4th Indian International Conference on Industrial Engineering and Operations Management
Hyderabad, Telangana, India, November 07-09, 2024
Publisher: IEOM Society International, USA DOI: 10.46254/IN04.20240112
Published: November 07, 2024

Conceptual Study of Breakthrough Technology for Free-Space Laser Satellite Communication Between Micro Satellite and Geo-Satellite

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Abstract

In recent years, developing micro satellites (50-100 kg) by Universities, NITs, and IITs have emerged as a new trend in satellite technology because of its advantages such as short time and low cost for development, low cost for launching. The capability of RF communication between a micro satellite and a ground station is limited in terms of the time duration for communication and data latency. The micro satellite cannot be transferred whole data to the ground station due to gap between each pass duration. These problems can be overcome by using a geostationary orbit satellite as a "Relay Satellite by using laser communications between a micro satellite and a geostationary satellite. RF communication is more dependable communication channels for satellite systems with existing technological limitations, atmospheric interference. To overcome the limitations and improving signal integrity and bandwidth, free-space satellite laser communication has potential to revolutionize networks, making them more robust against environmental factors. Satellite communication providers and research institutions focused on exploring and expanding the frontiers of free-space laser communication with new methods in laser communication, significantly enhancing the performance and reliability of their satellite communication systems. In proposed communication model, the micro satellite in Low Earth Orbit (about 600 km altitude) will use laser to communicate with the geostationary orbit satellite which is at the altitude of 36,000 km. The communication speed is improved considerably, higher speed and large capacity with laser as carrier comparing to the radio frequency. This paper addresses an idea to provide the feasibility study of laser communications between micro satellites in LEO and geostationary satellites in GEO. A simulation model to be built for analysing the performance of laser communications between LEO micro satellites and GEO satellites.

Keywords
Laser Communications, LEO Micro Satellites, GEO Satellites, Feasibility, Laser Components

1. Introduction (Motivation of Research)
The motivation goal of this research is providing the feasibility study of the laser communications system link between a micro satellite in low earth orbit and geo-stationary satellite in geo-synchronous orbit by using cutting-edge technologies. An Optical/Laser inter-satellite communication has been attracting worldwide attention because of the growing need for larger capacity and higher speed transmissions. Both RF and optical waves are electromagnetic waves and having many advantages for using optical waves in space. These include reduced mass, power, and volume

of equipment, higher data rates. Its features such as not needing the frequency coordination and the ease in which confidentiality is ensured compared to radio frequency (RF) communication. Comparison of difference in beams from satellites between RF and Optical communication in Figure 1 and illustrated the comparison of laser communication via GEO satellite vs direct RF communication to ground station from micro satellite indicated in Table 1.

Figure 1. Image of difference in beams between RF and Optical communication

Table 1. Optical Communication via GEO and RF Communication to ground from micro satellite

Parameters	Relay communication via GEO	Direct communication to ground station
Number of communication sessions	~15 (FOV of GEO: 20°)	3-4
Communication duration per one orbit	~ 45 minutes	~ 10 minutes
Amount of data with the same data rate	Bigger	Smaller
Data latency	Almost real time	Long time to wait
Pointing requirement	Stringent	Much loosen

1.1 Objectives

The main drawback of micro satellite in low earth orbit can only communicate with the ground station at most several times per day and the duration of each communication window is only up to 10 minutes. During each pass, which the data stored in the micro satellite cannot be transferred to the ground stations. To overcome the mentioned issues, solution may be possible establishing communication between micro satellite to ground station via geo-stationary satellite as relay satellite with laser communications between micro satellite and a geostationary orbit satellite and RF communication or laser communication between geostationary satellite to ground station.

The objective of this research is to provide conceptual feasibility study of the laser communications between low earth orbit micro satellite to a geostationary satellite in GSO as shown in Figure 2. The research is likely involved to provide feasibility study of laser communication link simulations, analysis, testing, and validation with help of software tools availability in open source for simulations or radiofrequency over fiber system (RFoF). The scope of this research idea is focused on feasibility study to develop laser/optical communication system by start-up private space industries in India with breakthrough technologies for satellites communication.

Figure 2. Author Imagination of laser inter-satellite communications between Micro & GEO satellites

2. Literature Review

Survey related to free space laser communication between satellite and satellite to ground station is discussed below: Nowadays, laser space communication becomes more and more popular in Europe, other countries and development is under progress in India. Many researchers and space agencies have demonstrated various techniques and approaches for new communication technologies for inter-satellite data relay. Many researchers and space agencies have demonstrated various techniques and approaches for new communication technologies for inter-satellite data relay.

In 2005 at Europe, European Space Agency (ESA) was a primary driver in the development of optical communications. Successfully demonstrated Laser communication possible between SPOT-4 (Micro satellite in LEO) and ARESMIS (GEO satellites in GEO orbit) and in turn SPOT-4 satellite could transmit its data via ARTEMIS to its ground station in Toulouse.

In 2007, USA and Germany have successfully demonstrated in setting up a laser data link between NFIRE satellite (USA) and TerrSAR-X satellite (Germany).

In 2013, NASA, USA was remarkable demonstrated the laser communications successful transmitting data from lunar orbit (lunar mission) to earth (ground station).

In 2019, Japan developed first optical link between satellite in LEO and satellite operates in GEO and transferring of its data to the ground station (earth) through GEO satellite. The Japan Aerospace Exploration Agency (JAXA) OICETS (LEO) satellite is a technology satellite with the objective to conduct inter-satellite laser communications with ARTEMIS (GEO) of ESA.

The literature suggests that laser communication can provide reliable communication for transfer of high data between satellites and ground stations. Overall, the literature on free space lase communication systems suggests that they have potential applications in a variety of satellite fields, including ground to space, LEO-LEO, Space station to ground via GEO satellite feeder.

3. Methods

The below block diagram describes the purpose of building this proposed systems methodology. The capability of communication between a micro satellite in LEO and a dedicated ground station is limited in terms of the time duration for communication and data latency. A micro satellite in LEO can only communicate with a ground station at most several times per day and the duration of each communication window is only up to 10 minutes [7]. In LEO satellite, the period for one orbit of a micro satellite is ~ 90 minutes and the micro satellite cycles around the earth about 15 times per day. To overcome the problems raised in micro satellites in LEO, a geostationary orbit satellite can be used as a relay station for the micro satellite and laser will be used as the carrier between micro and GEO satellites in Figure 3. Free space laser inter-satellite communication with an optical communication system on-board in satellite and laser as the carrier helps to solve almost of problems of RF communication in LEO satellite to ground stations. Laser communications will not be interrupted between LEO and GEO since there is no cloud and atmosphere in the space [4]. The goal of this paper is to bring out the feasibility study of designing the communications system between a micro satellite and a GEO satellite.

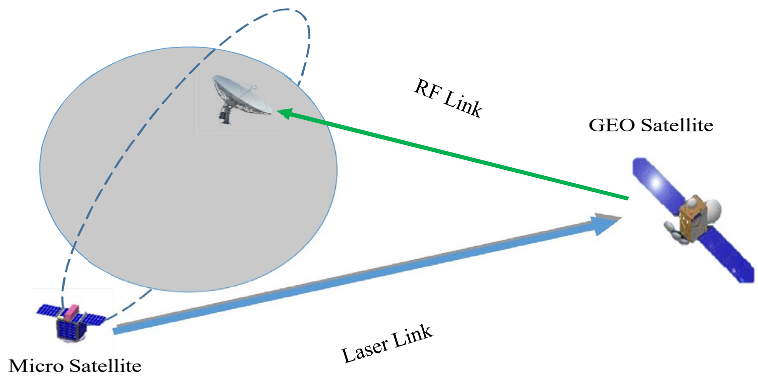

Figure 3. Proposed System model image of laser inter-satellite communications between Micro & GEO satellites

3.1 Optical acquisition and tracking technology

In optical communications in space, the laser beam plays two roles such as establishing a link and as a carrier wave for communications. Optical acquisition and tracking technology are necessary to establish this link. Information on the locations of the two communicating satellites can be predicted to a certain degree using orbit calculations. It is essential to have a technology that allows both parties to scan the transmitted laser beam and, at the same time, receive, locate, and track the laser beam from the partner satellites.

In the optical capture operation, the laser beam is first scanned in the expected direction of the communication partner satellite. The partner satellite detects that laser beam with its own optical acquisition sensor to determine the exact location or position of the other satellite and emits a laser beam in that direction. As a result of both satellites performing these operations, the satellite will eventually track the laser beams from the other satellite and continue to lock the laser beams.

Figure 4 shows an image of a spiral scan between a satellite in geostationary orbit (GEO) and one in low earth orbit (LEO). This spiral scan, one of the possible scan shapes, is capable of scanning a wide acquisition area at high speeds. Other scan shapes include the raster scan and the random scan. Each of them has its own characteristics depending on the sequence.

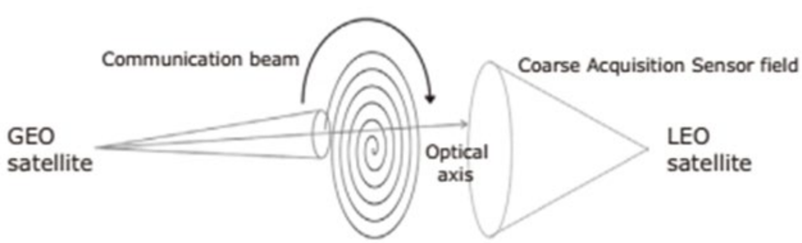

Figure 4. Image of spiral scan during acquisition between LEO and GEO satellites

4. Data Collection

The size of both transmitting and receiving antennas in laser communications are much smaller than in RF communication. The link budgets for RF systems in Ka band and an optical link of a GEO-LEO distance of 42,000 km.

Considering link budgets for RF systems (Ka-band) and an optical link at λ=1.55 µm at a bit rate =2.5 Gbps with a GEO-LEO distance of 42,000 km (Table 2).

Table 2. Comparison of link budget for RF and Optical Communication Systems

Parameters	**RF Systems (Ka)**	**Optical System**	**Parameters**	**RF Systems (Ka)**	**Optical System**
Transmit power	50 W, 17 dBW	10 W, 40 dBm	Rx antenna diameter	2.2 m	10.2 cm
Frequency	32 GHz	193 THz	Rx antenna gain	55.1 dBi	106.3 dB
Wavelength	9.4 mm	1.55 m	Feeder/Rx loss	-2.1 dB	-2 dB
Tx antenna diameter	2.2 m	10.2 cm	Receive power	-93.7 dBW	-42.4 dBm
Tx antenna gain	*55.1 dBi*	*109.3 dB*	System noise	29.6 dBK	NA
Feeder/Tx loss	-3 dB	-2 dB	G/T	23.4 dB/K	NA
EIRP/ Strehl ratio	69.1 dBW	-0.4 dB	Noise density	-199.0 dBW	NA
Pointing loss	-0.3 dB	- 3 dB	C/N_0 / Receive sensitivity	105.3 dBHz	90 photons/bit
Beam divergence	0.25 deg	19.3 rad	Required C/N_0 / Required power	102.0 dBHz	45.4 dBm
Path loss	-215.0 dB	-290.6	Link margin	**3.4** dB	**3 dB**

4.1 System design and requirement

The micro satellite moves around the Earth at the altitude from 500-1000 km (LEO orbit) while the height of the orbit of the GEO terminal is about 36,000 km (GEO orbit) [1] (Figure 5).

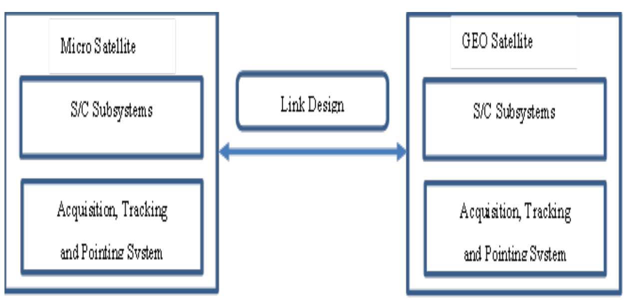

Figure 5. Design of the communications system between micro and GEO

In communication between the micro satellite and the GEO satellite, two crucial requirements for the systems are the Bit Error Rate (BER) requirement and the pointing requirement. The required BER is 10^{-6} for any successful laser free space communications. Assumptions made that the data rate of laser communications from the micro satellite to the GEO satellite is 300 Mbps which is approximate to the best speed of radio communication for micro satellites currently. The wavelength of laser is 1.55 µm and the aperture of the telescope will vary in range of 35 cm to 45 cm for GEO satellite. The link requirements for communication between the micro satellite in LEO and the GEO is shown below in Table 3.

Table 3. Link requirements of LEO-GEO Communication

SN	Parameters	System Requirement& Assumption
1	Date Rate	300Mbps
2	Link (Slant) range	40,000 km
3	Average BER	Asymmetrical Duplex Link 10^{-6}
4	Pointing accuracy	Several µrad
5	Tx o/p Power	<10 W
6	Tx aperture	>10 cm
7	Link budget margin	≥ 3 dB

4.2 Link budget requirement

Analysing communication between a transmitter and a receiver by using a link equation for any communications system. Based on the link equation, the required signal at the receiver side is calculated with respect to gains and losses of the communications system [11]. In laser communications between the micro satellite and the GEO satellite, the signal delivering is expressed in the equation

$$P_r = P_t\, G_t\, L_t\, L_R\, G_r\, L_r \quad (1)$$

P_r = Receiving signal power (dB), P_t = Transmitted optical power at the output of the transmit antenna (dB),
G_t = Effective transmitting antenna gain (dB), L_t = Efficiency transmitter loss (dB), LR = Free space range loss (dB),
G_r = Receiving antenna gain (dB), L_r = Efficiency loss associated with the receiver (dB)

Calculation of Link Budget for Free Space Laser communication of LEO-GEO satellites as shown below in Table 4.

Table 4. Calculation of Link Budget for LEO-GEO Communication

SN	Parameters	Data
1	Transmit Power	2 W, 33 dBm
2	Frequency	1.93 THz
3	Wavelength	1.55µm
4	LEO Tx antenna diameter	5 cm (0.05 m)
5	LEO Tx antenna gain	103.5 dB
6	Distance (Slant range)	40,000 km
7	Path Loss	~ -290 (dB)
8	GEO Tx antenna diameter	35 cm (0.35 m)
9	GEO Tx antenna gain	117 dB
10	Receiver Power	-44.1 dBm
11	Receiver sensitivity (photon/bit)	90
12	Data rate	1Gbps
13	Required Power	-49.4 dBm
14	Link Margin	~5.3 dB

5. Results and Discussion

To evaluate free space laser communication link performance the actual satellite signal was used for testing with Radio Frequency over Fiber (RFoF) system at ground system setup which is similar of laser/optical communication link in free space. The graph represents the results optical communication link behaviour or performance shown in Figure 6. The input satellite signal was passed through RFoF system (optical fiber link) and the output shows anominal signal without any loss as expected from fiber link.

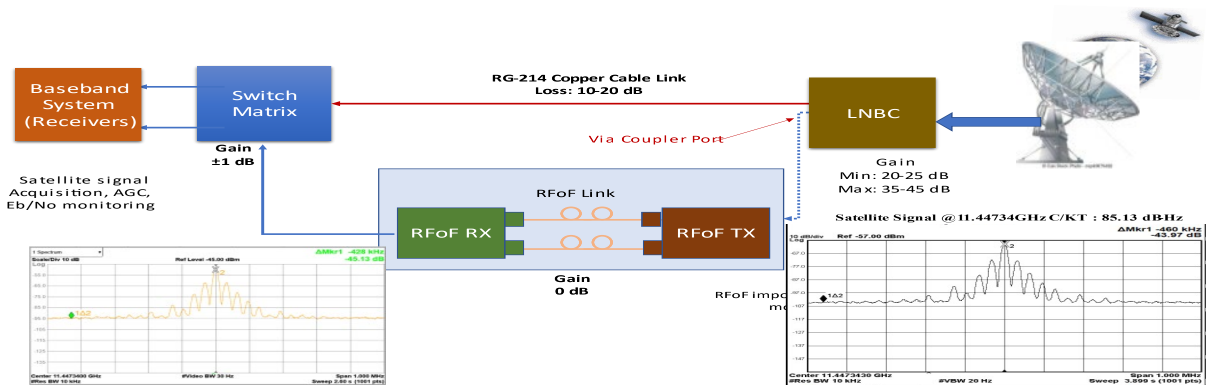

Figure 6. Image of Satellite Signal Acquisition through-RFoF system

Figure 7 graph shows satellite signal AGC, E_b/N_o measurements recorded by using spectrum analyzer between satellite ground station (Earth station) to Base-band system through RFoF (Radio Frequency over Fiber) system link.

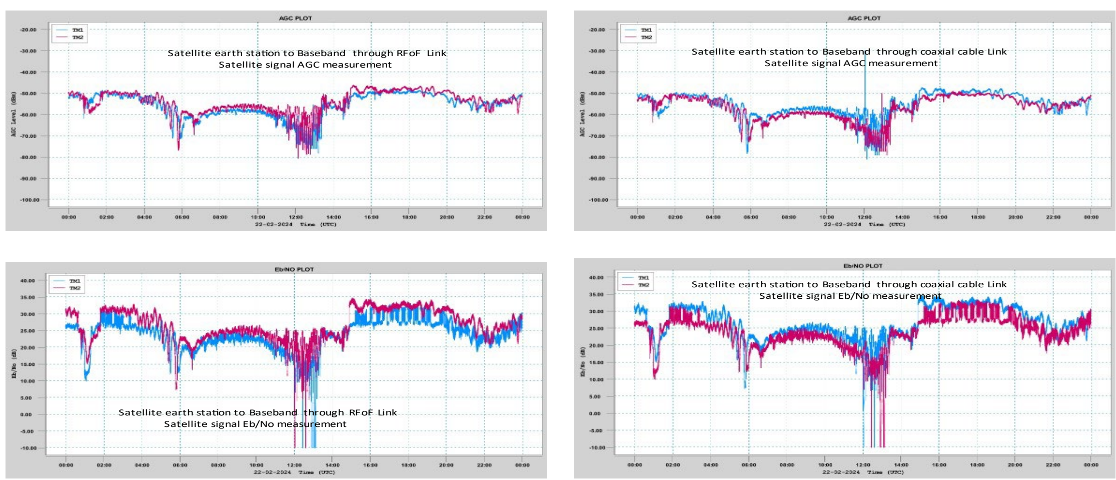

Figure 7. Image of Performance Comparison RFoF and Coaxial cable Link

5.1 Simulation and Analysis

The objective of this simulation is to verify the communication link between the micro satellite and the GEO satellite and find out a good design point for the optical communications system. A model of the laser communications link from the micro satellite to the GEO satellite is built by using the free trial version of opti-system simulation software shown in Figure 8

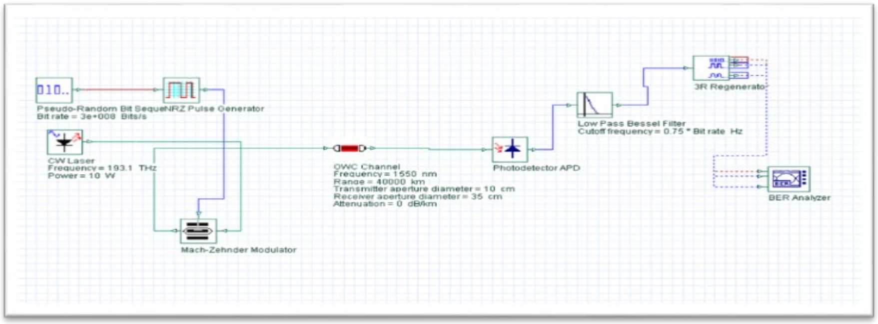

Figure 8. Layout of the link simulation

Laser communication link simulation in free space environment was not feasible by simulation software tool, instead of that, RF over Fiber (RFoF) systems has been used to simulate optical link performance in ground for satellite signal. Satisfactory results were achieved through RFoF systems for received satellite signal which is same behaviour in space for optical communication link performance.

6. Conclusion

This paper gives a conceptual idea to research in laser communication in free space and provide the feasibility study of laser communications between the micro satellite and the GEO satellite. The overall design of the communications system which includes the micro satellite, the GEO satellite, and the communication link between them. The system design, requirement and link budget calculation were done based on assumed data for laser and RF communication for comparison purpose.

A model of communication link between the micro satellite and the GEO satellite to be built and verification is being done by using the simulation software. The goal of this paper is to bring out the feasibility study of designing the communications system between a micro satellite and a GEO satellite. Overall design of the communications system which includes the micro satellite, the GEO satellite, and the communication link between them is discussed. A set of full-scale demonstrations of high-speed laser satellite communication links is needed as the next step for optical communications in space in order that the future needs of intersatellite communication can be met with appropriate technologies.

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Bachu Yesobu obtained B. E degree in ECE, an M. Tech degree in Digital Electronics and Communication Systems from Visvesaraya Technological University (VTU), Belgaum, Karnataka. He is an industry working professional (Satellite Communication Engineer) in reputed R&D organization for the last 30+ years, where he played multiple roles as a Systems Engineer, Operation Project Manager, Operations Project Director and Deputy Project Director for various projects. He has travelled in abroad London, U.K, Riyad, Saudi Arabia on official assignments. He achievements and contributions, got many awards such as Team Excellence Award and Work Excellence Award. He published various papers in national and international conferences, has 8 Technical papers to his credit and many of his conference papers are won "BEST Paper Awards". He has been involved in Academics for the last 20 years as a member of Governing Council, Board of Syllabus (BOS), Board of Examiner (BOE), Department Advisory Board (DAB), Industry Expert in Electronics & Communication Engineering for various reputed engineering colleges and universities. He has delivered a many technical lectures in various Engineering Collages including NIT, Puducherry, NIT, Suratkal, NNMIT university, Mangalore and JSS University, Mysore as an Industry resource person. His Field of Interest are Statistical Signal Processing, Image Processing System, Multimedia communication systems, Satellite interference mitigation techniques, Advance computer networking, Sensor networks, Embedded Systems Design, Modular based satellite system design and Expert System design in Satellite Mission Operations with A./ML. He is also a Research scholar at BESTIU. His research area of interest is optical/laser inter-satellite communication systems between satellites in different orbits and Space stations.

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