Special Report

Trends of research and development of optical space communications technology

NICT

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Introduction

Radio frequencies (RFs) are usually used for long-distance links in space. However, recent progress in optics and laser technologies, especially in fiber optics, is ushering in an era of inter-orbit communications using laser beams. Both RFs and optical waves are electromagnetic waves; however, using optical waves in space has many advantages. These include reduced mass, power, and volume of equipment, higher data rates, and no tariffs or regulatory restrictions, unlike RF bands. These advantages are a consequence of the high frequency of optical waves. In Europe, the European Space Agency (ESA), in its Semiconductor Laser Intersatellite Link Experiment (SILEX), has routinely used a 50-Mbps optical communication link twice a day between a low earth orbit (LEO) satellite and a geostationary earth orbit (GEO) satellite since 2003. In Japan, the Optical Inter-orbit Communications Engineering Test Satellite (OICETS) developed by the Japan Aerospace Exploration Agency (JAXA) was launched in August 2005, and a laser communication link with the SILEX terminal was successfully established. By contrast, the National Aeronautics and Space Administration (NASA) canceled the Mars Telecommunications Orbiter project, which would have used a laser communication link between Mars and Earth in 2010. The research and development of optical space communications are being continued all over the world, and part of the technology is used for stratosphere optical communications. Here, recent trends of such research and development are reported.

In-orbit demonstration of optical space communications

The NASA free-space laser communications programs are concentrated around the Jet Propulsion Laboratory (JPL). The Galileo Optical Experiment was conducted on Dec. 9-16, 1992, during its second Earth flyby. Optical transmitters at the JPL Table Mountain Facility in California and the Starfire Optical Range in New Mexico transmitted optical pulses to Galileo, where they were successfully received using the Solid-State Imaging camera as the optical receiver, for ranges from 600,000 to 6,000,000 km [1]. In 1995, a ground-to-space optical communications demonstration called the Ground/Orbiter Lasercomm Demonstration was conducted with the Japanese Engineering Test Satellite VI (ETS VI) [2]. The Mars Laser Communications Demonstration project, which would have used a laser communication link between Mars and Earth at 1–30 Mbps in 2010, was canceled in 2005 [3].

The Ballistic Missile Defense Organization (BMDO) of the Department of Defense developed laser communications terminals that communicated at rates above 1 Gbps and demonstrated the ability to acquire and track the counter terminal in full daylight using atomic filter technology. The space-qualified transceivers were used for the BMDO Space Technology Research Vehicle 2 (STRV2) experiment. Due to a large attitude error of the satellite, the BMDO STRV2 experiment unfortunately ended in failure [4]. The National Reconnaissance Office (NRO) successfully launched its Geosynchronous Lightweight Technology Experiment advanced demonstration satellite in May 2001, which had a laser communications experiment and an operational ultra high frequency (UHF) communications mission on board. The demonstration was successfully performed, but detailed results have not yet been reported [5].

The ESA developed SILEX, whose laser satellite communication terminals were designed for 50 Mbps LEO-GEO and GEO-GEO inter-satellite link (ISL) applications. The SILEX laser communication demonstration was performed in November 2001, which was the first transmission of an image at 50 Mbps via a laser link from the System Probatoire/Satellite Pour d'Observation de la Terra 4 (SPOT-4) satellite to the Advanced Relay Technology Mission Satellite (ARTEMIS) [6]. The ground-to-ARTEMIS optical communication experiment was successfully conducted with the optical ground station in Tenerife, Spain run by the ESA [7]. In September 2003, the optical acquisition, tracking and communication tests between ARTEMIS in orbit and the Laser Utilizing Communications Equipment engineering model on the ground, which was developed for the OICETS, were successfully performed, and the compatibility of their optical interfaces was confirmed before the launch of the OICETS [8].

In Japan, the first bi-directional laser communications demonstration using the Laser Communication Equipment on the ETS VI satellite was successfully performed by the Communications Research Laboratory (CRL), although the ETS VI had to remain in its elliptical GEO transfer orbit in August, 1994 due failure of the apogee engine. Despite these problems and limitations, both up- and down-link transmissions at wavelengths of 0.514 and 0.830 μm at a data rate of 1 Mbps took place successfully [9]. The Japanese OICETS satellite was launched in August 2005, and the inter-orbit optical communication link experiment was successfully established, which is described in a latter section.

Trends of optical space communications

The hottest topic in 2005 was the successful in-orbit verification of the inter-orbit optical communication link experiment between the OICETS developed by JAXA and the ESA's ARTEMIS satellite in December [10]. The OICETS was launched by a Dnepr Launch Vehicle from the Baikonur Cosmodrome in the Republic of Kazakhstan and injected into LEO at an altitude of 610.0 km and an inclination of 97.8° [11]. Optical technology using 0.8-μm semiconductor lasers and an avalanche photodiode were used, and the optical isolation was designed using both the polarization and the wavelength. The functions of the satellite systems were checked for first three months, and the acquisition and tracking of stars and planets was successfully performed. In December 2005, the first bi-directional laser communications demonstration between OICETS and ARTEMIS was successfully conducted with a return link of 50 Mbps and a forward link of 2 Mbps. The basic technology for the inter-orbit optical communication was established. Considering the in-orbit verification used only Japanese technology development based on the interface control documents with the ESA, the establishment of an international interface standard for optical ISLs is quite significant.

In addition, in November, 2004, the National Institute of Information and Communications Technology (NICT) developed a compact stratosphere optical terminal, and the first flight of the test flight airship for the optical link experiment was successfully performed on November 22, 2004. Bi-directional acquisition and tracking using a 980 nm/970 nm laser beacon between the test flight airship at an altitude of 4.0 km and the ground terminal were performed, but fine tracking and optical signal transmission could not be performed due to the limited flight time [12]. The optical terminal for the airship has a compact fast-steering mirror and a compact fiber coupler at 1.55 µm. NICT is also developing a next generation laser communication terminal onboard the SmartSat-1 satellite, which will be launched in 2007, but verification of the optical terminal has been postponed to the next flight of the SmartSat series [13].

The next space demonstration after OICETS will be the TerraSAR-X project. TerraSAR-X is a new German radar satellite that will be launched in 2007 into LEO at an altitude of 514 km with an inclination of 97.44° (Fig. 1). The scheduled lifetime is 5 years. It carries a high frequency X-band Synthetic Aperture Radar (SAR) sensor developed by the German Aerospace Center (DLR), and the data measured will be downloaded to the ground station via a 5.5-Gbps optical link. The in-orbit-verification program is called “LCTSX” (LCT on TerraSAR-X.) The onboard optical terminal for LCTSX is being developed by Tesat Spacecomm, and uses the homodyne BPSK (Differential Phase Shift Keying) scheme (Fig. 2) [14]. Bi-directional communication with a bit error ratio (BER) of 10^{-9} can be performed at 8 Gbit/s across 6,000 km and 1 Gbit/s across 20,000 km with an optical transmit power of 0.7 W, and 500 Mbps across 72,000 km with a high power laser (typically 5-7 W) using a 125-mm diameter telescope. The terminal mass is less than 30 kg, and the power consumption is below 130 W. Tesat Spacecomm ensures a reliability of 0.9998 over ten years of operation. In a follow-up program an inter-satellite link will be established between the TerraSAR-X satellite and a second LEO satellite, NFIRE of the U.S. Army, to verify a bi-directional communication link with a data rate of 5.5 Gbps [15]. The SAR radar has 384 phased array sensors operating in the X-band in different operation modes: "Spotlight" mode with 10 x 10 km^2 scenes at a resolution of 1-2 meters, "Stripmap" mode with 30 km wide strips at a resolution between 3 and 6 meters, and "ScanSAR" mode with 100 km wide strips at a resolution of 16 meters. Under DLR contract, Astrium is currently developing and building the satellite. Astrium will set up a distribution system for the commercial use of the TerraSAR-X data and products. Distribution and value adding will be the task of the Infoterra GmbH.

The DLR is also developing a Transportable Optical Ground Station for broadband optical communications and atmospheric-turbulence measurements. The ground station is designed for a wide range of application scenarios, including satellite links, balloon links, and ground-to-ground links. The system is optimized for communication wavelengths in the range from 700 to 1600 nm. The station is designed to be deployed anywhere in the world due to its light-weight construction and highly flexible software for calibration. The system includes a 40-cm Cassegrain telescope, several cameras for the tracking system and measurement instruments, and a data processing system (Fig. 3) [16]. The capabilities of the ground station were tested in a major trial with a stratospheric balloon. The balloon was launched in August and September 2005 from the balloon and rocket test area ESRANGE, in Kiruna, Sweden, with an optical payload on-board to an altitude of over 60 km. The Transportable Optical Ground Station successfully received data at rates of up to 1.25 Gbit/s and performed extensive atmospheric measurements to test optical transmission in a turbulent atmosphere [17].

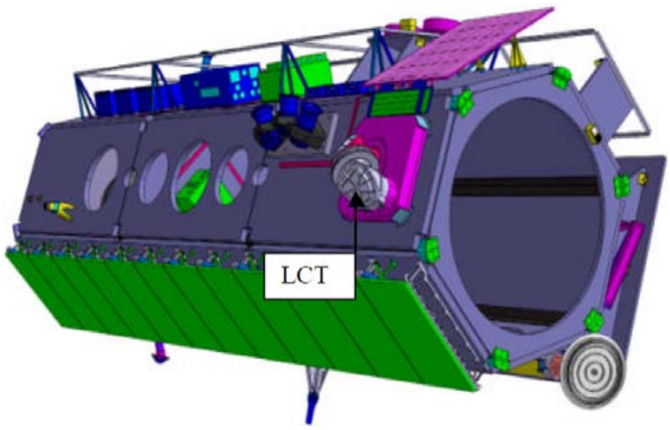

Fig. 1 Laser communication terminal (LCT) mounted on TerraSAR-X satellite, LCTSX [15]

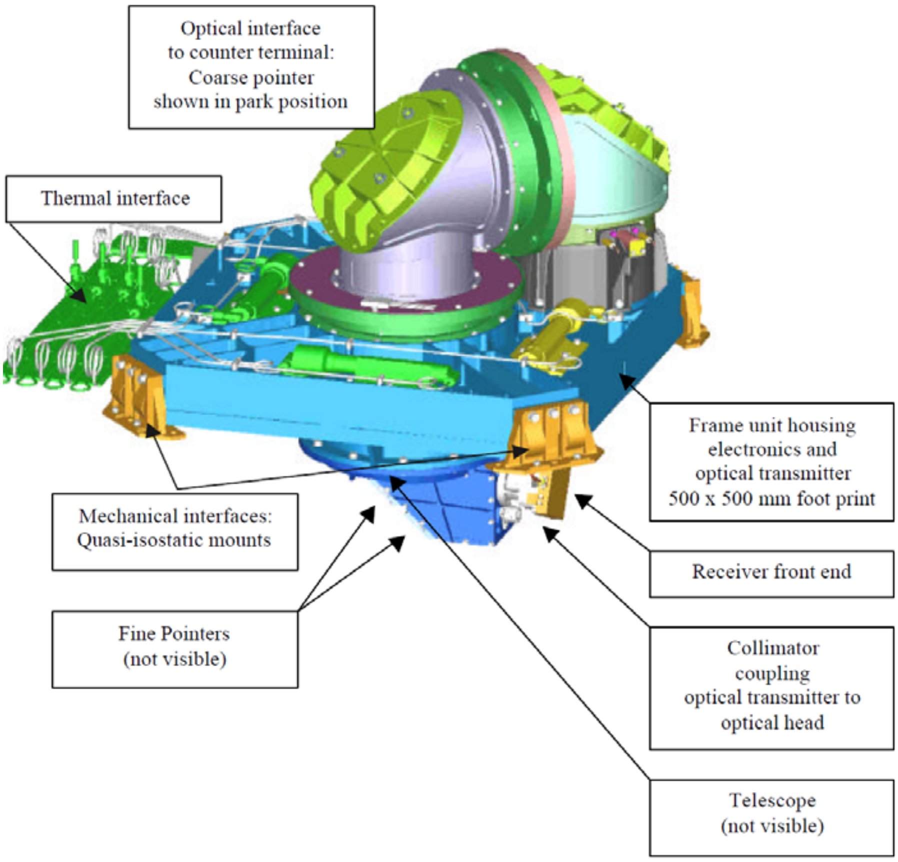

Fig. 2 Drawing of LCTSX developed by Tesat Spacecom [15]

Fig. 3 Transportable Optical Ground Station during balloon trial in Kiruna, Sweden (August 2005) [16]

Additionally TerraSAR-X supports the reception of interferometric radar data for the generation of digital elevation models with TanDEM-X (TerraSAR-X add-on for Digital Elevation Measurement), which has the goal of generating a global Digital Elevation Model (DEM, < 12 m posting and < 2 m height accuracy) [18]. This goal will be achieved by means of a second SAR satellite (TanDEM-X) flying in a tandem orbit configuration with TerraSAR-X. TanDEM-X has SAR system parameters that are fully compatible with TerraSAR-X-1, allowing not only independent operation from TSX-1 in a mono-static mode, but also synchronized operation (e.g. in a bi-static mode). The TanDEM mission is designed for five years of nominal operation. Phase A of TanDEM-X started in September 2004, and phase B started in autumn 2005.

The DLR performed an optical high bit rate downlink from a stratospheric balloon. The objectives of the CAPANINA stratospheric optical payload experiment were to plan and built the necessary hardware to demonstrate and carry out channel measurements for a high speed optical backhaul downlink from a stratospheric platform testbed to the ground with data rates of up to 1.25 Gbit/s. The Freespace Experimental Laser Terminal (FELT) is an optical transmission terminal with a 6.5-cm diameter optical antenna that was mainly developed for the CAPANINA stratospheric experiments (Fig.4) [16]. The constraints for the design have been the environmental conditions of the stratosphere, with temperatures down to –70ºC in a near-vacuum, high possible rotation speeds of the balloon, up to 9 rotations per minute, lightweight and streamlined design for a possible trial with an aerodynamic high altitude platform, and autonomous and robust acquisition of the ground receiver. With the stratospheric balloon campaign at ESRANGE, in Kiruna in August and September 2005, the optical communication experiments at 622 Mbit/s and 1.25 Gbit/s were successfully performed over a distance of 60 km.

Fig. 4. Freespace Experimental Laser Terminal (upper) developed by DLR and the underneath view of the payload (lower) onboard the balloon [16]

Contraves Space has designed a family of optical communications terminals to address many applications (Fig. 5) [19].

- OPTEL-02: short range optical communication terminal at 1.5 Gbit/s across 2,000 km
- OPTEL-25: medium range terminal at 1.5G bit/s across 25,000 km
- OPTEL-25 GEO: medium range terminal optimized in terms of mass and size for GEO applications
- OPTEL-80: long range terminal at 2.5 Gbit/s across 80,000 km
- OPTEL-DS: deep space communication terminal for deep space telemetry links to Mars and L2 to Earth
- OPTEL-AP: optical crosslink demonstrator for airborne platforms

The OPTEL-AP and OPTEL-DS terminals are the latest members of the Contraves Space OPTEL terminal family – designed for optical communications cross-links between airborne platforms and optical deep space telemetry links as part of an integrated RF-Optical Tracking Telemetry and Command (TT&C) subsystem. OPTEL-AP uses electroformed mirrors developed at Media Lario, in Italy, to produce a complete Ritchey-Cretien-type telescope of 250 mm, which has a large enough margin for the link budgets [20,21]. The optical terminal for high altitude platforms is for temporal needs, like theater and sporting events, which is a niche market but requires large-capacity temporal communications. OPTEL-DS is designed for optical deep space telemetry links from Mars to Earth and L2 to Earth [22]. Some L2 missions exist, such as XEUS, DARWIN, LISA, JWST, Herschel/Planck, GAIA, and Eddington, for the ESA. The data rates of the telemetry links are 10 Mbit/s at 0.01 AU, 2.8 Mbit/s at 0.5 AU, and 0.3 Mbit/s at 3.0AU, using the onboard terminal with an antenna diameter of 26 cm and a mass of 20 kg, and the consumption power of 50 W. The 10-m class optical telescope will be used for the optical ground station.

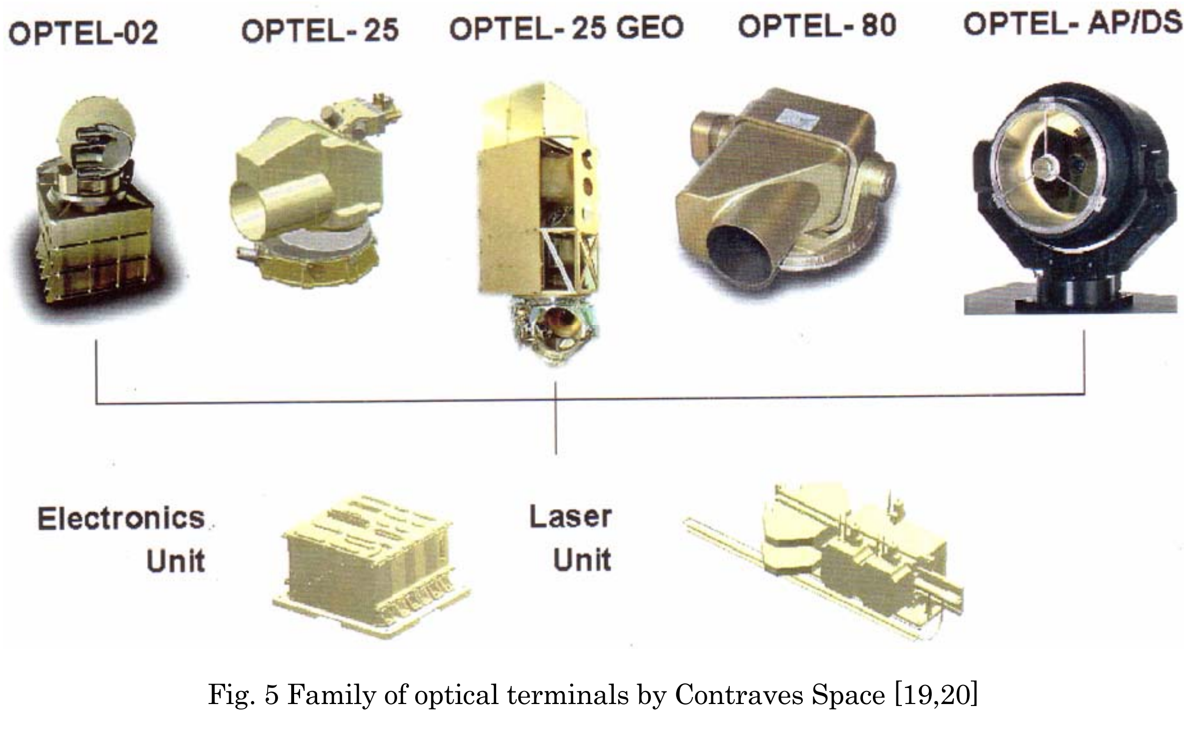

Fig. 5 Family of optical terminals by Contraves Space [19,20]

Contraves Space has developed the microwave optical harness (MOHA) for the SMOS satellite for an L-band (1.4 GHz) interferometric radiometer mission. The SMOS satellite will be launched in 2007 and will perform microwave imaging using aperture synthesis made possible by the optical fiber technology [23]. Sixty-nine antenna elements are connected with each other, and the acquired signal is transmitted to a central correlator unit, which performs interferometry cross-correlations of the signals between all possible combinations of receiver pairs. Then a two-dimensional image is acquired using digital signal processing. This is a kind of Radio over Fiber (ROF) technology for space use. This kind of micro- and millimeter wave/photonics technology will be used in the near future for interferometric measurement among clusters of satellites.

The ESA is conducting the SkyLAN project, which is a network of satellites resulting from the distribution of functions usually performed by a single communication satellite among several satellites connected with ISLs. The cluster of smaller and less expensive satellites replaces large satellites and does away with the drawbacks of large satellites. It allows a gradual commissioning of services and reduces the initial investment [24]. OPTEL-02, with a diameter of 3.5 cm and a wavelength of 1064 nm, will be used and will communicate at 512 Mbps across 3000 km.

EADS Astrium is considering a follow-up mission after ARTEMIS [25]. The optical terminal will be equipped on Alphasat, which is based on the Alpha satellite bus and has one forward link of 155 Mbps and three return links of 311 Mbps for the data relay service. The second generation SILEX terminal will have a 0.4-W communication beam, a 30-W beacon beam, and about 1 Gbit/s capability per terminal. In November 2005, there were proposals to also include the Tesat TerraSAR-X optical terminal and the Contraves Space OPTEL terminal on the Alphasat. Alphasat is expected to be launched in 2009. As mentioned, EADS Astrium (France) has proposed to embark a second generation SILEX terminal for commercial use. In addition it is planned two Phase A studies with TESAT (which belongs to EADS Astrium in Germany) and with Contraves (Switzerland) for data relay demonstration (using homodyne BPSK) and deep space optical communications demonstration respectively. ESA is already investigating synergies in order to merge some of the proposed terminals.

The new topic for optical space communications will be quantum space communications. A quantum communication demonstration has proposed by Prof. Zeilinger et al., of the University of Vienna as a scientific mission for ESA onboard the Columbus module in the International Space Station (ISS), which is called SPACEQUEST [26]. The optical terminals for SPACEQUEST have been already considered by Contraves Space and a pair of OPTEL-25 terminals will be equipped on the ISS (Fig. 6) [27]. Quantum cryptography using entangled photons will be demonstrated using three optical ground stations in Europe (two in Spain, one in Italy). The current evaluation of the human spaceflight, research and applications program board of the ESA shows “outstanding” for this mission and it will be launched in 2011.

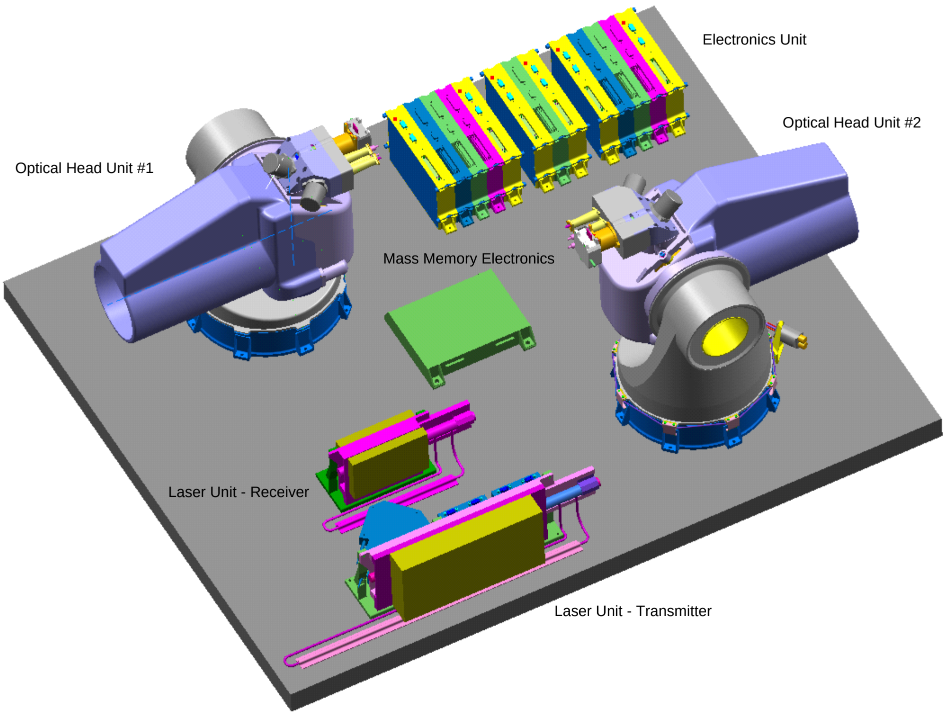

Fig. 6 Entangled photon pair experimental payload onboard SPACEQUEST [27]

Summary

Optical technologies for satellite networks are expected to revolutionize space system architectures, and space communications will undergo many improvements [28]. Many applications will be developed, such as high-speed optical inter-satellite networks and optical satellite networks as enabling technology for shared space-borne processing, sensor resolution upgrades via upgradeable analogue/digital technology, multiplatform multi-static sensing using ROF technology, on-orbit upgradeable satellite communications, interoperable satellite communications, multiplatform high-performance data satellite communications, and reconstitution of disconnected terrestrial networks. In Fig. 7, satellite communications are classified with respect to beam divergence and data rate [29]. Optical communication systems should be used in conjunction with narrow beams as they are required and for appropriate purposes. Micro- and millimeter wave/photonics technology will be used for space-borne networks in the near future.

As an aspect of space policy, Germany has an original space development program and can proceed with original German optical communications projects like TerraSAR-X without any future optical communications plan from the ESA. This is a good model for Japan to follow.

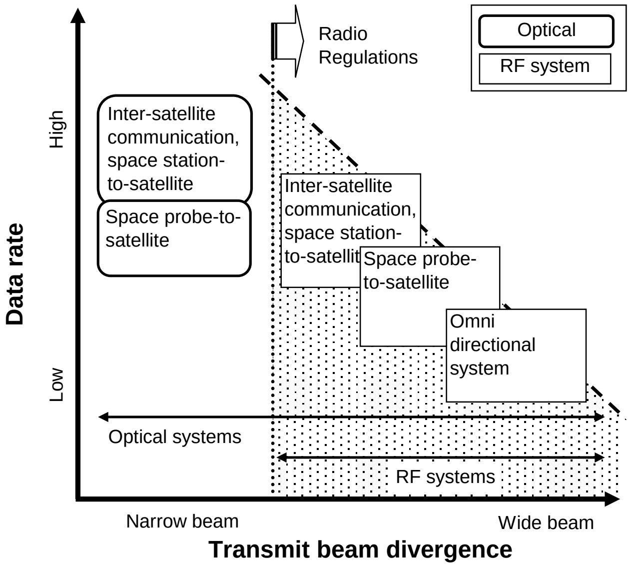

Fig. 7 Classification of satellite communication systems by beam divergence and data rate. (The dotted region shows where RF communication systems are preferred [29].)

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