2.8 Gb/s
Rx wavelength	847 nm	819 nm	1064 nm	1064 nm
Tx diameter	125 mm	250 mm, 130 mm	125 mm	135 mm
Tx power	35 mW	70 mW, 100 mw	1 Watt	5 Watt
Tx data rate	2 Mb/s	50 Mb/s	5.6 Gb/s	2.8 Gb/s
Tx wave length	819 nm	847 nm	1064 nm,	1064 nm
Link distance	<45,000 km	<45,000 km	<6000 km	<45,000 km
Mass of terminal	157 kg	150 kg, 170 kg	35 kg	45 kg
Power consumption	200 W	150 W	120 W	140 W
Orbital location	GEO 21.5°	LEO 825 km LEO 610 km	LEO 508 km, LEO 350 km	GEO 25°E LEO 800 km

High Speed Laser Communication Systems

High speed laser communication is an enabling technology and desperately needed by intersatellite system and uniquely needed by industry to fulfil their requirements for high bandwidth. Laser communications offers several distinct advantages over traditional radio frequency links such as [12]:

- No frequency license required and no need for International Telecommunication Union (ITC)
- Ultra-high data rate currently up to 10 Gbps, with further potential for increase by using parallel links at different wavelengths
- Large distance communication over several thousand km in space
- Secure, practically not to be tapped, jammed or spoofed due to the narrow divergence of laser beam

High speed laser intersatellite cross links is great choice for intersatellite communications due to the high data rate, as well as light weight, smaller size and lower power consumption. To establish line of sight between the satellites can be very complex task due to narrow base beam which has to be used over long distance between satellite platforms. However, effects of radiation and radiation hardening have to be considered for any design and development. Therefore it is important to design a system to defend against the radiation from ionizing, gamma, and other attacks. There are numerous methods to protect them from radiation, including shielding, error correction, and using radiation resistance shielding and radiation hardening.

High speed laser has been considered by ESA and they have placed strong emphasis on the development of several types of lasers including Nd:YAG laser based coherent communication system technologies since 1989. Nd:YAG and diode –pumped communication has stimulated the investigation of advanced concepts, such as optical amplifiers and semiconductor technology. Optical-phased arrays provide laser communication systems with inertia-free, hence ultrafast, beam scanning ability needed for accurate beam pointing, efficient area scanning, and reliable link tracking in presence of space craft attitude jettier [13].

ESA in order to achieve the ultimate system miniaturization, highest transmit data rates and sufficient growth potential to comply with optical intersatellite links, new class of satellite emerged with the intended deployment of extensive satellite networks for mobile communications and interactive multimode services (SROIL). For this system a laser diode pumped Nd:YAG laser transmitter together with coherent detection receiver was designed. The pointing system of the SROIL terminal was based upon a periscope-type pointing assembly in front of a 35 mm diameter aperture telescope, allowing almost full hemispherical pointing. Terminal of this system is shown in Figure 11 [13].

Figure 11: Engineering model of short range optical intersatellite links [13]

Radiation Effect on Laser for Harsh Environment of Space

Laser diodes are increasing are used for space applications, either to pump solid state lasers, in photonics payloads, or as source for LIDAR. A great deal of effort has been devoted to study specifically the effect of radiation on performance of the most common visible and near infrared emitting semiconductor based diode lasers [14].

Figure 12 illustrated a summary of study done on gamma radiated, proton radiated on GaSb-based distributed feedback laser diodes emitting in the 2,100 nm wavelength range and integrated in Butterfly package with output power of around 10 mW. As demonstrated radiation related degradation was not observed up to 100 krad of gamma. The results shows that mid-infrared lasers based on GaSb are suitable candidates for harsh environment of space applications [14].

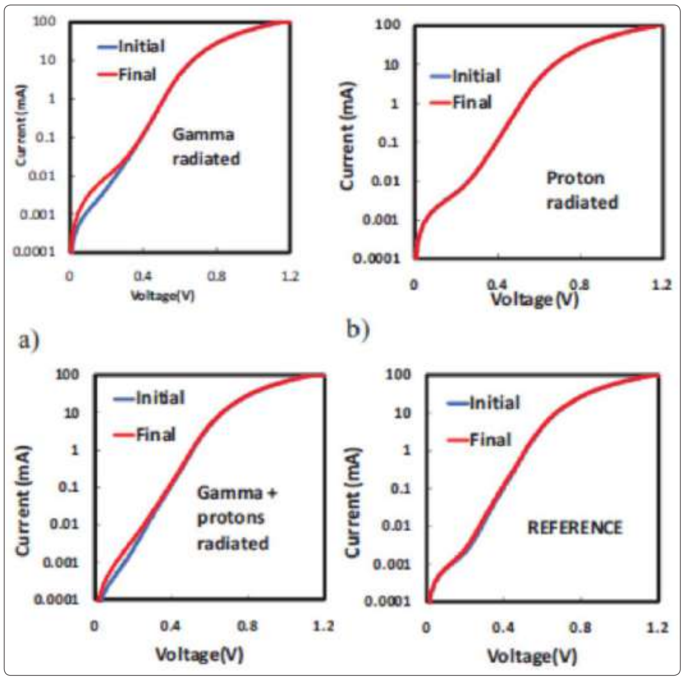

Figure 12: Radiation effect on diode laser. Current-voltage characteristics of laser exposed to (a) gamma radiation, (b) proton radiation, (c) gamma and proton radiation, and (d) reference sample [14]

Advantages of Using Laser Based Communication Systems

The use of inter-satellites laser-based links has many key advantages compared with those of microwave RF inter-satellites links (see Figure 13). Some of these advantages are listed below: [3-4]

1. Smaller size and weight of the optical,
2. Power efficiency,
3. High security and resistance to interference,
4. High data transmit rate,
5. Denser satellite orbit population,
6. High bandwidth,
7. Small optical antenna size,
8. Narrow field of view,
9. High precision of communication.

Although, the recent developments in optical laser communication technology are very encouraging for the potential operation of optical satellite cross links and the optical links in space which in part can boast to an incredible number of high technology achievements as is evidenced in the optical terrestrial networks, however there still remains formidable challenge to test, qualify and successfully integrate in real world full scale deployment. Thanks to the coherent beam that can be focused to spot sizes of the order of the wavelengths of the laser light which approach the diffraction limit. This has both a positive and negative side. On the positive side, a narrower beam width means that the potential for interference to or from adjacent satellites is greatly reduced. This is particularly important in large LEO constellations. Acquisition, Tracking and Pointing (ATP) and the impact that this may have on the space craft that is moving at 3 km/s for GEO to 7 km/s for LEO is a formidable task. Accurate ATP is critical to the acceptance of optical intersatellite-link (ISL) [1].

Figure 13: Recent development in optical laser communication in the inter-satellites laser links has many key advantages compared with those of microwave inter-satellites links [3,4]

Another important advantage in optical systems is the aperture size of the optical telescopes needed as compared to the microwave (Antennas) used in the transmitter / receiver sections favor the optical domain by a factor of at least 100. For example a communication system operating at 1 Gb/s requires an aperture of approximately 15 cm. In contrast a RF system with 1 Gb/s millimeter wave system would require an antenna with minimum aperture size of 2.7 m. This parameter alone results in considerable weight and size savings in the satellite payload resulting in reduced disturbance and shaking to the sensitive sensors on board the satellite. These considerations are sufficient to tilt the optical approach in favor of the traditional RF radio used in the last 30 years that have reached a high level of maturity [1].

Future Trends of Space Laser Based Systems

As demand for high-data rate transmission from space borne platform is steadily increasing, the use of free-space laser optical communication systems are expected to grow and play an important role for satellite network and optical technologies for satellite networks are expected to revolutionize space system architecture. Since data rate and receiver sensitivity for different optical systems shows the sensitivity of receiver at 800 nm wavelength band is poor because of the intensity modulation and direct detection, wavelength bands at 1550 nm are considered for high data rate communications with higher sensitivity. This is due to the fact at 1550 nm using the wavelength division multiplexing (WDM) technique has the ability to increase the data rate to much higher level. See Figure 14 [11].

Application to micro-satellites is another data rate trends for small satellite is being considered. CUTE-I is the first generation cube satellite used Frequency Shift Keying (FSK) at 1200 B/s. Cute-1.7 APD is the second generation satellite used Gaussian-filtered Minimum Shit Keying (GMSK) at 9.6 Kb/s by employing ham radio communications because of the resource constraints in the nano-class satellites. See Figure 14 [11].

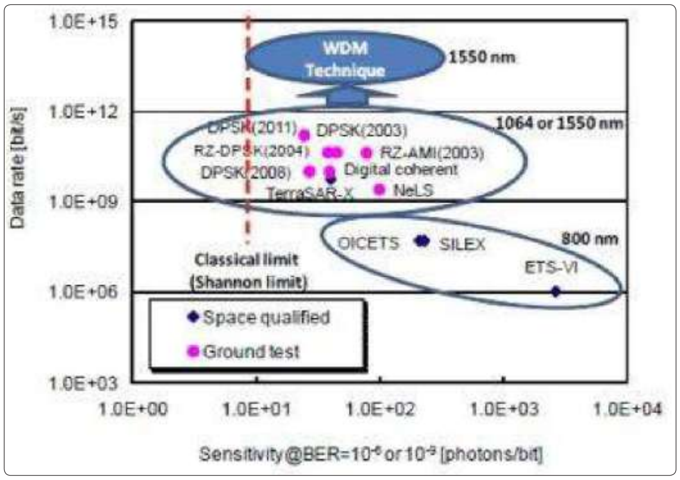

Figure 14: Future trends of data rate and receiver sensitivity for different optical communication systems which includes using wavelength division multiplexing (WDM) [11].

For future trend, small satellites in 50 kg class that currently use S-band communications links at 1 Mb/s, is expected that the data rate can be increased using advanced laser communication technologies from the 10-Kb/s to the 10 Mb/s range, even in the several 10 kg class satellites. Finally, small satellite market will be an attractive area to apply laser communication systems particularly since for 1 Mb/s s-band links are only available at national space organization that own special ground stations with corresponding large antennas, and for private companies and universities to have s-band ground facilities is expensive and these micro satellite could be launched with the main host satellite as a piggyback, See Figure 15 [11].

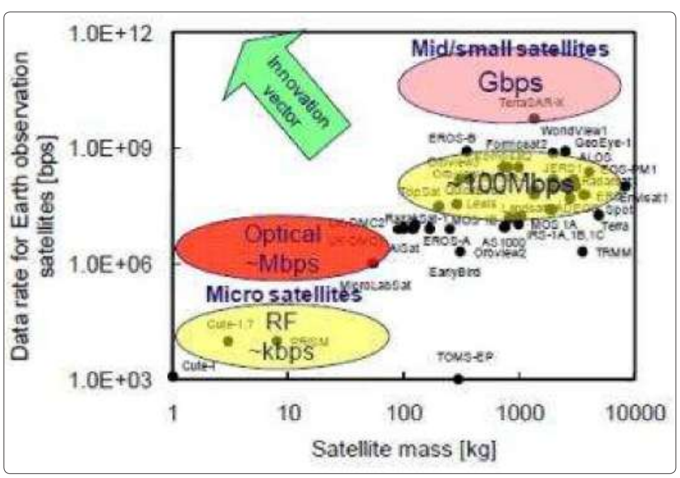

Figure 15: Data rate for Earth observation on mid/small and micro-satellites [11]

Conclusion

Optical inter-satellites are the requisite subsystems of the future optical networks in the sky. There still exist many tough technological and architectural design issues in implementing a cost effective, space qualified high data rate power efficient systems for harsh environment of space applications. New research and development point to even higher performance systems with many advantages and substantial gains over what can be achieved today. Recent developments in optical laser communication technology are very encouraging for the potential operation of optical satellite cross links. While the optical links in space can boast to an incredible number of high technology achievements as is evidenced in the optical terrestrial networks, however there still remains formidable challenge to test, qualify and successfully integrate in real world full scale deployment.

Finally, laser-based systems for intersatellite communication are far superior to microwave communication with following key critical advantages:

- Smaller size and weight of the optical,
- Intrinsic narrow-beam and high-gain nature of laser,
- High security and resistance to interference,
- High data transmit rate,
- Denser satellite orbit population,
- High bandwidth,
- Larger capacity,
- Lower power consumption,
- Greater security against eavesdropping,
- Small optical antenna size,
- Narrow field of view,
- High precision of communication.

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