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Chapter Glossary

(ADCS)	Attitude Determination and Control System
(BPF)	BandPass Filters
(CDH)	Command and Data Handling
(COTS)	Commercial-off-the-Shelf
(DORA)	Deployable Optical Receiver Aperture
(DLR)	German Aerospace Center
(DSN)	Deep Space Network
(DSP)	Digital Signal Processing
(DVB-S2)	Digital Video Broadcast Satellite Second Generation
(FCC)	Federal Communications Commission
(FIPS)	Federal Information Processing Standard
(FPGAs)	Field Programmable Gate Arrays
(FSM)	Fine-steering Mirror
(FSO)	Free Space Optical
(IARU)	International Amateur Radio Union
(IEEE)	Institute of Electrical and Electronics Engineers
(ISARA)	Integrated Solar Array and Reflectarray Antenna
(ISM)	Industrial, Scientific, and Medical
(ISOC)	Inter-spacecraft Optical Communicator
(ISS)	International Space Station
(JAXA)	Japanese Aerospace Exploration Agency
(JPL)	Jet Propulsion Laboratory
(LADEE)	Lunar Atmosphere and Dust Environment Explorer
(Lasercom)	Laser Communications
(LCH)	Laser Clearing House
(LCT)	Laser Communication Terminals
(LDPC)	Low-Density Parity-check Code
(LLCD)	Lunar Laser Communications Demonstration
(LNA)	Low Noise Amplifier
(LSRB)	Laser Safety Review Board
(MA)	Multiple Access
(MarCO)	Mars Cube One
(MEMS)	Micro-Electro-Mechanical Systems

(MRR)	Modulating Retro-Reflector
(NEN)	Near Earth Network
(NICT)	National Institute of Information and Communications Technology
(NOAA)	National Oceanic and Atmospheric Administration
(NPR)	NASA Procedural Requirements
(NSN)	Near Space Network
(NTIA)	National Telecommunications and Information Administration
(OCSD)	Optical Communication and Sensor Demonstration
(OCTL)	Optical Communication Telescope Laboratory
(OSIRIS)	Optical Space Infrared Downlink System
(PAT)	Pointing, Acquisition, and Tracking
(RF)	Radio Frequency
(SBIR)	Small Business Innovative Research
(SCaN)	Space Communications and Navigation
(SDR)	Software Defined Radios
(SME)	Subject Matter Expert
(SNR)	Signal-to-Noise Ratio
(SOTA)	Small Optical Transponder
(SWaP)	Size, Weight, and Power
(SST)	NASA Small Spacecraft Technology Program
(TDRS)	Tracking and Data Relay Satellite
(TMA)	Technology Maturity Assessments
(TRL)	Technology Readiness Levels
(TT&C)	Tracking, Telemetry & Command
(USTP)	University SmallSat Technology Partnerships
(VSOTA)	Very Small Optical Transponder
(WFF)	Wallops Flight Facility

9.0 Communications

9.1 Introduction

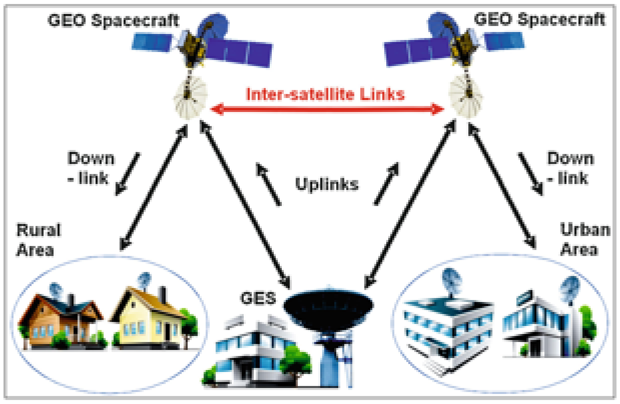

Figure 9.1: Satellite uplink, downlink, and crosslink. Credit: D. Stojce (2019).

For most missions, the communication system enables the spacecraft to transmit data and telemetry to Earth, receive commands from Earth, and relay information from one spacecraft to another. A communications system consists of the ground segment—one or more ground stations located on Earth—and the space segment—one or more spacecraft and their respective communication payloads. The three functions of a communications system are receiving commands from Earth (uplink) and transmitting data down to Earth (downlink), and transmitting or receiving information from another satellite (crosslink or inter-satellite link) (Figure 9.1). There are two types of communication systems: radio frequency (RF) and free space optical (FSO); FSO is also referred to as laser communications (lasercom).

Most spacecraft communications systems are radio-frequency-based. They typically operate within the designated Institute of Electrical and Electronics Engineers (IEEE) radio bands of 300 MHz to 40 GHz. RF systems communicate by sending data using electromagnetic waves to and from antennas. Information is modulated onto radio frequency electromagnetic waves and sent over a channel, through the atmosphere or space, to the receiving system where it is demodulated (Figure 9.2).

Although RF systems are typically used for low-rate space communication, recent developments in FSO communications have made FSO a compelling alternative to RF systems, particularly for high-rate communication. FSO systems consist of a transmitting terminal and receiving terminal. Like an RF system, information is modulated onto electromagnetic waves (at optical frequencies) and sent over a channel to the receiving system. FSO links operate at higher frequencies than RF links, generally in the near-infrared bands (e.g., 1064 nm or 1550 nm). Visible light is often

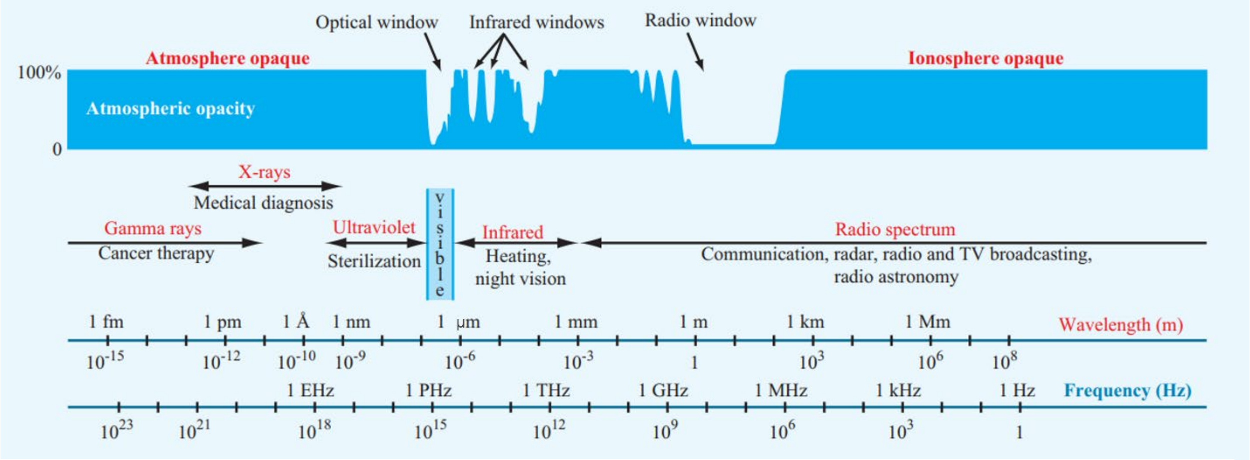

Figure 9.2: Atmospheric opacity of the electromagnetic wave spectrum with the infrared and radio windows used by spacecraft for communication. Credit: Microwave Radar and Radiometric Remote Sensing by Ulaby and Long.

not used due to eye safety concerns for technicians at the terminals. The use of higher frequencies and wider bandwidths can support higher data rates, but the shorter wavelengths also result in narrower beamwidths that require more accurate pointing towards the communication terminal with greater accurately and precisely.

This chapter organizes the state-of-the-art in small spacecraft communications technologies into two main categories: RF and FSO. Tables at the end of each section list hardware options for RF and developing FSO technologies for mission designers to consider.

The information described below is not intended to be exhaustive, but provides an overview of current state-of-the-art technologies and their development status for a particular small satellite subsystem. The list of organizations/companies in this chapter is not all-encompassing and does not constitute an endorsement from NASA. There is no intention of mentioning certain companies and omitting others based on their technologies or relationship with NASA. The information is for awareness and guidance only. The performance advertised may differ from actual performance since the information has not been independently verified by NASA subject matter experts and relies on information provided directly from the manufacturers or available public information. It should be noted that TRL designations may vary with changes specific to the payload, mission requirements, reliability considerations, and/or the environment in which performance was demonstrated. Readers are highly encouraged to reach out to companies for further information regarding the performance and TRL of the described technology.

9.2 State-of-the-art: Radio Frequency Communications

A radio communication system includes a radio transmitter, a free-space communication channel, and a radio receiver. At the top level, a radio transmitter system consists of a data interface, modulator, power amplifier, and an antenna. The transmitter system uses the modulator to encode digital data onto a high-frequency electromagnetic wave. The power amplifier then increases the output RF power of the transmitted signal to be sent through free space to the receiver using the transmit antenna.

The radio receiver system uses a receiving antenna, low-noise amplifier, and demodulator to produce digital data output from the received signal. The receiving antenna collects the electromagnetic waves and routes the signal to the receiver, which then demodulates the wave and converts the electrical signals back into the original digital message. Low-noise amplifiers are sometimes employed to minimize thermal noise in certain frequency bands and/or increase the received signal strength. In many cases, the functions of the modulator and demodulator are combined into a radio transceiver that can both send and receive RF signals.

Radio frequency communications for spacecraft are conducted between approximately 30 MHz and 60 GHz. The lower frequency bands (up to S-band) are typically more mature for SmallSat use; however, extensive use of these bands has led to crowding and challenges in acquiring licensing. Higher frequencies offer a better ratio of gain-to-aperture-size, but this is offset by the increased atmospheric attenuation at those frequencies and the higher free space loss that is directly proportional to the square of the frequency.

9.2.1 Frequency Bands

Satellite communications are conducted over a wide range of frequency bands. The typical bands considered for small satellites are UHF, S, X, and Ka. The most mature bands used for CubeSat communication are VHF and UHF frequencies. There has been a shift in recent years towards S and X, with Ka-band also being used for recent and future small satellite communications. The move to higher frequency bands has been driven by a need for higher data rates. At the higher frequencies, there is generally greater atmospheric and rain attenuation adding to increased free space loss. This needs to be compensated for with higher power transmission and/or higher gain antennas with narrower beamwidths. Moving to higher-gain antennas increases the pointing accuracy required for closing the link. See Table 9-1 for a list of RF bands.

Table 9-1: Radio Frequency Bands

Band	Frequency
VHF	30 to 300 MHz
UHF	300 to 1000 MHz
L	1 to 2 GHz
S	2 to 4 GHz
C	4 to 8 GHz
X	8 to 12 GHz
Ku	12 to 18 GHz
K	18 to 27 GHz
Ka	27 to 40 GHz
V	40 to 75 GHz

NASA spacecraft, which use the government bands of S-band, X-band, and Ka-band, may use the NASA Near Space Network (NSN). The primary frequency bands of S, X, and Ka are more advantageous than using the UHF band, which has a higher probability of local interference. Satellite Tracking, Telemetry & Command (TT&C) is typically conducted over S-band. Non-NASA spacecraft have access to a wide variety of ground system options ranging from do-it-yourself to pay-per-pass services.

In L-band, CubeSats can take advantage of legacy communications networks such as Globalstar and Iridium by using network-specific transponders to relay information to and from Earth. These networks reduce dependence on dedicated ground station equipment. However, they can only be used at orbital altitudes below the communication constellation and require experimental frequency authorization.

Ku-, K-, and Ka-band communication systems are the state-of-the-art for large spacecraft, especially in spacecraft-to-spacecraft communications, but they are still young technologies in the CubeSat world. They are becoming more attractive to SmallSat designers as the lower frequencies become more congested. At the higher frequencies, rain fade becomes a significant problem for communications between a spacecraft and Earth (1). Nonetheless, the benefits of operating at higher frequencies have justified further research by both industry and government alike. At JPL, the Integrated Solar Array and Reflectarray Antenna (ISARA) mission demonstrated high bandwidth Ka-band CubeSat communications with over 100 Mbps downlink rate (2). The back of the 3U CubeSat was fitted with a high gain reflectarray antenna integrated into an existing solar array. The successful demonstration of the reflectarray on ISARA became the basis for the Mars Cube One (MarCO) mission to Mars. The MarCO mission uses two twin CubeSats for a communications relay between the InSight lander and Earth. Using a X-band reflectarray they were able to successfully complete their mission (3). Another mission to use Ka-band for DTE communications was the Kepler telescope, launched in 2009. With future missions being increasingly data hungry, we are likely to see a shift towards Ka-band and, possibly, even higher frequencies.

CubeSats have also used the unlicensed Industrial, Scientific, and Medical (ISM) bands for communications. The Ames TechEdSat team has successfully demonstrated WiFi to downlink data at 1 Mbps. Notably, a group at Singapore's Nanyang Technological University used a 2.4 GHz ZigBee radio on its VELOX-I mission to demonstrate commercial-off-the-shelf (COTS) land-based wireless systems for inter-satellite communication (4). Similarly, current investigations are exploring the use of wireless COTS products, such as Bluetooth-compatible hardware, for inter-satellite communications (5).

9.2.2 System Architecture

A small satellite RF communications system consists of a transceiver comprised of a radio, an amplifier, and an antenna. Radios receive a message from the onboard computing subsystem, then produce and modulate an electromagnetic wave to create a signal. They are responsible for generating the signal and modulating or demodulating it. The radio is also where coding may be added to the signal. Channel coding is added to provide data error detection and correction capabilities, which ensures reliable communication under the conditions imposed by the satellite transmission path. From Shannon's equation (6), it is known that the information capacity of a channel is related to its bandwidth and signal-to-noise ratio (SNR). The channel capacity (information flow) can be increased by increasing the SNR or the bandwidth, and many modulation and coding schemes make effective use of this tradeoff.

Radios offer some power amplification, but often the signals from small satellites require a greater boost. The power amplifier will take the signal from the radio and increase the RF output power before sending it to the transmit antenna. On the receive side, a low noise amplifier will take the weak signal from the receive antenna and amplify it while minimizing thermal noise. A bandpass filter might be used before the LNA to reject undesired frequencies. The radio will then be able to process the stronger signal with higher accuracy. In RF communications the role of the antenna is to increase and focus the strength of the signal in a specific direction. The digital message encoded on the RF carrier signal will be sent to and from the antennas of each system. See Figure 9.3 for an example transmit and receive block diagram.

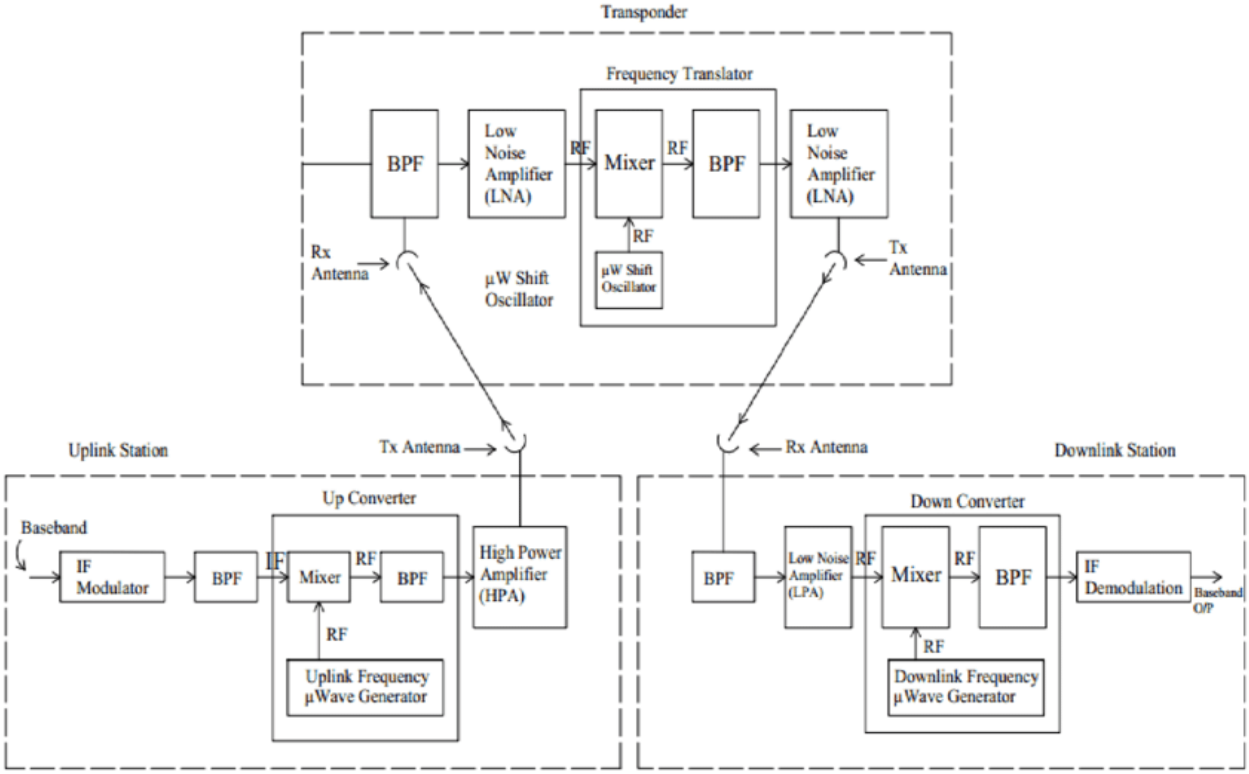

Figure 9.3: Transmit and receive block diagram. Credit: Karim et al. (2018). http://creativecommons.org/licenses/by/4.0/

9.2.3 Major Components in SmallSat Communication Systems

- Radio or Modulator/Demodulator: on the transmit side, it produces, modulates, codes, and amplifies an electromagnetic wave to create a signal. Adds modulation and coding as needed. As a receiver it decodes and demodulates received signals.
- Mixers: RF mixers are used in communications systems to change the frequency of the signal. If the frequency generated by the radio is not the desired transmit frequency, then an upconverter will convert the signal to a higher frequency for transmit. Similarly, the downconverter will downconvert a receive frequency to a lower one for processing.
- Filters: bandpass filters are used to reject undesired frequencies, typically before the LNA or downconverter.

- Amplifier: a power or gain amplifier is required for a transmit system. A low noise amplifier (LNA) is required for a receive system. LNAs, in addition to amplifying the (low power) received signal, serve to minimize the system noise temperature.
- Antenna: increases the strength of a signal in a specific direction, relative to the same signal strength without directionality. Transmits signals fed to it by a transmitter and receives signals propagated across free space. Antennas can be low-gain and omni-directional with a broad beam, or high-gain & directional with a narrow beam.
- Encryption: a cryptographic unit is an integrated encryptor/decryptor device that provides secure uplink, downlink, or crosslink for satellite communication links. Most small satellite designers will not require a cryptographic payload unit based on their threat level and may be able to use the communications radio for simple encryption schemes.
- Spread-spectrum communication applies a known frequency spreading function to the signal, which helps reduce interference from other transmitters, and provides more secure communications; as such, it is often used for multi-way communication networks. For example, the NASA Tracking and Data Relay Satellite (TDRS) multiple-access mode requires spread spectrum signals to support multiple simultaneous communication links.

9.2.4 Design Considerations

As with all spacecraft subsystems, there are power and mass constraints placed on the communications system. Based on these restrictions, several trade studies need to be performed to choose the optimal design. When designing an RF communications system, the first trades performed are for data rate, power consumption, and total mass. For example, a mission with high data rate needs would select a high frequency such as X-band for downlink and a directional high-gain antenna. Based on the ground station locations available, engineers would perform link budget analyses to determine the minimum power needed for a specific ground station antenna. This analysis would factor in rain and atmospheric attenuation, as well as modulation and coding. A few different link budget trades will be run, varying antenna size, RF output power and data rate. Each link will return a different margin of decibels, representing the reliability of the system. The engineers will proceed to calculate the final mass and power for each configuration. The mission designer will have a limit on mass and power constraints for the communications subsystem. Each configuration traded will compare data rate, power, and mass. A high data rate downlink may cost a high amount of mass for the antenna and power for the amplifier and radio. Conversely, a low-power, low-mass system may have a lower data rate.

Another factor that is considered in the design phase is pointing. Depending on the orbit of the satellite and whether the link is uplink/downlink, or crosslink, the system may have a specific pointing requirement. Large satellites frequently use gimbals—platforms that can pivot to point their antennas. The addition of a gimbal will increase the overall mass and power draws of the system. CubeSats frequently trade high-gain antennas for low-gain, omni-directional ones to maintain the link regardless of directionality. CubeSats may also change their attitude to point a body-mounted antenna, rather than use a gimbal.

9.2.5 Policies and Licensing

Any non-Federal U.S. spacecraft with a transmitter must be licensed by the Federal Communications Commission (FCC). The types of RF licenses used by small satellites are: Amateur (FCC Part 97) and Experimental (FCC Part 5) (7). An amateur license type of authorization is limited to hobbyists and non-profit use and comes with many FCC restrictions. Experimental Part 5 licenses are commonly used for university CubeSats and can be granted for a CubeSat operating in the amateur band (a SmallSat or SmallSat constellation can also apply under provisions of Part 25). A spacecraft with any sort of remote sensing capability must contact the National Oceanic and Atmospheric Administration (NOAA) to find out if a NOAA license is required. A NOAA license is not an RF license and conveys no authority for the radiation of RF energy for communication. For government missions the National Telecommunications and Information Administration (NTIA) is the licensing authority.

For amateur licensing, there must be an FCC licensed amateur radio control operator. Downlink telemetry and communications cannot be obscured (encrypted). Use of science gathered via amateur radio downlink for profit ("pecuniary interest") is prohibited. Frequency "assignment" in the amateur-satellite allocations requires coordination, a process administered by the International Amateur Radio Union (IARU) (8).

In 2018, the FCC adopted a Notice of Proposed Rulemaking to develop a new authorization process tailored specifically to small satellite operations, keeping in mind efficient use of spectrum and mitigation of orbital debris. Small satellites that would qualify for the new rules include those with 10 or lesser number of satellites under a single license. All individual satellites will have to be at least 10 cm or larger in the smallest dimension and weigh less than 180 kg. The maximum in-orbit lifetime of each individual satellite will be six years, including de-orbiting time, and they would have to be deployed under 600 km altitude. Each satellite will have a unique telemetry marker for tracking and will not release any debris (9).

9.2.6 Encryption

Encryption is the process of encoding information to conceal it from outside actors. Small satellites can use a cryptographic unit to encrypt or decrypt data prior to transmission. When data is being prepared for transmission, it is divided into packets. These packets are then scrambled according to the encryption scheme being used. An encryption scheme uses an encryption key generated by an algorithm to encode the data. The authorized receiver of the encrypted data will be able to decrypt the message using the appropriate key. Without the authorized key, decrypting the data will be extremely difficult.

With the increased proliferation of small satellites in low-Earth orbit comes an increase in vulnerabilities. Many SmallSats are comprised of COTS hardware and/or open-source software. While this strategy allows for a more flexible design approach, adversaries can gain insight into the design. Encryption of data in transit helps prevent other actors from commanding satellites or intercepting transmissions.

NASA requires any of its propulsive spacecraft within 2 million kilometers of Earth to protect their command uplink with encryption that is compliant with Level 1 of the Federal Information Processing Standard (FIPS) 140-3 (10). The FCC has also considered requiring encryption on the telemetry, tracking, and command communications as well as mission data for propulsive spacecraft, but decided not to incorporate a specific requirement at this time. A satellite with an amateur license cannot encrypt transmissions in any way and must consist of open information. The eligibility rules are listed in 47 CFR Part 97 (11).

9.2.7 Antennas

Antennas are used for propagating data through free space using electromagnetic waves. RF antennas are typically sized for their respective frequencies. This means that antennas are often chosen or designed specifically for their mission. COTS antennas are available for SmallSats and can be built to order. For missions that don't have high data rate requirements, a simple patch or monopole antenna with low gain and efficiency will suffice. Due to their low directionality, these antennas can generally maintain a communication link even when the spacecraft is tumbling, which is advantageous for CubeSats lacking good attitude and accurate pointing control. New developments in antenna design have put technologies like the deployable reflector antenna, reflectarray, and passive or active array antennas on the horizon for small satellites. Please see Table 9-2 for information on commercially available antennas for SmallSats/CubeSats.

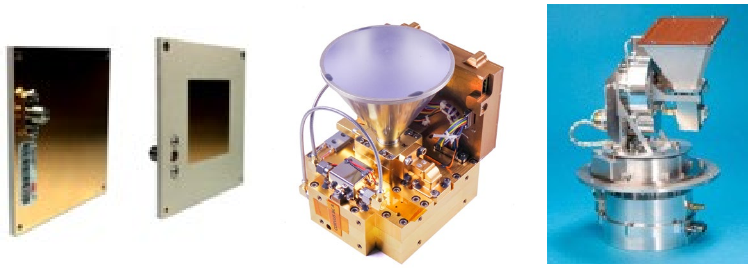

Figure 9.4: (from left to right) CubeSat-compatible S-band patch antenna (IQ spacecom), X-band high-gain antenna and pointing mechanism (Surrey Satellite Technology, Ltd.), and Ka-band transmitter with a horn antenna (Astro Digital).

There are two primary classifications of antenna: fixed or deployable. Fixed antennas do not require any power or triggering mechanisms. They remain stationary in the position that they are attached to the spacecraft. This includes patch antennas, array antennas, monopole antennas, omni-directional antennas, and horn antennas (see Figure 9.4). Deployable antennas require power to deploy and use mechanisms to configure into their final position. This includes whip antennas, parabolic reflectors, reflectarrays, helical and turnstile antennas (see Figure 9.5).

A communications link is often characterized by the frequency and data rate. The antenna is a key design decision for meeting data rate objectives by increasing link margin. Increasing the aperture or diameter of an antenna increases the link margin, which can allow designers to increase the data rate of the system or reduce the necessary transmit power.

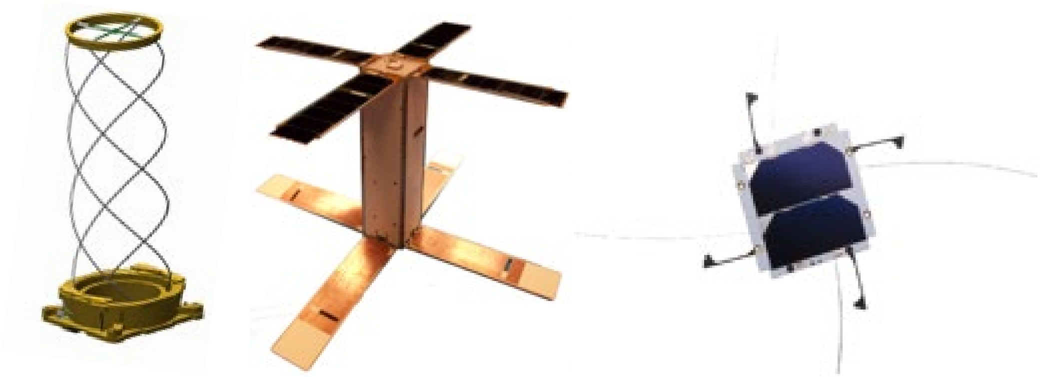

Figure 9.5: (from left to right) Example of deployable quadrifilar helical antenna (Helical Communication Technologies), SNaP spacecraft with Haigh-Farr's deployable UHF Crossed Dipole antenna (Space Missile and Defense Command), and EnduroSat UHF antenna with EnduroSat solar panels (EnduroSat).

9.2.8 Radios

Radios for SmallSat downlink are transceivers (transmitter and receiver in one). Transceivers convert digital information into an analog RF signal using a variety of modulation and coding schemes. Radios for TT&C are designed for low data rates, with high reliability and only need to transmit health data and receive commands. Traditional radios may be locked to a single frequency band and modulation/coding scheme based on their design and build. Software-defined radios (SDR) have some or all the radio's functions implemented in digital signal processing (DSP) software rather than hardware, Figure 9.6. Furthermore, spacecraft teams can change such characteristics on-orbit by uploading new settings from the ground. By using Field Programmable Gate Arrays (FPGAs), SDRs have great flexibility that allows them to be used with multiple bands, filtering, adaptive modulation, and coding schemes, without much (if any) change to hardware (12). SDRs are especially attractive for use on CubeSats, as they are becoming increasingly small and efficient as electronics become smaller and require less power. NASA has been operating the Space Communications and Navigation (SCaN) Testbed on the International Space Station since 2012 for the purpose of SDR TRL advancement, among other things (13). Many radios can provide RF output power to the antenna directly. For higher power applications, an external RF amplifier or high gain antenna may be used. See Table 9-3 for information on commercially available radios for SmallSat/CubeSats.

Figure 9.6: Example of software defined radio, tunable in the range 70 MHz to 6 GHz. Credit: GomSpace.

This report recommends efficient modulation and coding schemes for spacecraft power and bandwidth to increase the data rate and meet bandwidth constraints with the limited power and mass for CubeSat spacecraft. Advanced coding, such as the Consultative Committee for Space Data Systems (CCSDS) low-density parity-check code (LDPC) family, with various code rates, is a powerful technique to provide bandwidth and power with high-order modulation to achieve high data rate requirements for CubeSat missions. Digital Video Broadcast Satellite Second Generation (DVB-S2), a significant satellite communications standard, is a family of modulations and codes for maximizing data rates and minimizing bandwidth use. DVB-S2 uses power and bandwidth efficient modulation and coding techniques to deliver performance approaching theoretical limits of RF channels. NASA's NSN has conducted testing at NASA Wallops Flight Facility (WFF) to successfully demonstrate DVB-S2 over a S-band 5 MHz channel achieving 15 Mbps with 16 APSK LDPC 9/10 code (14).

Table 9-2: Antennas									
Manufacturer	**Product**	**Type**	**Min Frequency**	**Frequency Band**	**Gain**	**Polarization**	**Mass**	**Dimensions**	**Flight Heritage**
---	**---**	**---**	**[MHz]**	**--**	**[dBi]**	**--**	**[g]**	**[cm]**	**---**
MMA Design	LAMBDA	Deployable Sinuous Antenna	100	UHF	>-1	Dual CP	4000	20x15x10 (stowed) 100x100 (deployed)	N
Oxford Space Systems	Helical antenna (high RF power handling)	Deployable	118-127/127-137	VHF	>2.5 (isoflux)	LHCP	<1400	40x35x34.5	Y
2NDSpace	CHORUS-01 LP	Dual Dipole	140 - 930	20	0	2x Linear	90	10x10x0.8	Y
2NDSpace	CHORUS-01 LP	Turnstile	140 - 930	20	0	Circular	90	10x10x0.8	Y
Oxford Space Systems	Yagi antenna	Deployable	156.5-162.5	VHF	>6.5	Dual Linear	<1000	92.5 x 50 (deployed)	Y
Spacemanic	Small Antenna Module	Dipole Cross Dipole	145 400 435	VHF, UHF	2.1	Linear/ RHCP	55	9.8X9.8X0.56	Y
Haigh-Farr, Inc.	Part Number: 17100	Crossed Dipole	307	VHF, UHF	--	RHCP	267	32x8x1	Y
Anteral	2211-301-01	Monopole antenna	400	UHF	--	Single linear polarized	--	--	Y
GomSpace	NanoCom ANT430	Omni Canted Turnstile	400-435	VHF, UHF	1.5	Circular	30	10x10	Y
Helical Communications Technologies	Helios Deployable Antenna	Helical	400-3000	VHF, S	3	Circular	180	10x10x3.5	Y
NanoAvionics	CubeSat UHF Antenna System 1x1U	Turnstile	400-500	UHF	1.37	--	33	10x10x0.7	Y
NanoAvionics	CubeSat UHF Antenna System 1x2U	Turnstile	400-500	UHF	2.31	--	50	20x10x0.7	Y

Table 9-2: Antennas

Manufacturer	Product	Type	Min Frequency	Frequency Band	Gain	Polarization	Mass	Dimensions	Flight Heritage
---	---	---	[MHz]	--	[dBi]	--	[g]	[cm]	---
NanoAvionics	CubeSat UHF Antenna System 2x2U	Turnstile	400-500	UHF	3.4	--	65	20x20x0.7	Y
EnduroSat	UHF Antenna IU	Whip/Burn-wire	435-438, 400-403	UHF, VHF	> 0	RHCP	85	10x10	Y
EnduroSat	UHF Antenna 2U	Whip/Burn-wire	435-438, 400-403	UHF, VHF	> 0	Linear	210	22.5x9.9x1.4	Y
SENyT	UHF antenna	Deployable turnstile	430-440	UHF	0	Circular	< 150	10x10x3 folded	N
ISISPACE	CubeSat Antenna System for 1U/3U	Tape	--	VHF, UHF	0	Circular, Linear	89	10x10x0.7	Y
Flexitech Aerospace	600MHz - 10GHz Spiral Antenna	Spiral	600-10000	UHF, L, S, C, X	3	Circular	1283	17x17x8.5	N
Oxford Space Systems	Helical antenna	Deployable	862–928	UHF	> 6.5-7.5	RHCP	<235	30 (deployed helical length)	Y
CesiumAstro	Vireo L-Band Phased Array	APA	960	L	22	Circular	49100	114x100x13.5	N
Anteral	2211-119-03 L2-Band DCP	2-port dual-circular-polarized (DCP) patch antenna	1200-1300	L	5.8	RHCP & LHCP	150	9.6x9.6x0.7 (excluding connector)	N
SENyT	Dual-band GNSS antenna	Patch	1215-1240 1560-1590	L	4.5	RHCP	< 100	10x10x0.35	N
EnduroSat	GNSS Patch Antenna L1+L2	Patch	1227.60 1575.42	L	3.3+	RHCP	114	8.3x9.8x0.8	N
Anteral	2211-119-02 L1-Band DCP	2-port DCP patch antenna	1550-1600	L	6	RHCP & LHCP	150	9.6x9.6x0.7 (excluding connector)	N
EnduroSat	GNSS Patch Antenna L1/E1	Patch	1559–1591	L	3.6+	RHCP	17	8.3 x 9.8 x 0.8	Y

Table 9-2: Antennas

Manufacturer	Product	Type	Min Frequency	Frequency Band	Gain	Polarization	Mass	Dimensions	Flight Heritage
---	---	---	[MHz]	--	[dBi]	--	[g]	[cm]	---
SkyFox Labs	piPATCH-L1E1	Patch	1575.42	GPS-L1 GALILEO E1	--	--	50	9.8x9.8x1.3	Y
NAL Research Corporation	Antenna SYN7391-A/B/C (Iridium)	Flat Mount	1610-1626.5	L	4.9	RHCP	31	4.6x.4.3x1.0	Y
Oxford Space Systems	Helical antenna (high RF power handling)	Deployable	1980-2200	S	>4.0-4.5	RHCP	<1200	60 (deployed helical length)	Y
IQ spacecom	S-Band Single Patch Antenna	Patch	1980-2500	S	6	Circular	49	7x7x0.34	Y
IQ spacecom	S-Band Dual Patch Antenna	Patch	1980-2500	S	6	Circular	62	8x10x0.34	Y
IQ spacecom	S-Band High Gain Patch Antenna	Patch	1980-2500	S	11.5	Circular	179	16x16x0.34	Y
Flexitech Aerospace	2-2.5GHz Turnstile Antenna	Turnstile	2000-2500	S	5	Circular	173	--	N
SkyLabs	S-band Patch Antenna	Patch	2025-2110	S	6	LHPC/RHPC	70	8.2x8.2x1.1	Y
Vulcan Wireless	ANT-S/S Unified S-Band Antenna	Patch	2025-2300	S	6.5	Circular	76	8x8x1	Y
EnduroSat	S-band Antenna Commercial	Patch	2025-2110	S	7	Selectable Circular	81	9.8x9.8x0.6	Y
Anteral	2211-114-02 Telecommand DCP	Patch	2000-2150	S	6	RHCP & LHCP	150	9.6x9.6x0.7 (excluding connector)	N
EnduroSat	S-band Antenna Wideband	Patch	2025-2110 2200-2290	S	5	RHCP	115	9.8x9.8x0.7	Y
SENyT	Dual-band S-band antenna	Patch	2050-2115 2215-2275	S	6.5	LHCP	< 100	10x10x0.35	N

Table 9-2: Antennas

Manufacturer	Product	Type	Min Frequency	Frequency Band	Gain	Polarization	Mass	Dimensions	Flight Heritage
---	---	---	[MHz]	--	[dBi]	--	[g]	[cm]	---
ANYWAVES	S-Band TT&C Antenna	Patch	2025-2290	S	6.5	RHCP/LHCP	132	8x8x1.2	Y
Haigh-Farr, Inc.	P/N 21060	Waveguide	2020-2120	S	25	LHCP	667	10x10x4.1	N
ISISPACE	S-Band Patch Antenna	Patch	2200-2290	S	6.5	RHCP	50	8x8x1	N
CesiumAstro	Nightingale AAA-2SF1	Patch	2025 2200	S	5	RHCP LHCP	480	12x9.5x5	Y
AeroSpace Lab	SBA-TX	Patch	2200–2290	S	6.1 dBic	RHCP	118	9.5x9.5x2.4	Y
AeroSpace Lab	SBA - RX	Patch	2025–2110	S	6.1 dBic	CP	117	9.5x9.5x2.4	Y
Satlab	SAS-2	Patch	2025-2110 2200-2290	S	6.1	RHCP	107	10x8.0x0.68	Y
Anteral	2211-113-2 SCP	Patch	2042-2092 2220-2270	S	5.5	RHCP	129g	9.9x9.9x0.65 (excluding connector)	Y
Anteral	2211-114-01 TTC DCP	Patch	2025-2290	S	6	RHCP & LHCP	150	9.6x9.6x0.67 (excluding connector)	N
Anteral	2211-113-01 SCP	Patch	2000-2300	S	7	RHCP	196	9.7x9.7x3.6	Y
Anteral	2211-114-03 Telemetry DCP	Patch	2170-2320	S	6	RHCP & LHCP	150	9.6x9.6x0.7 (excluding connector)	N
Haigh-Farr, Inc.	S-band Patch Antenna	Patch	2245-2245	S	--	RHCP	48	4.8x6.5x6.5	Y
EnduroSat	S-band Antenna ISM	Patch	2400-2450	S	8.3	LHCP	64	9.8x9.8x0.6	Y
SENyT	S-band antenna	Patch	2400-2450	S	3.5	LHCP	<80	5x5x0.5	N
Anteral	2211-114-05 ISM DCP	Patch	2400-2450	S	6.5	RHCP & LHCP	150	9.6x9.6x0.7 (excluding connector)	N

Table 9-2: Antennas

Manufacturer	Product	Type	Min Frequency	Frequency Band	Gain	Polarization	Mass	Dimensions	Flight Heritage
---	---	---	[MHz]	--	[dBi]	--	[g]	[cm]	---
Oxford Space Systems	Offset Reflector Antenna (muti feed)	Deployable	5030-5500	C	>41	Linear	<27200	350 (deployed reflector diameter, scalable to 600)	N
IQ spacecom	X-Band Single Patch Antenna	Patch	7145-7250 8025-8400	X	6	Circular	10	3.5x3.5x0.18	Y
IQ spacecom	X-Band High Gain Antenna	Patch	7145-7250 8025-8400	X	10	Circular	12	4x6x0.18	Y
Oxford Space Systems	"Hinged Rib" Cassegrain Antenna	Deployable	17500-20200 27500-30000	K/Ka	> 38/41	Dual Circular (2 channels for Tx & Rx)	< 2500	60 (deployed reflector diameter, scalable to 150)	N
Anteral	2211-128-22 X-Band SCP	Patch	7900-8500	X	12	RHCP/LHCP	100	5.5x5.5x0.65 (excluding connector)	N
Anteral	2211-128-44 X-Band SCP	Patch	7900-8500	X	>18	RHCP	127	9.9x9.9x0.65 (excluding connector)	Y
Anteral	2211-128-UPL-R-8x8-01 X-Band 8x8 Array	Patch	7900-8500	X	22	RHCP/LHCP	500	22x22x0.52 (excluding fixings and connector)	N
Anteral	2211-205-03 X band	Waveguide antenna	8000-10500	X	15-17	RHCP & LHCP	450	9.74x9.9x17.6	Y
PICOSATS	BEAMSAT X band 4 x 4 patch antenna	Patch	8000 - 8500	X	>16	RHCP	125	98x98x10.8	N
EnduroSat	X-band Patch Antenna	Patch	8025-8400	X	6	RHCP	2.2	2.4x2.4x0.2	Y

Table 9-2: Antennas

Manufacturer	Product	Type	Min Frequency	Frequency Band	Gain	Polarization	Mass	Dimensions	Flight Heritage
---	---	---	[MHz]	--	[dBi]	--	[g]	[cm]	---
EnduroSat	X-band 2x2 Patch Antenna	Patch	8025-8400	X	12	RHCP	23.2	6.0x6.0x0.3	Y
EnduroSat	X-band 4x4 Patch Antenna	Patch	8025-8400	X	16	RHCP	53	9.8x8.3x0.3	Y
EnduroSat	X-Band 8x12 Patch Antenna	Patch	8025 - 8400	X	26	RHCP	490	25.4 x 17.2 x 0.7	N
ANYWAVES	X-band Payload Telemetry Antenna	Patch	8025-8400	X	11.5	Circular	65	7.3x7.3x11	Y
MMA Design	T-DaHGR	Deployable Reflectarray	8400 - 10000	X	29 – 42.5	Configurable	1300 to 11000	10x10x10 - 20x20x20 (stowed) Ø70-Ø200 (deployed)	N
MMA Design	NeuSAR	Deployable Reflectarray	10000	X	>45.5	V+H Linear	16550	52x52x25 (stowed) Ø300 deployed	Y
Anteral	2211-133-DWL-L-44-02 Ku-Downlink 4x4 Array	single-port right-handed-circular-polarized patch antenna	10700 - 11700	Ku	17	RHCP & LHCP	120	9.9 x 9.9 x 0.61 mm (excluding connector)	N
PICOSATS	BEAMSAT Ku band horn antenna	Horn antenna	10700-12750, 12750-14800	Ku	>15 >16	Linear	633	109.1x109.1x 205.3	N
Anteral	2211-212 Ku band	4-port DCP dual-band waveguide antenna	10700-12700 13750-14800	Ku	17	RHCP & LHCP	700	8.9 x 10.2 x 22.1	N

Table 9-2: Antennas

Manufacturer	Product	Type	Min Frequency	Frequency Band	Gain	Polarization	Mass	Dimensions	Flight Heritage
---	---	---	[MHz]	--	[dBi]	--	[g]	[cm]	---
Anteral	2211-133-UPL-R-44-01 Ku-Uplink 4x4 Array	single-port right-handed-circular-polarized patch antenna	14000-14500	Ku	26	RHCP & LHCP	120	0.99x0.99x0.061 (excluding connector)	N
EnduroSat	K-band Patch Antenna	Patch	17700-20200	K	18	RHCP	76	6.5x6.5x1	N
PICOSATS	BEAMSAT K band 8 x 8 patch antenna	Patch antenna	17300 - 21200	K	>20	LHCP	135	94.5x94.5x14	N
Anteral	2211-138-8x8 - K-Band 8x8 Array	single-port right-handed-circular-polarized patch antenna	17800-20200	K	22.5	RHCP/LHCP	120	10x10x0.61 (excluding connector)	N
PICOSATS	BEAMSAT K/Ka band horn antenna	Horn antenna	17300 – 21200, 27000 - 31000	K/Ka	>19.6, >23.75	LHCP RHCP	570	88x88.8x218	Y
Anteral	2211-218	Waveguide antenna	17300 – 21200, 27000 - 31000	K/Ka	>21	LHCP & RHCP	620	10.2x10.2x19.7	Y
PICOSATS	BEAMSAT Ka band 8 x 8 patch antenna	Patch antenna	27000 - 31000	Ka	>20	RHCP	76	78x78x13.5	N
CesiumAstro	APA-1AT1	APA	24500	Ka	26.5	RHCP or LHCP	500	18x18x2	Y
CesiumAstro	Vireo Ka 288 Tx DRA	APA	20200	Ka	28	Circular, switchable on orbit	14500	27x23x16	N
CesiumAstro	Vireo Ka 576 Tx DRA	APA	17000	Ka	31	RHCP or LHCP,	26000 - 34000	40x 40x26.5	N

Table 9-2: Antennas

Manufacturer	Product	Type	Min Frequency	Frequency Band	Gain	Polarization	Mass	Dimensions	Flight Heritage
---	---	---	[MHz]	--	[dBi]	--	[g]	[cm]	---
						switchable on orbit			
CesiumAstro	Vireo Ka 288 Rx DRA	APA	30000	Ka	28	Circular, switchable on orbit	7000	18x15.5x15.5	N
CesiumAstro	Vireo Ka 576 Rx DRA	APA	27000	Ka	31	RHCP or LHCP, switchable on orbit	23000 to 29500	40x40x26.5	N
Anteral	2211-250 EO	2-port DCP waveguide antenna	25500-27000	Ka	30	RHCP & LHCP	1000	20x20x20	N
Anteral	DCPCRS-500-40-EO	2-port dual-DCP cassegrain reflector antenna	31500-32500	Ka	40	RHCP & LHCP	2500	52.4 x52.4 x 25.5	N
PICOSATS	BEAMSAT horn antenna	Horn antenna	37500 - 43500	Q	>20	RHCP & LHCP	150	49x49x110	N
PICOSATS	BEAMSAT horn antenna	Horn antenna	37500 – 43500, 47500 - 52500	QV	>30	RHCP & LHCP	250	119x119x65	N
Anteral	2211-229	Waveguide antenna	37500-52400	QV	30.5	RHCP & LHCP	280	10x10x15.77	N
PICOSATS	BEAMSAT ADE antenna	ADE antenna	59000 - 71000	V	>30	RHCP & LHCP	83	79.5x79.5x43.4	N
EnduroSat	W-band Patch Antenna	Patch	71000-75000	W	23-29	RHCP	37	8.7x8.1x2.0	N
Anteral	2211-236	Waveguide antenna	71000-86000	E	31.5	RHCP & LHCP	152	7.5x7.5x9	N

Table 9-3: Radios

Manufacturer	Product	Type	Min Frequency	Frequency Band	Data Rate	Tx Power	Mass	Dimensions	Flight Heritage
---	---	---	[MHz]	--	[kbps]	--	[g]	[cm]	---
Aerospace Lab	SSDR	SDR	6	S	1840	29 dBm RMS	575	12.6x11.1x5.3	Y
Vulcan Wireless	NSR-SDR	Radio	20.100-21200, 30000-31000	K/Ka	200,000	5W	615	18.3x9.2x3.6	N
Aerospacelab	XSDR	SDR	58	X	206,000	29 dBm RMS	555	12.6x11.1x5.3	Y
Space Micro	MicroSDR-C	SDR	70-3000	VHF, UHF, L, S, C	42,000	0	750	10x10x8	Y
Rincon Research	ASTROSDR	SDR	70-6000	VHF, UHF, L, S, C	--	5 dBm	95	9.0x9.0x1.613	Y
GomSpace	NanoCom SDR	SDR	70-6000	VHF, UHF, L, S, X	--	--	271	9x9x6.6	Y
NI Ettus Research	B205mini	SDR	70-6000	VHF, UHF, L, S, X	--	10 dBm	24	8.3x5.1x8	Y
Alén Space	TOTEM	SDR	70 - 6000	VHF, UHF, L, S	–	7 dBm	130	9.33x8.93x1.36	Y
Alén Space	TREVO	SDR	70 - 6000	VHF, UHF, L, S	–	7 dBm	<714	9.33x8.93x27.88	Y
Vulcan Wireless	NSR-SDR-MUOS	Transceiver	300-320, 360-380	UHF	64	8W	450	10x10x5.6	N
AAC Clyde Space	PULSAR-VUTRX	SDR	--	VHF, UHF	9.6	1.5 W	100	9.6x9x1.6	Y
SkyLabs	NANOcomm-2	Transceiver	130-470	VHF, UHF	< 25	31 dBm	110	9.5x9.1x1.2	Y
AstroDev	Helium-100	Transceiver	120-150, 400-450	VHF, UHF	38.4	3 W	78	9.6x9x1.6	Y
AstroDev	Lithium-1	Transceiver	130-450	VHF, UHF	9.6	0.25-4 W	48	1.0x3.3x6.5	Y
AstroDev	Beryllium-2	Transceiver	130-450	VHF, UHF	9.6	0.25-4 W	52	1x3.3x6.5	Y
GomSpace	NanoCom AX100	Transceiver	143-150, 430-440	VHF, UHF	0.1-38.4	30 dBm	24.5	6.5x4x7	Y
Spacemanic	Murgas	Transceiver	145 400 435	VHF, UHF	0.1 - 38.4 9.6	30dBm	25	6.7x4.2x0.7	Y
LY3H	SatCOM TP0	FM Repeater	144-146, 430-440	VHF, UHF	--	217 mW	59	--	Y

Table 9-3: Radios

Manufacturer	Product	Type	Min Frequency	Frequency Band	Data Rate	Tx Power	Mass	Dimensions	Flight Heritage
---	---	---	[MHz]	--	[kbps]	--	[g]	[cm]	---
ISISPACE	TRXVU	Transceiver	145.8-150.05, 400.15-440	VHF, UHF	9.6	27 dBm	75	9x9.5x1.5	Y
Needronix	Cormorant	Transceiver, DNxD-capable digipeater, Morse beacon	145 - 220 or 390 - 500	VHF or UHF	9.6	30	22	4x7x0.65	Y
Emxys	ODALISS TTC	Transceiver	200	VHF, UHF	1.2	1 W (31 dBm)	<50	8.7x8.7x0.93	N
CesiumAstro	SDR-1001	SDR	300	UHF, L, S, C		-5 to 6	110	5x8.4x1.35	
CesiumAstro	SDR-2104	SDR	600	L, S, C, X		-5 to 6	900	16x10x2.54	
CesiumAstro	Nightingale RFPU	SDR	300, 24500	UHF, L, S, C, Ka		-5 to 6	3500	20x14.85x13.4	
CeisumAstro	SDR-1001	SDR	300 – 6000	UHF, L, S, C	< 62,500	-	100	5x8.4x1.3	N
AAC Clyde Space	TRX-U	Transceiver	390-450	UHF	19.2	2	140	8.3x5.7x1.6	Y
NanoAvionics	SatCOM UHF	Transceiver	395-440	VHF, UHF	2.4-38.4	3 W	7.5	5.6x3.3x6.6	Y
EnduroSat	UHF Transceiver Type II	Transceiver	400-403, 430-440	UHF	≤ 9.6	30 - 33 dBm	94	9.6x9.6x1.1	Y
SatRev S.A.	UHF Radio	Transceiver with AES128 encryption	400-405	UHF	0.45	<2W	158	9.6x9.95x1.565	Y
SENyT	Q-COMM	Transceiver	410-475 2400-2480	UHF, S	500	27 dBm	< 150	9.6x9.0x1.5 w/ enclosure	N
L3 Communications Inc. /SDL	Cadet	SDR	450	VHF, UHF	3,000	--	200	6.9x7.4x1.34	Y
CesiumAstro	Vireo RPU	SDR	600	L, S, C, X		-5 to 6	5000	25x15x20.3	N
sci_Zone, Inc.	LinkStar-STX3	Transmitter	1610-1625	L	0.009	--	48	8.6x5.3x2.9	Y
Qualcomm	GSP-1720	Transmitter	1610-1626.5, 2483.5-2500	L, S	9.6	31 dBm	60	11.9x6.5x1.5	Y

Table 9-3: Radios

Manufacturer	Product	Type	Min Frequency	Frequency Band	Data Rate	Tx Power	Mass	Dimensions	Flight Heritage
---	---	---	[MHz]	--	[kbps]	--	[g]	[cm]	---
NAL Research Corporation	NAL Iridium 9602-LP	Iridium Satellite Tracker	1616-1626.5	L	--	1 W	136	6.9x5.5x2.4	Y
Near Space Launch	EyeStar-S4 Iridium	Transceiver	1618.75	L	0.1	31.96 dBm	29	6x3x2.1	Y
L3Harris	CXS-1000	Transponder	1700-2100	L, S	20,000	1-5 W	1360	10x10x11	Y
Tethers Unlimited	SWIFT-SLX	SDR	1700-2500	S	6,000	33 dBm	300	9x9.8x3.6	Y
Tethers Unlimited	SWIFT-XTS S Transceiver X Transmitter	SDR	1700-2500, 7000-8500	S, X	6,000-25,000	34 dBm	800	9x9.8x6	Y
AAC Clyde Space	TX-2400	Transmitter	2000-2300	S	6,000	2.5	70	6.8x3.5x1.5	Y
Syrlinks	EWC27 + OPT27-SRX	Transceiver	2025-2110	S	100,000	27-33 dBm	400	9x9.6x3.9	Y
Dragonfly Aerospace	CTRS	Transceiver	2200-2290	S	150 400	up to 0.5W	460	120x160x35	Y
Vulcan Wireless	NSR-SDR-S/S	Transceiver/Transponder	2025-2115, 2200-2300	S	4,000	4W	375	9.2x9.5x3.4	Y
Dragonfly Aerospace	CTRS	Transceiver	2025-2115, 2200-2300	S	512	up to 2W	1000	16x12x3.5	N
Vulcan Wireless	NSR-SDR-X/S	Transceiver/Transponder	2025-2115, 8000-8500	S, X	10,000	5W	375	9.2x9.5x3.4	N
Vulcan Wireless	NSR-SDR-X/S HP	Transceiver/Transponder	2025-2115, 8000-8500	S, X	10,000	10 W	615	18.3x9.2x3.6	N
Orion Space Solutions	Triton-XST	Transmitter	2200, 8000	S, X	<670 Mbps	25-50 W	500g	10x10x10	N
CesiumAstro	Vireo RPU	SDR	17000 27000	Ka	--	-5 to 6	7400	25x22.6x20.3	N
IQ spacecom	HISPICO	Transmitter	2100-2500	S	1,000	27 dBm	100	9.5x4.6x1.5	Y

Table 9-3: Radios

Manufacturer	Product	Type	Min Frequency	Frequency Band	Data Rate	Tx Power	Mass	Dimensions	Flight Heritage
---	---	---	[MHz]	--	[kbps]	--	[g]	[cm]	---
Innoflight, Inc.	SCR-104	SDR with AES-256 Encryption	2200-2290 1760-1840 2025-2110	S L/S	>4,500 1000	--	250 - 290	8.2x8.2x2.5 9.8x8.2x3.3	Y
CUBECOM	STXG2	Transmitter	2200-2290 2400-2480	S	25,000	--	137	9.6x9.0x13	N
Emhiser Research, Inc.	ETT-01EBA102-00	Transmitter	2200-2400	S	--	1 W	57	3x8.6x0.8	Y
Quasonix	NanoTX	Transmitter	2200.5-2394.5	S	50	1-10 W	--	3.3x8.6x0.8	Y
IQ spacecom	SLINK-PHY	Transceiver	2200-2290, 2025-2110	S	64-4000	30 dBm	275	6.5x6.5x13.7	Y
ISISPACE	TXS	Transceiver	2200-2290	S	4.3	27-33 dBm	132	9.8x9.3x1.4	Y
Space Inventor	STTC-P3	SDR	2200-2290	S, X	9 – 10,000	33 dBm	230	9.1x9.4x1.7	Y
Satlab	SRS-3	Transceiver	2200-2290	S	512	30 dbM	190	8.7x9.3x1.7	Y
Satlab	SRS-4	Transceiver	2200-2290	S	-	33 dbM	253	9.3x8.7x1.75	Y
Syrlinks	S-band Transponder	Transponder	2200–2290	S	8-2000	27-33 dBm	--	--	Y
Syrlinks	EWC15-NG	Transceiver	2025-2110 2200-2290	S	512 2,000	33 dBm	1280	17.2x12x6.7	N
Syrlinks	EWC31	Transceiver	2025-2110 2200-2290	S	256 2,000	33 dBm	405	9.5x9.5x5.3	Y
Syrlinks	EWC31-NG	Transceiver	2025-2110 2200-2290	S	512 2,000	33 dBm	360	9.5x9x3.2	N
EnduroSat	S-band Transceiver II	Transceiver	2200 – 2290, 2025 - 2110	S	< 125	27-33 dBm	246	9.4x8.8x2.3	Y
EnduroSat	S-Band Transceiver III	Transceiver	2200 - 2290, 2025 – 2110,	S	≤ 3000	27 - 33 dBm	340	9.6x9.6x2.5	N
EnduroSat	S-band Transmitter	Transmitter	2200-2290, 2400-2450	S	≤ 20000	27 - 33 dBm	250	9.6 x 9.6 x 1.5	Y
General Dynamics	S-Band TDRSS/DSN	Transponder	2200-2300 2025-2220	S	12,000	0.03 W	4900	19x23x15	Y

Table 9-3: Radios

Manufacturer	Product	Type	Min Frequency	Frequency Band	Data Rate	Tx Power	Mass	Dimensions	Flight Heritage
---	---	---	[MHz]	--	[kbps]	--	[g]	[cm]	---
SkyLabs	NANOlink-S base Gen2	Transceiver	2200-2300	S	< 4000	30 dBm	126	9.5x9.1x1.2	Y
SkyLabs	NANOlink-S boost Gen2	Transceiver	2200-2300	S	< 4000	37 dBm	250	9.5x9.1x2.2	Y
SkyLabs	NANOlink-S boost-dp Gen2	Transceiver	2200-2300	S	< 4000	31.5 dBm	391	9.5x9.1x3.2	Y
Microhard	Nano N2420	Modem	2400-2483.5	S	230	0.1-1 W	210	5x3x0.6	Y
Paradigma Technologies	PFES-1 ISL S Band TDD Front End	Transceiver	2400-2500	S	-	25 dBm	150	5.0x3.0x 1.0	N
Tethers Unlimited	SWIFT-XTX X Transmitter	SDR	7000-8500	X	25,000	33 dBm	300	9x9.8x6	N
General Dynamics	X-Band Small Deep Space	Transponder	7145-7230, 8400-8500	X	100,000	0.06	3200	18x17x11	Y
Space Dynamics Laboratory	IRIS V2.2	SDR Transponder	7145–7235 GHz 8400–8500 GHz	X, Ka, S, or UHF	0.1 - 10000	36	875	10.1x10.1x5.6	Y
Paradigma Technologies	PTX-1	Transmitter	7700 - 8500	X	-	43.5 dBm	800	12.5x10x3.0	N
Innoflight, Inc.	SCR-106	SDR with AES-256 Encryption	7800-8500 760-1840 2025-2110	X L/S	20,000 1,000	0.02-2.5 W	250 - 290	8.2x8.2x2.5 9.8x8.2x2.8	Y
Innoflight, Inc.	SCR-108	SDR with AES-256 Encryption	19200-21200 29000- 31000	Ka Ka	1 Gbps 20,000	0.02-3 W	404	9.8x8.7x3.9	Y
EnduroSat	X-band Transmitter	Transmitter	7900-8400	X	≤1.5 Gbps	27-33 dBm	270	9.6x9.6x2.6	Y
Dragonfly Aerospace	HDRTX-1.5	Transmitter	8025-8400	X	1.5 Gbps	< 4W	1600	17.5 × 14.5 × 5.5	Y
Dragonfly Aerospace	HDRTx-3	Transmitter	8025-8400	X	3 Gbps	up to 4W	1600	17.5×14.5×5.5	N
SkyLabs	NANOcast	Transmitter	8025-8500	X	<1 Gbps	37 dBm	164	9.5x9.1x1.3	N
CUBECOM	XTXG2	Transmitter	8025-8400	X	2.5 Gbps	--	137	9.6x9.0x1.3	N

Table 9-3: Radios

Manufacturer	Product	Type	Min Frequency	Frequency Band	Data Rate	Tx Power	Mass	Dimensions	Flight Heritage
---	---	---	[MHz]	--	[kbps]	--	[g]	[cm]	---
CUBECOM	µHDTRX-X	Transmitter	8025-8400	X	1.5 Gbps	--	250	9.6x9.0x2.0	Y
CUBECOM	HDRTX	Transmitter	8025-8400	X	1 Gbps	--	250	9.6x9.0x2.0	Y
Satlab	SRX-8	Transmitter	8024-8400	X	<1 Gbps	33 dBm	300	9.3x8.7x2.2	Y
IQ spacecom	XLINK	Transceiver	8025-8500, 7145-7250	X	64-25,000	30 dBm	--	<1 U	Y
SkyLabs	NANOcast	Transmitter	8025-8500	X	< 1 Gbps	37 dBm	164	9.5x9.1x1.3	N
Syrlinks	EWC27	Transmitter	8025-8500	X	1.4 Gbps	27-33 dBm	235	9x9.6x2.6	Y
Syrlinks	EWC27 + OPT27-SRX	Transceiver	2025-2110 8025-8500	S, X	256 1 Gbps	33 dBm	320	9.6x9x3.9	Y
Syrlinks	N-XONOS	Transmitter	2025-2110 8025-8400	S, X	256 4 Gbps	33 dBm	385	9.5x9x3.1	Y
Syrlinks	XONOS	Transmitter	2025-2110 8025-8500	S, X	256 6.3 Gbps	40 dBm	2400	20.6x15.2x6.9	N
Argotec	UST-Lite	Transponder	2025-2120 2200-2300 7145-7235 8400-8500 22550-23550 25500-27500	S, X, K, Ka	< 1 Gbps (higher possible with NRE)	8 dBm (input to SSPA)	<4000 (quad-band)	19.9x14.1x12.1 (quad-band)	N
Tethers Unlimited	SWIFT-KTX Ka Transmitter	SDR	20200-21200 24000-27000	Ka	25,000	33 dBm	300	9x9.8x4	N
Tethers Unlimited	SWIFT-KTRX Ka Transmitter	SDR	24000-27000	Ka	---	35 dBm	1,000	16x9.6x6	N
SpaceMicro	microKaTx-300	Transmitter	25250-27250	K	1 Gbps	2 W	1000	10x10x8	Y
AAC Clyde Space	PULSAR-DATA XTX X-Band Transmitter	SDR	--	X	50,000	2 W	130	9.6x9x1.1	Y
EnduroSat	X-band SDR	Transmitter	8000 - 8400	X	≤ 6 Gbps	27 - 33 dBm	<2500	9.2 x10x11.5	Y
Paradigma Technologies	PTRKU-1	Transponder / Transceiver	10700-12700 12750-14000	Ku	-	33 dBm	350	9.4x9.4x2.2	N

Table 9-3: Radios

Manufacturer	Product	Type	Min Frequency	Frequency Band	Data Rate	Tx Power	Mass	Dimensions	Flight Heritage
---	---	---	[MHz]	--	[kbps]	--	[g]	[cm]	---
EnduroSat	K-band SDR	Transmitter	25500-27000	K	≤ 2 Gbps	27 - 33 dBm	<5000	9.2x10x15	N
AAC Clyde Space	PULSAR-DATA STX	SDR	--	S	7,500	1 W	100	9.6x9x1.7	Y
Honeywell	STC-MS03	Transceiver	--	S	6,250	3.16 W	1000	16x11x4.4	Y
Innoflight, Inc.	SCR-106HDR	SDR with AES-256 Encryption	7800-8500 1760-1840 2025-2110	X L S	1 Gbps 20,000	-	250 - 290	8.2x8.2x2.5 9.8x8.2x2.8	Y
EnduroSat	Versatile Wideband SDR (VW-SDR)	Transceiver	75 - 6000	VHF, UHF, L, S, C	982,000	-10 dBm	<1500	9.8x9.8x7.5	Y
Trident	RDRT	SDR – RF System on Chip (RFSoC)	100	L/S	8-channels 250MHz, 6554MH, 8-channels 250MHz, 4096MHz	-1 dBm Full-scale	571	10x14.6x2.54	N
Trident	ADCM	SDR – MPSoC Basecard and -SP converters - RX only	100	L, S, C	6.4GSPS single channel, 3.2 GSPS dual-channel	2.8dBm Full scale input	690	10x14.6x2.54	N
Space Dynamics Laboratory	Iris Radio V3	SDR Transponder	Various	Simultaneous Multiband: X, Ka, S	0.1 - 10000	34	720	10.1x10.1x3.8	N
PICOSATS	RADIOSAT	Transponder	17300 - 21200 27000 - 31000	K/Ka	-	5	690	93.5x114.15x45.6	Y

Table 9-3: Radios

Manufacturer	Product	Type	Min Frequency	Frequency Band	Data Rate	Tx Power	Mass	Dimensions	Flight Heritage
---	---	---	[MHz]	--	[kbps]	--	[g]	[cm]	---
PICOSATS	RADIOSAT	Transponder	10700 -12750 12750 -13250 13750 -14800	Ku	-	5	< 1000	93.5x 114.2x62.1	N
PICOSATS	RADIOSAT	Transceiver	17300 - 21200 27000 - 31000	K/Ka	4 Gbps 1 Gbps	5	900	83.50 x 114.15 x 53	N
PICOSATS	BEAMSAT	Transceiver	10700 -12750 12750 -13250 13750 -14800	Ku	4 Gbps 1 Gbps	5	1000	93.5x114.2x70.6	N
PICOSATS	RADIOSAT SDR	Modem/Transceiver (SDR)	300 - 7000	UHF, L, S, C	4 Gbps 1 Gbps	0,001	< 500	83.5x96x25	N
Paradigma Technologies	PEWR-1 Wideband Receiver	Receiver	100 - 22000	VHF to Ka	-	0 dBm	550	20x10x1.5	N
Paradigma Technologies	PTRKA-1	Transponder / Transceiver	17200 - 21200 27000 - 31000	K/Ka	-	33 dBm	350	9.4x9.4x2.2	Y
PICOSATS	BEAMSAT	Transmitter	25500 - 27000	Ka	4 Gbps	5	900	83.5x114.15x53	N
Paradigma Technologies	PTRQV-1	Transponder / Transceiver	37500 - 42500 47200 - 52400	K/Ka	-	30 dBm	350	9.4x9.4x2.2	N
Paradigma Technologies	PTQ-1	Transmitter	37500 - 42500	Q	-	22 dBm	350	9.4x9.4x2.2	Y
Paradigma Technologies	PTRQV-1	Transponder / Transceiver	37500 - 42500 47200 - 52400	QV	-	30 dBm	350	9.4x9.4x2.2	N

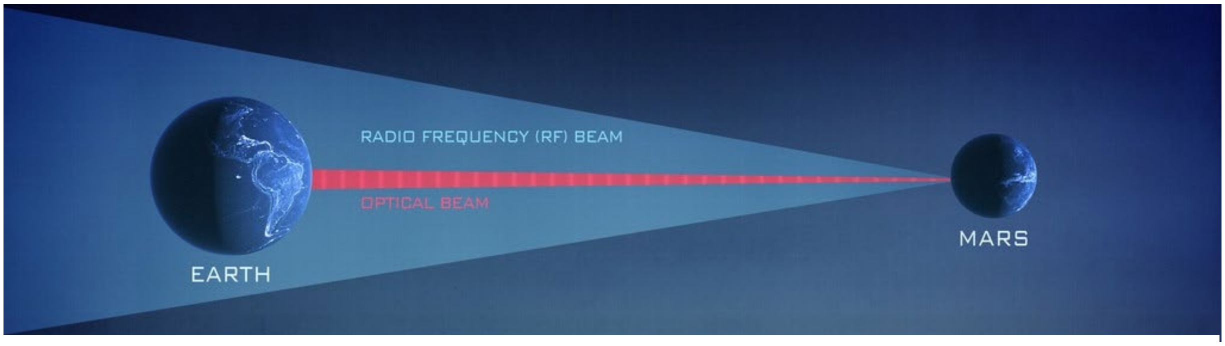

Figure 9.7: Laser vs RF link and data downlink. Credit: NASA

9.3 State-of-the-art: Free Space Optical Communications

Free space optical communications, or lasercom, uses optical wavelengths of electromagnetic radiation to transmit messages wirelessly between user terminals. While few small satellite optical communications terminals have flown, availability is improving, and optical communication is becoming a more common wireless communication technology for small satellites.

Due to the higher frequencies of electromagnetic energy used in lasercom, the amount of bandwidth available for communicating is much larger than that available for RF. This increase in bandwidth over RF enables much higher data rates. The beam width of a lasercom link is also typically much narrower than that of the RF link (displayed in Figure 9.7). The amount that a transmitted beam spreads as a function of its propagation distance is called its divergence. The divergence of a beam is proportional to the wavelength of the electromagnetic wave transmitted divided by the transmitted beam diameter. The high frequencies used in lasercom mean that the wavelength of the transmitted energy is orders of magnitude smaller than RF systems. These small wavelengths mean that the transmitter diameters and beam divergence of lasercom systems can also be much smaller, which enables the size, weight, and power (SWaP) of lasercom systems to be lower than those of similarly performing RF systems. Laser communications have a low probability of intercept, are difficult to jam, and encounter very little interference because of the narrow beamwidth. At present, optical frequencies are unregulated, unlike RF systems that require a licensing process to be able to communicate with a spacecraft.

Lasercom is not without its disadvantages, which include the required beam pointing accuracy and the impact that weather has on the signal. The small beam divergence of lasercom transmit beams means that the acceptable pointing error of the narrow beam is much smaller than that of typical RF systems. The frequencies used in lasercom systems are also susceptible to large amounts of attenuation due to moisture in clouds. This attenuation prohibits communication while there is cloud cover and incentivizes operators to build their optical ground stations in areas with infrequent cloud cover. While larger missions such as the Geosynchronous Lightweight Technology Experiment (GeoLITE), Near Field Infrared Experiment (NFIRE), and Lunar Laser Communication Demonstration (LLCD) demonstrated laser communications downlinks and crosslinks decades ago, SmallSats and CubeSats have successfully demonstrated laser communication downlinks from space. For example, The Aerospace Corporation, in cooperation with

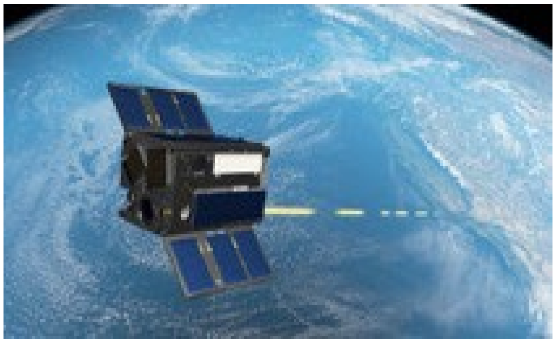

Figure 9.8: An artist rendering of laser communications for the OCSD. Credit: NASA.

NASA ARC, launched three CubeSats in its AeroCube Optical Communication and Sensor Demonstration (OCSD) series (Figure 9.8). OCSD-B and C demonstrated a 200 Mbps downlink from a 1.5U CubeSat to a 40 cm ground station (16). The Aerospace Corporation transmitter has also successfully flown on follow-on missions that were able to use lasercom systems to downlink science data (17).

9.3.1 System Architecture

An optical modem, optical amplifier, and optical head typically comprise a lasercom terminal (LCT) (see Figure 9.9 for an example system diagram of an optical head). As with radio terminals, component locations in optical terminals can vary; for example, the modulator may not be located near the optical front end. Also, the pointing mechanism might differ from the one shown in Figure 9.9.

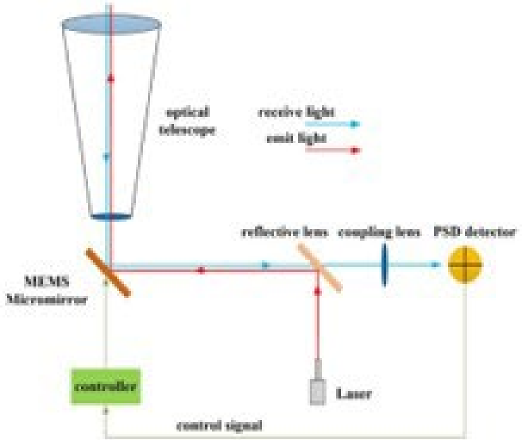

Figure 9.9: Optical head architecture diagram. Credit: Wang et al. 2023.

The key parameters of an optical communication system are frequency, modulation, aperture size, and range. Successful optical communications links require high pointing accuracy. The optical communication terminal on a spacecraft typically has a two-stage pointing system, with a coarse-pointing stage and a fine-pointing stage. The optical communication system often relies heavily on the spacecraft attitude determination and control system (ADCS) for coarse pointing and may use a second pointing mechanism such as a gimbal as additional support for coarse pointing. Fine pointing is often implemented with additional mirrors in the payload. However, pointing that is solely dependent on spacecraft attitude control has also been demonstrated. On transmit, energy passing through the optical aperture forms a very narrow beam. The larger the aperture, the narrower the beam; this creates higher power density at a receiver for a given range, but comes at the expense of more demanding pointing requirements for the transmit beam.

For two communication terminals to locate each other, they may shine higher-power and broader-beam “beacon” lasers to find each other before engaging the narrower and higher data rate link. Other strategies are possible, for example, scanning the direction of the data beam until acquisition is achieved. The beacon itself may also be modulated. Optical modems may be software-defined and can support multiple modulation and coding schemes, similar to RF.

9.3.2 Optical Ground Stations

The ground stations for optical communications understandably differ significantly from RF ground stations due to the need for the receiving aperture (typically a mirrored telescope) to maintain an optical-quality surface to focus the collected optical energy onto a receiver. Optical ground stations are often located at or near astronomical telescope sites, as they are located in favorable “seeing” environments, that is, locations with a low chance of cloud cover and calm, non-turbulent air.-Optical ground stations are typically mounted inside protected domes or other structures to cover them during bad weather. These structures typically need to be opened for clear access to the sky. Since optical ground stations often have beacons, it is important to consider laser safety and their proximity to airports. Typical ground-to-space beacons are on the order of tens of watts of optical power for low-Earth orbit missions. Most optical ground stations are experimental facilities used for campaigns with specific research missions, although there have been recent developments in commercial optical ground stations. For a more detailed descriptions of existing optical ground stations, refer to the *Ground Data Systems and Mission Operations* chapter.

9.3.3 Design Considerations

Lasercom terminals can offer a smaller footprint and lower power draw compared to those of an RF terminal. However, lasercom pointing requirements are significantly more demanding. One of the largest challenges to widespread implementation is the pointing accuracy required for the LCT. To manage the pointing challenges, there are different types of system implementation and components that can be used, depending on resource constraints, performance requirements, and mission lifetime. The LCTs that have been designed, built, and operated on small satellite and CubeSat platforms have some significant differences from LCTs designed for larger spacecraft. Given the size, weight, and power constraints for SmallSat LCTs, mechanical gimbals are typically not used. SmallSat lasercom systems may rely entirely on the body pointing of the satellite to point the LCT at the ground station, or they may use an internal fine pointing mechanism to achieve the required fine-pointing performance.

On SmallSat platforms, the limited volume and tight packaging is often a major challenge in the design of low-SWaP LCTs. There are thermal management challenges during operation, as it is difficult to radiate enough heat given the limited surface area for radiators. There are also power constraints due to limited surface area for solar arrays and secondary battery systems. In addition, not all SmallSat platforms can achieve the pointing requirements necessary for laser communications. Typically, both precise three-axis reaction wheels for actuation and attitude determination sensing from at least one star tracker are necessary.

While RF bands with high frequency and bandwidth are also affected by clouds and rain, cloud cover can prove difficult or even insurmountable for optical communications systems due to the high levels of attenuation. If the cloud coverage is too great at a specific ground station, the transmission may be held for a later time or passed off to a different ground station. With advances in intersatellite networking and the development of extensive networks of optical communication ground stations, routing data around weather may become more feasible.

The atmosphere is also a source of aberrations for optical communication systems, particularly for terminals with larger apertures and more complex receivers designed to support higher data rates. For example, some high-rate optical downlink terminals that require coupling the received light into fiber receivers must use adaptive optics to correct atmospheric effects on the incident wavefront. Without correction of the wavefront, there would be a lack of received signal power to couple into the receive optical fiber due to the perturbed wavefront of the received light. Adaptive optics systems take a sample of the incident wavefront before it reaches the receiver and measure the aberrations of the wavefront to provide input to the control of the adaptive optics system that acts on the received light and counters the aberrations.

Lasercom crosslinks can provide a high bandwidth connection between two satellites, as well as perform ranging between the satellites, potentially with high ranging precision. Connecting two satellites across different orbit planes can help with data routing and can reduce how long it takes to route data to the end user. Lasercom crosslink systems are now in use for both commercial and government missions. Lasercom crosslink demonstrations have been performed from GEO-LEO, LEO-GEO, LEO-LEO, and are operational as part of the European Data Relay Service (43)(44), but these LCTs were developed for much larger spacecraft (20)(21). Crosslinks also have the challenge of both terminals being resource-constrained onboard a spacecraft. Space-to-ground links have an advantage in that the ground station apertures can be large with essentially unconstrained resources relative to what is available on a satellite. The challenges facing inter-satellite optical communications also center on pointing, acquisition, and tracking (PAT) requirements. Satellites in different orbital planes can have high relative velocities and performing pointing, acquisition, and tracking of the terminal can be a challenge. An advanced opto-mechanical system may be needed to surmount this challenge, and special consideration may be needed in the design of the receive optics to manage high Doppler shifts.

9.3.4 Policies and Licensing

Given the early stages of implementation for satellite optical communication systems, both policy and regulatory approaches are still evolving. In the policy realm, there is an initial draft of the CCSDS Pink Book in process (CCSDS 141.0-P-1.1) with a goal to facilitate interoperability and cross-support between different communication systems. There is also an optical communications working group with NASA and ESA participation. The U.S. government Space Development Agency has also recently released its Optical Communications Terminal (OCT) Standard Version 4.0.0 (28th June 2024), which is a widely used design reference for space lasercom terminals, although not yet targeted specifically to small satellite terminals.

Regarding licensing and regulation, the situation is very different from the radio frequency domain. Currently there are no licensing requirements for laser communications. In the radio frequency spectrum, the main goal for licensing is to prevent interference between transmitters.

Lasercom interference is not currently coordinated by a regulatory body (like the ITU or NTIA in RF), although there have been historical ITU World Radiocommunication Conference resolutions that have considered implementing regulations. There is currently no regulation for two major reasons:

1) Laser communications is highly directional, which makes interference unlikely, due to the narrow divergence of the transmitting beam and corresponding small beam footprint at the receiver.
2) The small number of organizations that deploy laser communication systems doesn't warrant a complex coordination body like the ITU.

However, in the U.S. there are three regulatory entities that are concerned with aspects of outdoor laser operations: the FAA, the DoD Laser Clearing House (for DoD missions) and the NASA Laser Safety Review Board (for NASA missions).

FAA coordination is required if potentially harmful laser irradiance is transmitted through navigable airspace. This includes prevention of injury as well as potential distraction of pilots by visible lasers. The FAA will most likely only be concerned about transmitters at ground stations because transmitters on spacecraft are hundreds of miles above the highest-flying aircraft and beam dispersion is large enough that there are usually no safety implications. Missions should coordinate with their local FAA service center to get approval, documented with a "letter of non-objection."

The DoD Laser Clearinghouse (LCH) works to ensure that DoD and DoD-sponsored outdoor laser use does not impact orbiting spacecraft or their sensors. That includes both US DoD and foreign assets. LCH and mission operators might enter close cooperation where LCH permits specific laser engagements. The process of coordinating with LCH to get to that point can take many months and should be started as early as possible. However, currently LCH will only engage DoD and DOD-sponsored missions.

NASA's Laser Safety Review Board (LSRB) is focused on personnel safety for all outdoor laser operations. NASA missions prepare safety documentation and submit to LSRB for review before launch. The LSRB will also verify FAA concurrence. Further information on regulations can be found in ANSI Z136.6, American National Standard for Safe Use of Lasers Outdoors, and in (45).

9.3.5 Mission Examples

SmallSat and CubeSat missions using lasercom terminals have shown viable pathways for overcoming the challenges associated with lasercom to enable high-bandwidth communications. Please refer to Table 9-4 for more information on lasercom missions. These efforts promote research toward practical applications of space optical communication technologies in the future.

The Small Optical Transponder (SOTA) project led by the National Institute of Information and Communications Technology (NICT) in Japan successfully demonstrated a laser space-to-ground link from a 50 kg microsatellite multiple times between 2014 and 2016 (22). This LCT was capable of up to 10 Mbps; the Very Small Optical Transponder (VSOTA) LCT, also developed by NICT, is capable of 1 Mbps. VSOTA was integrated into the Rapid International Scientific Experiment Satellite (RISESAT) from Tohoku University and launched in 2019 (23). Planned for 2027 is the demonstration of several technologies to enable optical communication constellations.

The German Aerospace Center (DLR) develops LCTs under its Optical Space Infrared Downlink System (OSIRIS) program to support laser downlinks from small satellites, using reference beacons for fine pointing. OSIRISv1 launched in 2017 on the University of Stuttgart's Flying Laptop satellite, demonstrated 200 Mbps downlinks using a body-pointing-only approach and continues to support testing of DLR's optical ground stations. The OSIRISv2 LCT, launched in 2016 on DLR's BiROS satellite, provided 1 Gbps and employed closed-loop body pointing with a beacon reference; portions of the terminal have been commissioned to date (24)(25)(26). The OSIRIS4 CubeSat transmitter, demonstrated in 2021, achieved an optical downlink in a 0.3U package using a MEMs fast-steering mirror for fine pointing. Designed to be compatible with a 60 cm optical receiver, this terminal has been commercialized through TESAT with the product name CubeLCT (28). A modified version, CubeISL by DLR, adds a receive optical path and fiber amplifier to support 100 Mbps crosslinks at distances up to 1000 km and 1 Gbps downlinks. The terminal has a mass below 1 kg, a volume of 1U, and an operating power of about 30 W (35). A dedicated on-orbit demonstration of these terminals is planned for 2026 using two 6U CubeSats as host platforms (36).

The Aerospace Corporation completed the first demonstration of optical communications from a 1.5U CubeSat platform with the NASA-sponsored Optical Communication and Sensor Demonstration (OCSD) mission. The terminals achieved a 200 Mbps downlink data rate to a 40 cm ground station and did not use a beacon for a pointing reference (16). This transmitter has been flown since on multiple missions such as R3 (17) and the Rogue Alpha and Beta CubeSats (18). An updated version was later demonstrated on the Slingshot mission, achieving downlink rates at 250 Mbps (19). In 2025, The Aerospace Corporation also demonstrated an optical crosslink between two 6U CubeSats at distances of roughly 560 km using its Flashlight Laser Crosslink Terminal. This terminal occupies approximately two units of volume and supports bidirectional data rates of 312.5 Mbps (46).

MIT Lincoln Laboratory developed the TeraByte InfraRed Delivery (TBIRD) terminal, which achieved 200 Gbps downlinks. The transmitter uses commercial fiber telecommunication transceivers and amplifiers to support very high data rate downlinks. This project used NASA JPL's Optical Communication Telescope Laboratory (OCTL), which hosts a 1 m telescope with the adaptive optics necessary to couple the received light back into an optical fiber connected to a transceiver for demodulation. This terminal development was sponsored by NASA and was launched on the PDT-3 6U CubeSat mission in June of 2022 (33). It has thus far achieved the transmission of 4.8 Tb in a single pass and has demonstrated the value of implementing an automatic repeat request protocol in the use of lasercom downlinks (31)(32).

As part of NASA's CLICK mission, MIT developed the 1.2U CLICK-A terminal. The first phase of the mission flew the CLICK-A downlink terminal on a 3U CubeSat to demonstrate an optical design that uses a secondary fine pointing micro-electromechanical systems (MEMS) fine-steering mirror (FSM) to achieve the necessary pointing requirements for optical communication without imposing those requirements on spacecraft body pointing or needing large gimbals. This LCT uses closed-loop fine pointing with a beacon reference and is designed to close its link with a 28 cm ground station. The terminal was integrated into a Blue Canyon Technology's XB1 spacecraft bus and was launched to and deployed from the ISS in 2022. The mission successfully demonstrated improved pointing with the MEMS FSM compared to body-only pointing. CLICK-A ultimately served as a risk-reduction phase for the CLICK-B and C mission operations (27).

The CLICK-B/C phase of the CLICK mission is developing a 1.5U crosslink LCT. The CLICK-B/C crosslink LCT is designed to establish a 20 Mbps link at separations from 25 to 580 km. CLICK-B and C will each be integrated into their own 3U Blue Canyon Technologies XB1 spacecraft. The LCTs are designed to be capable of precision ranging up to a precision of 50 cm relative to each other. The spacecraft will be launched to and deployed from the ISS in late 2026 and will fly in the same orbital plane (27).

The Laser Crosslink Experiment (LaCE) by Los Alamos National Laboratory consisted of two 6U CubeSats that demonstrated the Skylight Laser Communication Terminal crosslink as their primary objective. The Skylight LCT was designed to actively steer the laser communication payload to establish an optical link between the two CubeSats which it successfully did in 2024 (47)(48). At a distance of 7.4 km between each CubeSat, 2 Tbit/s was achieved in an urban environment with atmospheric turbulence. Future efforts aim to miniaturize the terminals while supporting data rates of up to 10 Gbit/s between a LEO spacecraft and the ground in 2026, and between a satellite and a high-altitude balloon in 2027.

Table 9-4: LCT Technologies

Vendor/Developer	Terminal	Platform	Data Rate	Mass	Power	Wavelength	Modulation	Launch Date
---	---	---	[Mbps]	[kg]	[W]	[nm]	---	---
NICT	SOTA	SOCRATES	10	5.9	16	976/800/1549	OOK	May 2014
DLR	OSIRISv2	BiROS	1000	1.65	37	1550	OOK	June 2016
DLR	OSIRISv1	Flying Laptop	200	1.3	26	1550	OOK	July 2017
Aerospace Corporation	OCSD-B&C	AeroCube-7	200	<2.3	20	1064	OOK	December 2017
NICT	VSOTA	RISESAT	1	<1	4.33	980/1550	OOK/PPM	January 2019
Sony/JAXA	SOLISS	ISS	100	9.8	36	1550	OOK	July 2019
DLR	OSIRIS4CubeSat	PIXL-1	100	0.4	10	1550	OOK	January 2021
MIT Lincoln Labs	TBIRD	PDT-3	200,000	<3	100	1550	QPSK	May 2022
MIT	CLICK-A	CLICK	10	1.2	15	1550	PPM	July 2022
AAC Clyde Space	CubeCat	NorSat-TD	1000	<1.33	15	1550	OOK	April 2023
MIT	CLICK-B/C	CLICK	20	1.5	30	1537/1563	PPM	Est. 2026
DLR	CubeISL	CubeISL	100	1	30	1537/1553	OOK	2025
CACI	Skylight		100	1.6	35	1536/1553	PPM	May 2024
Emxys	ODALCOM	Optical transceiver	200	<1	2.6	1550	Unipolar NRZ	Est. 2026

9.4 Future Communications Technologies

As SmallSat missions become more complex, there is a greater need for higher data rates that drive the development of higher frequency communication systems—such as Ku-band, Ka-band, and W-band—for SmallSats. These bands enable higher-speed and higher-capacity data transmission and help alleviate the already overcrowded RF spectrum in lower frequency bands. Both RF congestion and interference risks have resulted from the rapid growth in the aerospace, commercial spacecraft, and 5G telecommunications sectors. Traditionally used for military radar and space communications, S-band allocations now face intense competition as commercial operators seek access to bands that were once reserved for more specialized applications. S-band remains widely used for higher-rate telemetry (up to ~10 Mbps), and many academic and commercial missions still rely on S-band transceivers.

Deployable Ka-band mesh reflectors have demonstrated gains above 40 dBi on 6U platforms (50). NASA's Investigation of Convective Updrafts (INCUS) mission aims to track the vertical dynamics of tropical convective storms, and each of the three identical ~100 kg SmallSats will carry active Ka-band radar and a deployable Ka-band mesh reflector antenna (51). Once fully deployed, the Ka-band reflector has a 1.6 m aperture on-orbit that will provide high-sensitivity Ka-band radar observations. At Ku-band, microstrip and dual-band shared-aperture phased arrays offer wide bandwidth, circular polarization, and up to ±55° electronic steering in low-profile formats suitable for CubeSats (52).

NEC Corporation is progressing with a technology demonstration of millimeter-wave Q/V-band transceiver equipment in orbit on a ~200-kg class spacecraft (53). This payload is designed to operate in the Q-band (approximately 33–50 GHz) and V-band (40–75 GHz), enabling high-capacity satellite downlinks and experiments to measure radio-wave propagation characteristics in these bands (54).

The other solution to the congested RF spectrum is to employ optical terminals for space-to-ground and space-to-space communication. Ongoing efforts are improving current optical communication in LEO for future SmallSat mission generations. While free space optical communication technology continues to progress toward fielding operational systems, other avenues of research have also been explored. Quantum key distribution is a protocol that shares a secret cryptographic key using entangled photons. Sources and optical front ends have been in development for transmitting these keys from small satellite spaceborne platforms (38)(39).

Another approach to expanding the communication windows for SmallSats in LEO is to form an intersatellite link to geosynchronous orbit. NICT is developing the CubeSat Small Optical Transponder (CubeSOTA) which aims to validate laser communication links between a 6U LEO CubeSat and a GEO satellite at data rates up to 10 Gbps (55). For larger spacecraft, one example is DLR's European Data Relay System (EDRS), which aims to enable near-real-time data relay between LEO and ground stations via GEO satellites equipped with laser communication terminals and Ka-band. Other terminals for larger SmallSats have been developed by Tesat, Mynaric (27), SpaceMicro (28), and SA Photonics in response to the development of the Space Development Agency's Proliferated Warfighter Space Architecture constellation and the use of LCTs in that architecture. Beyond this, DARPA has funded the Space-BACN program, which seeks to develop a reconfigurable multi-protocol inter-satellite LCT that can be supported on small satellites.

As SmallSats employ more autonomous onboard systems, multi-spacecraft missions will ultimately exchange navigation data directly between spacecraft, which will reduce reliance on ground control. Recent generations of CubeSat deep-space transceivers have integrated radiometric ranging capabilities in which timing codes embedded in the RF waveform provide one-way or two-way ranging measurements. When combined with directional information from ground antennas, these radiometric observables enable accurate trajectory reconstruction for spacecraft operating beyond LEO.

Inter-spacecraft relay capabilities are gaining interest because they will enhance crosslink communication to extend the effective coverage of limited ground station networks. As SmallSats venture farther into space, transponders may offer a more efficient pathway for high-rate communications back to Earth. The limitations in RF power and antenna aperture further motivate the need for cooperative networks in which small spacecraft relay data through a larger, more capable mothership. Although transponders are common in traditional spacecraft, networked SmallSat swarms with fully operational RF crosslinks in deep space have not yet flown.

As of 2026, several CubeSats—including the MarCO pair, CAPSTONE, BioSentinel, ArgoMoon, and LunaH-Map—have operated beyond low-Earth orbit using the Iris deep-space transponder. The MarCO spacecraft employed deployable X-band reflectarray high-gain antennas and full-duplex UHF/X-band radios, enabling near-real-time relay of telemetry during the InSight lander's descent and landing on Mars. Following the success of these missions, the deployment of additional SmallSats to cislunar and interplanetary destinations is anticipated. In the longer term, crosslink-enabled relay architectures, in which clusters of CubeSats provide communication hops for larger spacecraft, are expected to play an increasingly critical role in deep-space exploration.

Through NASA's Small Spacecraft & Distributed Systems (SSDS) capability, the University SmallSat Technology Partnerships (USTP) initiative has begun advancing RF and optical communication systems. Listed below in Table 9-5 are USTP projects focused on SmallSat communications technology advancement. Further information can be found at the USTP website:

https://www.nasa.gov/smallspacecraft/university-smallsat-technology-partnership-initiative/

Table 9-5: USTP Initiative Communication Projects

Project	University	Current Status	Reference
*FIGARO, 5G arrays for lunar relay operations	San Diego State	Still in development	USTP Technology Expo presentation
*A Small Satellite Lunar Communications and Navigation System	University of Colorado, Boulder	Still in development	USTP Technology Expo presentation

9.5 Summary

There is already strong flight heritage for many UHF/VHF and S-band communication systems for CubeSats. Less common, but with growing flight heritage, are X-band systems. Higher RF frequencies already have CubeSat flight heritage, and the performance is improving. Although there are limited Ka-band systems for CubeSats today, high-rate transmitters such as the Astro Digital AS-10075 demonstrated 320 Mbps in the Landmapper-BC 3 v2 mission. While laser communication has been demonstrated on multiple CubeSat platforms, it is still not yet considered to be an established technology for SmallSats, however, this will likely change in the near future. More demonstrations are in development, with some already launched and operating, to demonstrate higher data rates and increased pointing performance. Since optical communications uplink and downlink can be blocked by clouds, RF is considered complementary to maintain contact under all conditions. There is growing interest among the NASA science community in using constellations of CubeSats to enhance observations for Earth and space science.

For feedback solicitation, please email: arc-sst-soa@mail.nasa.gov. Please include a valid business email for further contact.

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