Trends in satellite communications and the role of optical free-space communications

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The communication needs of Earth observation satellites is steadily increasing. Within a few years, the data rate of such satellites will exceed 1 Gbps, the angular resolution of sensors will be less than 1 μrad, and the memory size of onboard data recorders will be beyond 1 Tbytes. Compared to radio frequency links, optical communications in space offer various advantages such as smaller and lighter equipment, higher data rates, limited risk of interference with other communications systems, and the effective use of frequency resources. This paper describes and compares the major features of radio and optical frequency communications systems in space and predicts the needs of future satellite communications.

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1. Introduction

Images sent from the National Aeronautics and Space Administration's (NASA) rover Opportunity indicate the former existence of a salty sea on Mars, which is essential information when investigating the origin of the planet [1]. Today, images like those from Opportunity, as well as other types of data, are routinely conveyed in real time to points all over the world. Radio frequencies (RF) are usually used for such long-distance links in space. However, the recent progress in optics and laser technologies, especially in fiber optics, is ushering in an era of inter-orbit communications using laser beams. 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 [2]. The Optical Inter-orbit Communications Engineering Test Satellite (OICETS) developed by the Japan Aerospace Exploration Agency (JAXA) will be launched in summer of 2005 and will feature a laser communication link with the SILEX terminal [3]. The SmartSat-1 project of the National Institute of Information and Communications Technology (NICT) in Japan plans to demonstrate in-orbit verification of a small optical terminal on board twin satellites in 2007 [4]. NASA, in its Mars Telecommunications Orbiter project, plans to establish a laser communication link between Mars and Earth in 2010, which will be able to transmit information at a data rate of 1~30 Mbps [5].

Both RF and optical waves are electromagnetic waves; however, there are many advantages to using optical waves in space. These include reduced mass, power, and volume of equipment, higher data rates, no tariffs and no regulatory restrictions as experienced for RF bands [6]. These assets are a consequence of the high frequency of optical waves. This paper is organized as follows. The next section describes trends in satellite communications and the future use of optical communications. The main features of RF and optical communications systems in a LEO-GEO scenario are discussed in Section 3. Section 4 compares LEO-GEO, LEO-LEO, GEO-GEO, and deep space communication scenarios. Section 5 classifies the RF and optical communications systems based on their beam divergence and data rate.

2. Trends in satellite communications

2.A. Support for manned space activity

Recently, the first private manned spacecraft exceeded an altitude of 100 km twice within a 14 day period [7]. In the near future, people who have not undergone astronaut training will be able to travel into space in space planes. High-speed Internet access should therefore be available in a space plane as well. In a manned space station like the International Space Station (ISS), the leisure available to the astronauts should reflect that available on the ground. For instance, to relieve stress, popular movies, audio, and multimedia contents should be available to astronauts in the ISS. A 1-Gbps optical communication link would enable us to send, e.g., the latest movies to the ISS within one minute. Another, may be more important aspect for the ISS, is data transmission of the many scientific missions to be performed. They produce massive scientific experimental data which, in many cases, should be downloaded instantaneously to a ground station. An optical communication link is the proper medium for such infrastructure in space.

2.B. Data transmission from observation satellites

Many Earth observation satellites have been developed for weather forecasting and for probing our environment. For more accurate measurements, higher resolution will be required from onboard sensors and the frequency and area of the observations will increase. Figures 1 and 2 show trends in the data rate and resolution of the sensors for non-military Earth observation satellites. The trends cover optical sensors and RF synthetic aperture radar (SAR) systems via intersatellite and direct communication links to ground stations [8]. The data rates seem to drop with passing time for GEO. However, the data relay satellites and commercial communication satellites are not included in the figure. As recently launched commercial satellites at GEO have the total transponder bandwidth of about 1 GHz even in GEO, the communication capacity does not drop [9]. Figures 3 and 4 show the trends in data storage capacity and the number of bits per pixel of stored image data. For 2010, one can easily make the following predictions: The data rate of some satellites will increase to several gigabits per second; the angular resolution of some satellites will be approximately 0.1 μrad, corresponding to a resolution of several ten centimeters on Earth; the data storage capacity of onboard data recorders will be several terabytes; and the number of bits per pixel will be larger than 13. The acquired information will drastically increase with monitoring frequency, observation area and the resolution of the images. Monitoring from satellites will not only be done for special area but real-time observations of the entire world will take place.

Gigabit-per-second-class direct links to ground stations will be necessary during the short download time of the direct communication link from a LEO satellite. Optical communication systems are preferable for this increasing communication demand.

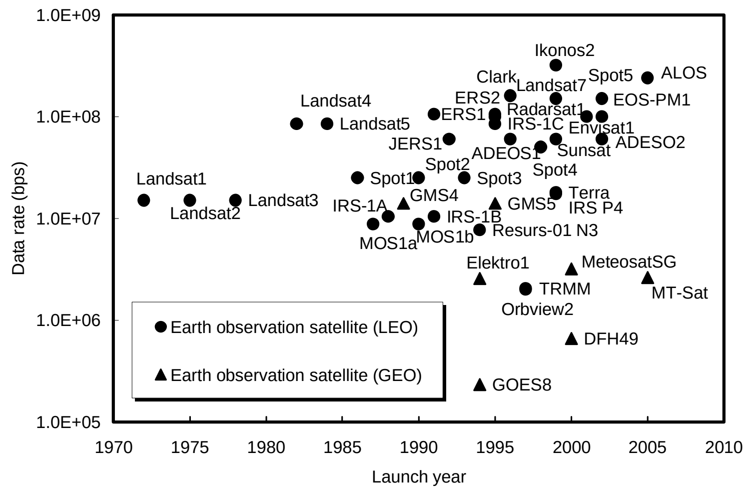

Fig. 1. Trends in data rate for the Earth observation satellites.

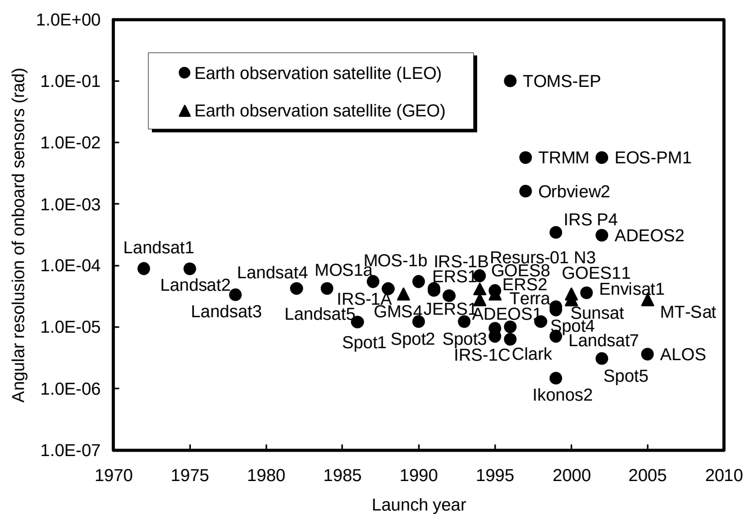

Fig. 2. Trend in the angular resolution of sensors onboard Earth observation satellites.

2.C. Data transmission from deep space probes

In deep-space probes the mass, power, and volume of onboard equipment is severely restricted and hence the antenna diameter and the transmit power are quite limited. Therefore, a large receive antenna and high power transmitter are usually installed in the ground station, which can compensate for the restrictions on the onboard resources. According to [10], lasercomm terminals for space probes have lower mass than RF systems. The mass reduction amounts to 0.65 and 0.55 for data volumes of 0.1 Gbit/day and 10 Gbit/day, respectively. If a large-aperture optical platform became available in a space station or a data relay satellite system, a small user terminal could be utilized in space probes. Such a platform would constitute an effective backbone communication station, unaffected by visibility conditions of the ground stations.

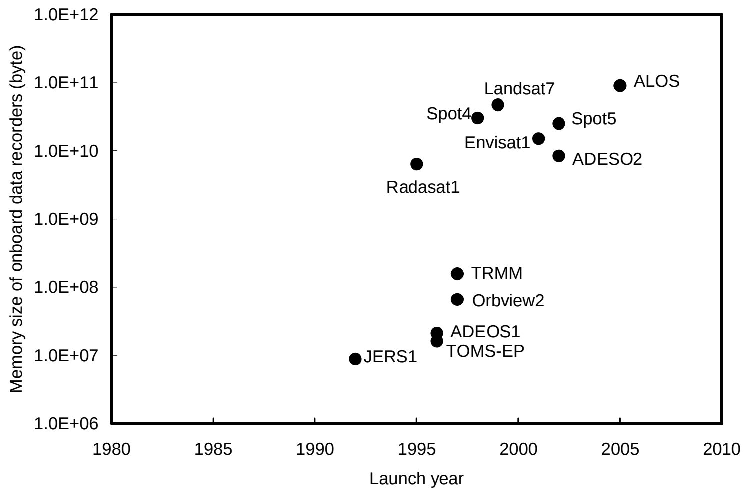

Fig. 3. Trends in the memory size of data recorders onboard Earth observation satellites in LEO.

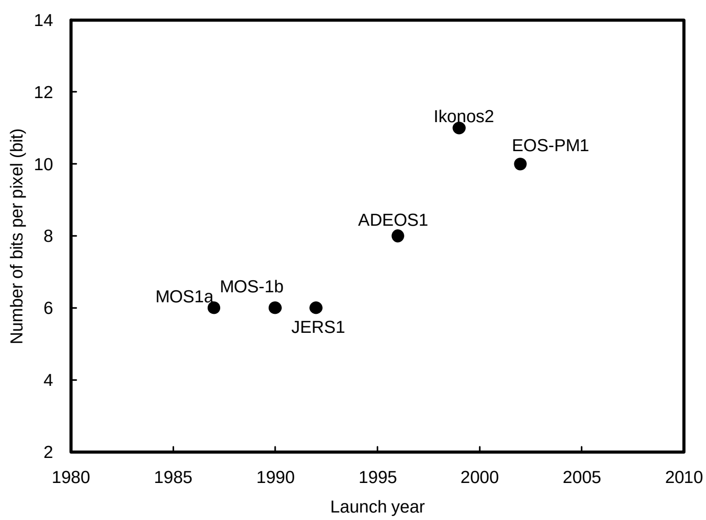

Fig. 4. Trends in the number of bits per pixel of stored image data onboard Earth observation satellite in LEO.

2.D. Communication within satellite clusters

Functions usually performed by a single large satellite can be divided among a number of co-located and interlinked smaller satellites [11]. Each small satellite may have a different limited function; however, as a whole the cluster acts as a single large satellite. Cooperative control and synchronization of maneuvers are required in order to maintain safety margins inside the co-location slots. An optical intersatellite link offers the best compromise between ease of interfacing with the switching matrix and the ability to support high-speed links among the small satellites, and there is also no interference of the optical signals [12]. A Gbit/s data link is required in the modem/switch satellite and server satellite [9]. Small terminals with antennas of a diameter of a few centimeters can establish Gbit/s communication links between small satellites, and the broadened beam divergence allowed by the short distance can strongly reduce tracking requirements.

2.E. Broadband Internet service to aircraft and space planes

In many aircraft, real-time high-speed Internet access is available in flight [13]. Aircraft equipped with Ku-band communication terminals (11.2~12.8 GHz for downlink, 14.0~14.4 GHz for uplink) offer either an Ethernet local area network (LAN) connection or a wireless 802.11b network connection, or both. The maximum data rates are presently 20 Mbps from the satellite to aircraft and 1 Mbps from the aircraft to satellite. Aircraft that fly above the cloud layer can be accessed from satellites without any attenuation by clouds and with little atmospheric turbulence. Like aircraft, high altitude platform systems and unattended aerial vehicles (UAV) are promising candidates for the application of optical communications systems [14]. Multiple access techniques employing optical phased arrays will be needed in such applications [15].

3. Features of RF and optical space communication systems

RF communications systems provide a wide-area coverage, multicasting service, and easy point-to-point wireless communications. Optical communications systems have no regulatory restrictions on the use of frequencies and bandwidths and are immune to jamming and interception by adverse parties [16]. In the following subsections, the major characteristics of the two systems are compared, considering, for simplicity, their use mainly in GEO-LEO data relay satellite communications.

3.A. Antenna diameter

To arrive at a representative value for RF satellite antenna diameters, we recall that the GEO Data Relay Test Satellite (DRTS) uses a 3.6-m center feed antenna in order to communicate with LEO user satellites at 240 Mbps in the Ka band (20/30 GHz) [17]. This antenna diameter is the maximum for the payload fairing of the Japanese H-II standard launch vehicle. A 4.6-m diameter onboard antenna will be possible when the 5S payload fairing is used for the H-IIA launch vehicle. The Delta IV and Ariane 5 launch vehicles have a payload fairing capacity of 5-m and 4.57-m diameter, respectively. However, as the antenna diameter is increased, one has to employ even lighter structures and materials. In addition, larger antennas suffer from the degradation of antenna gain due to wavefront distortion, mispointing loss, and the higher moment of inertia. Large RF antennas can be constructed right in space and several deployable and inflatable antennas have been proposed and demonstrated, but it is difficult to obtain the required surface accuracy of 0.3~0.5 mm (rms) [18].

For the optical system we resort to the SILEX system, which serves a similar purpose as the above mentioned GEO-LEO RF system. The Advanced Relay Technology Mission Satellite (ARTEMIS), which is SILEX's GEO terminal, has a 25 cm diameter optical antenna and communicates with the LEO satellite at 50 Mbps [19].

The results of link budget analyses of two RF systems (32 GHz and 60 GHz) and an optical communications system for a GEO-LEO link are summarized in Table 1 [20]. To allow a comparison with material presented in a latter section, one and the same antenna diameter for the transmitter and the receiver is taken. A 2.5 Gbps communication link can be established in all cases, assuming antenna diameters of 2.2 and 1.9 m for the Ka- and Millimeter-bands and 10 cm for the optical system, respectively.

Table 1. Examples of link budgets for two RF systems (*f*=32 GHz and *f*=60 GHz) and an optical link at λ=1.55 μm with a GEO-LEO distance of 42,000 km at a data rate of 2.5 Gbit/s.

	RF systems			
	Ka-band		Millimeter-band	
Transmit power	17.0	dBW	13.0	dBW
	50.0	W	20.0	W
Frequency	32.0	GHz	60.0	GHz
Wavelength	9.4	mm	5.0	mm
Tx antenna diameter	2.2	m	1.9	m
Tx antenna gain	55.1	dBi	59.3	dBi
Feeder loss	-3.0	dB	-2.0	dB
EIRP	69.1	dBW	70.3	dBW
Pointing loss	-0.3	dB	-1.0	dB
Polarization loss	-0.5	dB	-0.5	dB
Beam divergence	0.25	deg	0.16	deg
Path loss	-215.0	dB	-220.5	dB
Rx antenna diameter	2.2	m	1.9	m
Rx antenna gain	55.1	dBi	59.3	dBi
Feeder loss	-2.1	dB	-1.5	dB
Receive power	-93.7	dBW	-93.8	dBW
System noise	29.6	dBK	29.8	dBK
G/T	23.4	dB/K	28.0	dB/K
Noise density	-199.0	dBW	-198.8	dBW
C/N_0	105.3	dBHz	105.0	dBHz
Required C/N_0	102.0	dBHz	102.0	dBHz
Link margin	**3.4**	dB	**3.0**	dB

Optical system		
Transmit power	40.0	dBm
	10.0	W
Frequency	193	THz
Wavelength	1.55	μm
Tx antenna diameter	10.2	cm
Tx antenna gain	109.3	dB
Tx loss	-2.0	dB
Strehl ratio	-0.4	dB
Pointing loss	-3.0	dB
Beam divergence	19.3	μrad
Path loss	-290.6	dB
Rx antenna diameter	10.2	cm
Rx antenna gain	106.3	dB
Rx loss	-2.0	dB
Receive power	-42.4	dBm
Receive sensitivity	90	photons/bit
Required power	-45.4	dBm
Link margin	**3.0**	dB

3.B. Antenna coverage and tracking accuracy

For a LEO satellite orbiting at 600 km, the antenna must have a hemispherical coverage of ±115 deg towards the GEO satellite. The GEO satellite must be able to point only ±9 deg towards the LEO satellite, thus the structure of the GEO antenna system can be simpler. The Ka-band antenna for DRTS has tracking accuracies of 0.1 and 0.0043 deg for programmed pointing and autonomous tracking modes, respectively. Millimeter-band antennas require higher tracking accuracy. The beam divergence angle becomes 0.16 deg for the millimeter-band antenna. Then a tracking system will be needed for the RF communication system [21].

For the optical communication system, however, the beam divergence angle of 19.3 μrad makes it much more difficult to acquire, track, and point to the counter satellite. Because of its small beam divergence, the optical communication system will always require an automatic tracking system. For example, the pointing accuracy of 2.6 μrad as required for OICETS would not be possible without a tracking system [3]. In the optical link, the point-ahead angle, caused by the finite speed of light and the relative movement of the satellite, is not negligible against the divergence angle of the transmit beam. It may amount to several ten μrad and must be taken care of by a point ahead device.

Figure 5 gives the required antenna pointing accuracy ε as a function of antenna diameter *D* and carrier frequency *f*. For this figure the approximate relation $\varepsilon=\lambda/(20D)$ has been used [22]. From Fig. 5, one finds that RF systems with antennas in the several-meter-class must be controlled with a pointing accuracy of 100 μrad (=0.006 deg). Optical communication systems have to be able to control several-centimeter-class antennas within an accuracy of 1 μrad (=0.00006 deg). Due to the narrow optical beam, any vibration of the platform degrades the bit error ratio (BER) of the communication system [23]. As countermeasures, one may use adaptive transmitter power [24] and intentionally broadening of the beam [25]. The optimum relation between the divergence angle and vibration amplitude is derived [26]. Recently onboard optical sensors have very high resolution of the order of 1 μrad as shown in Fig. 2. Such accurate antenna tracking has been verified, e.g., in the SILEX project. It is obvious that the pointing accuracy required by optical communications systems can be obtained using currently available technology.

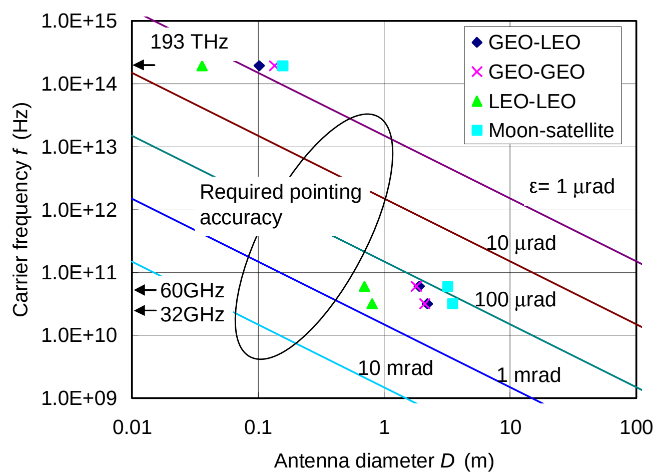

Fig. 5. Relation between carrier frequency *f* and antenna diameter *D* for different pointing accuracy ε. The symbols represent the cases discussed in Table 2.

3.C. Acquisition sequence

The procedure for the initial acquisition is the same in RF and optical communications systems. First, the antennas of the data relay and the user satellite are pointed toward each other, based on orbital calculations. At that moment, the prediction error of the antenna directions and the attitude error of the platform must be smaller than the field of view of the tracking sensors. Then the data relay satellite emits the forward beacon, the user satellite receives it, and autonomous tracking is initiated. For RF communications systems, the forward beacon may not have to be scanned if the beam divergence angle is sufficiently wide. Optical communication systems usually require forward beacon scanning. Next, the user satellite sends the return beam which will be received by the data relay satellite. The acquisition process finishes upon the convergence of the tracking error. For tracking, RF systems use a monopulse system that detects the sum and differential signals of the received power, whereas optical systems use spatial sensors such as CCD sensors, CMOS sensors and quadrant detectors.

3.D. Communication system

To cite representative transmit powers, the DRTS transmitter has an output power of 50 W in the Ka band [21], while the Communications and Broadcasting Engineering Test Satellite (COMETS) had a 20-W output power transmitter operating in the millimeter band [27]. From Table 1, establishing a 2.5-Gbps communication link is possible in the Ka and millimeter bands when the antenna diameters are 2.2 and 1.9 m for transmit powers of 50 and 20 W, respectively. In RF communication systems, the data rate is limited to about one tenth of the carrier frequency corresponding to several gigabits per second. On the other hand, as already indicated in Table 1, the corresponding optical link only requires 10 W. The data rate of optical communication systems is often limited by the received power, not by the frequency band the system offers. Thus wavelength division multiplexing (WDM) techniques enable us to set up optical links with data rates of several hundred Gbps.

4. Comparison of onboard requirements

Table 2 compares onboard resources for RF and optical communication systems. One and the same data rate of 2.5 Gbps is assumed with distances of 5,000 km, 42,000 km and 73,000 km for LEO-LEO, LEO-GEO, and GEO-GEO scenarios, respectively. For the Moon-to-satellite scenario we assume a data rate of 155 Mbps and a distance of 400,000 km. The antenna diameters are derived from the link budget analyses. Mass and power are estimated from operating systems such as DRTS and ARTEMIS by assuming the some ratios of mass and antenna diameters (power and antenna diameters). The optical antenna diameter can be smaller than for RF antennas by a factor of 13, and the mass and power for optical systems will be half of that for RF systems.

4.A. GEO-to-GEO link

GEO-GEO communication links are used to relay data from LEO user satellites, e.g. within the Space Network Interoperability Panel (SNIP). Three satellites in GEO orbit with a mutual angular distance of 120 deg can cover the entire Earth. Antennas with 2.1 and 1.8 m diameters are required for 2.5-Gbps communication links of Ka- and millimeter-band, respectively. The background temperature noise to the RF antenna is lower in the GEO-GEO link than in the GEO-LEO link; however, a major restriction is frequency interference due to the narrow positioning allocation for GEO satellites. An antenna diameter of 13.5 cm is required for the optical communication system at the same data rate. The control and structure of the antenna system are easy because the line of sight towards the counter GEO terminal is stationary.

4.B. Space station link

For a manned space station in LEO, like the ISS, to be able to continuously communicate with a ground station it is necessary to use a data relay satellite in GEO. The micro-vibration on the manned space station is usually worse than that for a satellite because of the activity of astronauts. When developing optical communications systems for a manned space station, special damping and isolation structures are required to reduce the tracking requirements. Also eye safety must be considered for the astronauts engaged in extravehicular activities (EVA). The maximum permissible exposure (MPE), which is a measure of eye safety, becomes larger at longer wavelengths; therefore, longer wavelengths should be used in a manned space station [28]. The prime power needed for the experiment can be easily provided by the main infrastructure and the thermal heat produced by the terminal can be transferred to the main structure via heat pipes, which are advantages specific for the space station.

4.C. Deep space probe-to-satellite link

If we assume a Moon-to-satellite communication link at a data rate of 155 Mbps, antenna diameters of 3.5 and 3.2 m are required for RF communication systems in the Ka and millimeter bands, whereas an optical communications system requires an antenna of only 15.7 cm diameter (see Table 2). Optical communication systems require less onboard resources. This will be especially important for deep space probes; it also reduces launch costs. In deep space communication systems, background radiation of the Earth can be used as the beacon signal for acquisition of the optical communications system.

Table 2. Comparison between optical and RF communication systems with transmit power of 10, 50, and 20 W for optical, Ka and millimeter band systems, respectively. Values in parentheses are normalized to the optical parameters.

Link senario	Data rate	Frequency band								
		Optical			Ka-band			Millimeter-band		
GEO-LEO										
Antenna dia.	2.5 Gbps	10.2	cm	(1.0)	2.2	m	(21.6)	1.9	m	(18.6)
Mass		65.3	kg	(1.0)	152.8	kg	(2.3)	131.9	kg	(2.0)
Power		93.8	W	(1.0)	213.9	W	(2.3)	184.7	W	(2.0)
GEO-GEO										
Antenna dia.	2.5 Gbps	13.5	cm	(1.0)	2.1	m	(15.6)	1.8	m	(13.3)
Mass		86.4	kg	(1.0)	145.8	kg	(1.7)	125.0	kg	(1.4)
Power		124.2	W	(1.0)	204.2	W	(1.6)	175.0	W	(1.4)
LEO-LEO										
Antenna dia.	2.5 Gbps	3.6	cm	(1.0)	0.8	m	(22.2)	0.7	m	(19.4)
Mass		23.0	kg	(1.0)	55.6	kg	(2.4)	48.6	kg	(2.1)
Power		33.1	W	(1.0)	77.8	W	(2.3)	68.1	W	(2.1)
Moon-satellite										
Antenna dia.	155 Mbps	15.7	cm	(1.0)	3.5	m	(22.3)	3.2	m	(20.4)
Mass		100.5	kg	(1.0)	243.1	kg	(2.4)	222.2	kg	(2.2)
Power		144.4	W	(1.0)	340.3	W	(2.4)	311.1	W	(2.2)

5. Classification of RF and optical communication systems

Figure 6 classifies satellite communications with respect to the beam divergence and the data rate. Alternatively, the abscissa can be read as the wavelength and the ordinate can be also interpreted as the transmit power. The hatched area represents the range where RF communication systems can be used, which is restricted by the transmitter power, the free space loss, and regulations. Employing frequencies below 3 THz must comply with radio regulations. RF communication systems should be used for multiple access, multicasting service, emergency, and omni-directional communication purposes. However, optical communication systems, with carrier frequencies of several hundred terahertz have no regulatory restrictions. Optical communication systems should be used in conjunction with narrow beams as they are required, e.g., for secure data transmission or for achieving high intensity at the receiver site.

A drawback of optical communication systems involving a ground station is the influence of atmospheric effects in the form of optical scintillation and of attenuation by clouds [29]. Theoretical analyses and some experimental results show that the uplink optical link has more serious degradation than the downlink [30,31]. Adaptive optics (AO) can compensate for optical scintillation [32]. For the transmission, the multiple laser beams can reduce the scintillation effect [33]. To reduce the effect of attenuation by clouds, a site diversity technique must be used in order to increase the link availability to satellites. For the U.S.A. it has been shown that over 90 % availability can be achieved using 4 to 5 optical ground stations set up in the mainland and in Hawaii [34].

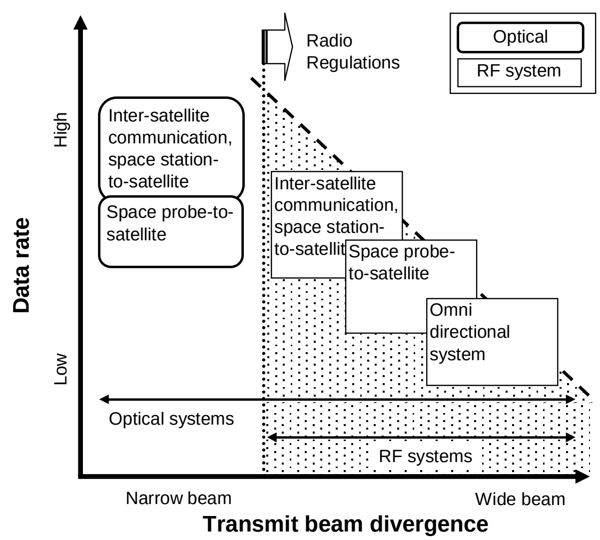

Fig. 6. Classification of the satellite communication systems by beam divergence and data rate. The hatched region shows where RF communication systems are to be preferred.

6. Conclusions

Optical communications systems have pronounced advantages over RF communications systems, such as 1/13 of the antenna diameter, half the mass and half the prime power, for achieving identical communication data rates. Considering the in-orbit verification of optical technology in the SILEX program, we are close to entering an era of inter-orbit communications using optical beams. RF communications systems provide wide coverage, multicasting service, and omni-directional applications, but optical communications systems will provide the means to meet the high-capacity and high-speed communication demands of the future. RF communication systems will continue to be the work horse for data transmission because of their proven performance and mature technology. For optical communication systems, in-orbit verification should be continued and a steady development cycle for commercializing verified technology is needed. 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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References and Links

1. http://www.nasa.gov/home/hqnews/2004/mar/HQ_04100_mars_water.html.
2. T. T. Nielsen, G. Oppenhaeuser, B. Laurent, and G. Planche, "In-orbit test results of the optical intersatellite link, SILEX. A milestone in satellite communication," in *Proceedings of 53rd International Astronautical Congress*, (IAC-02-M.2.01, Huston, Oct. 2002) pp.1-11.
3. M. Toyoshima, S. Yamakawa, T. Yamawaki, K. Arai, K. Yabe, and K. Shiratama, "Reconfirmation of the optical performances of the laser communications terminal onboard the OICETS satellite," Acta Astronautica, **55**, 261-269 (2004).
4. Y. Koyama, E. Morikawa, K. Shiratama, R. Suzuki, Y. Yasuda, "Optical terminal for NeLS in-orbit demonstration," Proc. SPIE **5338**, 29-36 (2004).
5. D. M. Boroson, "Overview of NASA's Mars laser communications demonstration system," Proc. SPIE **5338**, 16-28 (2004).
6. B. M. Folio and J. M. P. Armengol, "Redio frequency and optical inter satellite links comparison for future identified scenarios," in *CNES Workshop on Intersatellite Links*, Toulouse, 27-28 November (2003).
7. http://www.scaled.com/projects/tierone/041004_spaceshipone_x-prize_flight_2.html.
8. D. Baker, ed., *Jane's Space directory*, (Sixteenth Ed. 2000-2001, Jane's Information Group, Surrey, 2000).
9. N. Nishinaga, Y. Takayama, T. Takahashi, Y. Ogawa, T. Kubooka, H. Umehara, "Study for HDR cross-link for formation flight satellite systems," Proc. SPIE **4975**, 45-56 (2003).
10. K. Wilson, and M. Enoch, "Optical Communications for Deep Space Mission," IEEE Commun. Magazine **38**, 134-139 (2000).
11. http://telecom.esa.int/telecom/www/object/index.cfm?fobjectid=8929.
12. W. R. Leeb, A. Kalmar, K. H. Kudielka, P. J. Winzer, "Optical terminals for microsatellite swarms," Proc. SPIE **4635**, 202-214 (2002).
13. http://www.connexionbyboeing.com/.
14. G. G. Ortiz, S. Lee, S. P. Monacos, M. W. Wright, A. Biswas, "Design and development of robust ATP subsystem for the Altair UAV-to-ground lasercomm 2.5-Gbps demonstration," Proc. SPIE **4975**, 103-114 (2003).
15. P. F. Mcmanamon, T. A. Dorschner, D. L. Corkum, L. J. Friedman, D. S. Hobbs, M. Holz, S. Liberman, H. Q. Nguyen, D. P. Resler, R. C. Sharp, and E. A. Watson, "Optical phased array technology," Proc. IEEE, **84**(2), 268-298 (1996).

16. G. Hyde and B. I. Edelson, "Laser satellite communications: current status and directions," Space Policy, **13**, 47-54 (1997).

17. S. Kosugi, Y. Sudo, N. Batori, N. Hotta, M. Amano, "Development of Data Relay Test Satellite (DRTS) Inter-orbit Communication Equipment (ICE) Proto-Flight Model (PFM)," in *Proceedings of 7th Ka-band Utilization Conf.*, (Italy, 2001) pp.85-92.

18. T. Iida and K. Okamoto, "A space station experiment on large antenna assembly and measurement," Acta Astronautica, **12**, 335-344 (1985).

19. A. Sbardellati, T. Sassorossi, M. Marinelli, and R. Guibilei, "The communication payload of the ARTEMIS European satellite," in *Proceedings of AIAA Conf.*, (AIAA-94-0905-CP, 1994), pp.22-32.

20. T. Iida, ed., in *Satellite communications*, (Ohmusha, Tokyo, 1997), Chap 4, p. 134 (in Japanese).

21. Y. Fujiwara and H. Nagano, H. Yonechi and H. Ebisutani, "The performance of attitude control system on orbit of Data Relay Test Satellite (DRTS)," in *Proceedings of 21st International Communications Satellite Systems Conf. of AIAA*, (AIAA-2003-2365, April 2003), pp.1-8.

22. V. W. S. Chan, "Optical satellite networks," J. Lightwave Technol. **21**, 2811-2827 (2003).

23. S. Arnon, "Power versus stabilization for laser satellite communication," Appl. Opt., **38**(15), 3229-3233 (1999).

24. S. Arnon, N. S. Kopeika, D. Kedar, A. Zilberman, D. Arbel, A. Livne, M. Guelman, M. Orenstain, H. Michalik and A. Ginati, "Performance limitation of laser satellite communication due to vibrations and atmospheric turbulence: down-link scenario," Int. J. Satell. Commun. Network., **21**, 561-573 (2003).

25. S. Arnon, S. Rotman, N. S. Kopeika, "Beam width and transmitter power adaptive to tracking system performance for free-space optical communication," Appl. Opt., **36**(24), 6095-6101 (1997).

26. M. Toyoshima, T. Jono, K. Nakagawa and A. Yamamoto, "Optimum divergence angle of a Gaussian beam wave in the presence of random jitter in free-space laser communication systems," J. Opt. Soc. Amer. A, **19**(3), 567-571 (2002).

27. T. Takahashi, H. Li, N. Yoshimura, K. Suzuki, and T. Ikegami, "In-orbit performance evaluation of O-band communication equipment on ETS-VI," IEICE trans. **J81-B2**, 373-380 (1998).

28. IEC specifications in *Safety of laser products*, "Part 12: Safety of free space laser communication systems used for transmission of information," IEC60825-12, Ed. 1.0 (2004).

29. L. C. Andrews and R. L. Phillips, in *Laser Beam Propagation through Random Media* (SPIE Optical Engineering Press, Bellingham, Wash., 1998).

30. M. Toyoshima and K. Araki, "Far-field pattern measurement of an onboard laser transmitter by use of a space-to-ground optical link," Appl. Opt., **37**(10), 1720-1730 (1998).

31. D. Bushuev, D. Kedar, S. Arnon, "Analyzing the performance of a nanosatellite cluster-detector array receiver for laser communication," J. Lightwave Technol., **21**(2), 447-455 (2003).

32. R. K. Tyson, "Adaptive optics and ground-to-space laser communications," Appl. Opt. **35**, 3640-3646 (1996).

33. M. Toyoshima, S. Yamakawa, T. Yamawaki, K. Arai, M. Reyes, A. Alonso, Z. Sodnik, and B. Demelenne, "Long-term statistics of laser beam propagation in an optical ground-to-geostationary satellite communications link," IEEE trans. Antennas and Propagat., **53**(2), 842-850 (2005).

34. R. Link, R. Alliss, M. E. Craddock, "Mitigating the impact of clouds on optical communications," Proc. SPIE **5338**, 223-232 (2004).