



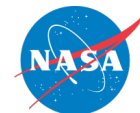
Chapter Contents

Chapter Glossary	ii
9.0 Communications.....	243
9.1 Introduction	243
9.2 Radio Frequency Communications	244
9.2.1 Frequency Bands	244
9.2.2 System Architecture	245
9.2.3 Major Components in Smallsat Communication Systems	246
9.2.4 Design Considerations.....	247
9.2.5 Policies and Licensing	247
9.2.6 Encryption.....	248
9.2.7 Antennas	248
9.2.8 Radios	249
9.2.9 On the Horizon RF Communications	250
9.3 Free Space Optical Communications.....	262
9.3.1 System Architecture	263
9.3.2 Optical Ground Stations.....	263
9.3.3 Design Considerations.....	264
9.3.4 Policies and Licensing.....	265
9.3.5 Mission Examples.....	265
9.3.6 Future Technologies.....	267
9.4 Summary.....	269



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 ClearingHouse
(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
(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
(TDRS)	Tracking and Data Relay Satellite
(TMA)	Technology Maturity Assessments
(TRL)	Technology Readiness Levels
(TT&C)	Tracking, Telemetry & Command
(VSOTA)	Very Small Optical Transponder
(WFF)	Wallops Flight Facility

9.0 Communications

9.1 Introduction

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), 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).

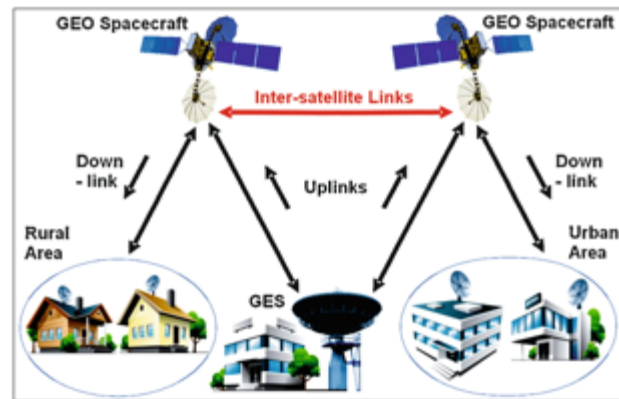


Figure 9.1: Satellite uplink, downlink, and crosslink. Credit: D. Stojce (2019).

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. A RF system communicates 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 it 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 a much higher frequency than RF links, generally at near-infrared bands (e.g., 1064 nm or 1550 nm). Visible light is often not

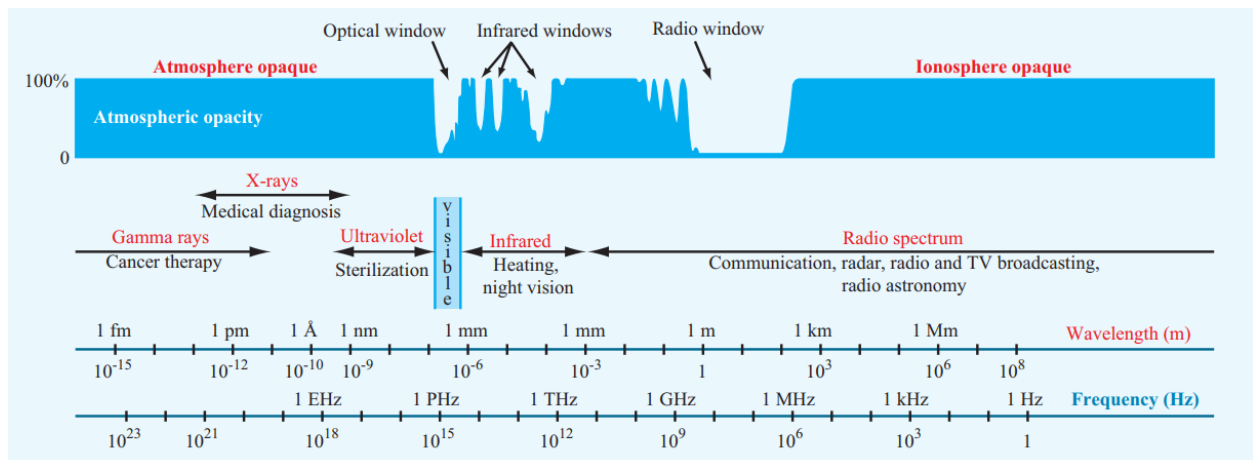


Figure 9.2: Atmospheric opacity of the electromagnetic wave spectrum with the infrared and radio windows used by spacecraft for communication. Credit: Microwave Radar and Radiometric Remote Sensing by Ulaby and Long.



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 both more 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.

This chapter is a survey of small spacecraft communications technologies as discussed in open literature and does not endeavor to be an original source. This chapter only considers literature in the public domain to identify and classify devices. Commonly used sources for data include manufacturer datasheets, press releases, conference papers, journal papers, public filings with government agencies, and news articles. There is no intention of mentioning certain companies and omitting others based on their technologies or relationship with NASA.

9.2 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 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 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 & 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

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



compensated for with higher power transmission and/or high 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.

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 remove 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 looking at using 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 Command and Data Handling (CDH) 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.

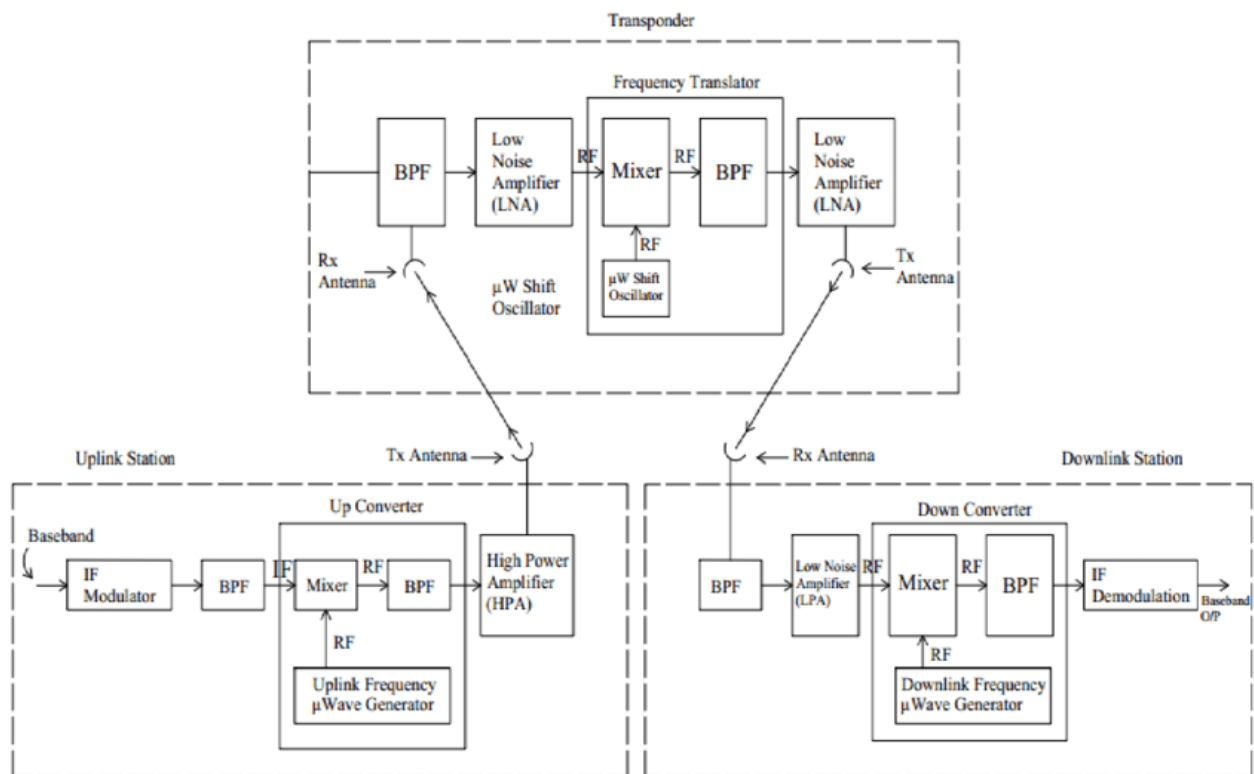


Figure 9.3: Transmit and receive block diagram. Credit: Karim et al. (2018). <http://creativecommons.org/licenses/by/4.0/>

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 down convert 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 & 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 comm 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 US 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 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 broken up 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 prevents 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 9-3 for information on commercially available antennas for SmallSats/CubeSats.

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.

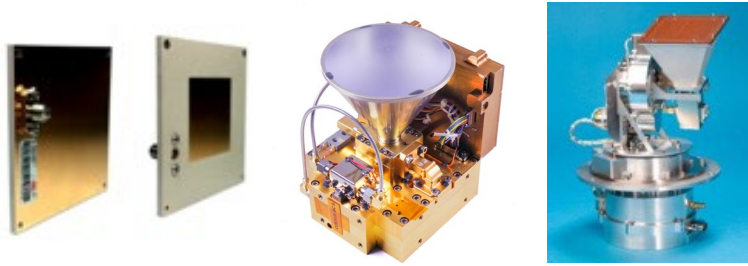


Figure 9.4: (from left to right) CubeSat-compatible S-band patch antenna (IQ Wireless), X-band high-gain antenna and pointing mechanism (Surrey Satellite Technology, Ltd.), and Ka-band transmitter with a horn antenna (Astro Digital).

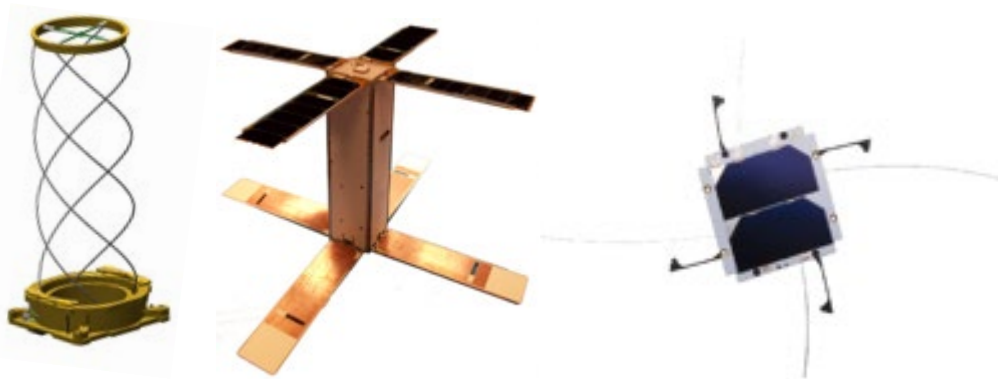


Figure 9.5: (from left to right) Example of deployable quadrifilar helical antenna (Helical Communication Technologies), SNaP spacecraft with Haigh-Farr's deployable UHF Crossed Dipole antenna (Space Missile and Defense Command), and EnduroSat UHF antenna with EnduroSat solar panels (EnduroSat).

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 of the radio's functions implemented in Digital Signal Processing (DSP) software rather than hardware, figure 9.6. Furthermore, spacecraft teams can change such



characteristics in-flight 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. The reader is encouraged to refer to the SmallSat Avionics chapter for further information on FPGAs and SDRs. Please see table 9-4 for information on commercially available radios for SmallSat/CubeSats.

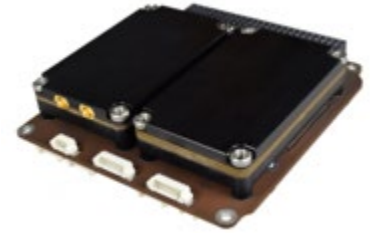


Figure 9.6: Example of software defined radio, tunable in the range 70 MHz to 6 GHz. Credit: GomSpace.

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 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).

9.2.9 On the Horizon RF Communications

A CubeSat constellation may involve numerous CubeSats in the constellation (e.g., tens or hundreds). Each CubeSat is typically identical from a communication perspective. One or more CubeSats may be mother ship-capable while the others may be subordinate (e.g., daughterships). CubeSat constellations optimize coverage over specific areas or improve global revisit times to fulfill mission objectives. There is growing interest among the NASA science community in using constellations of CubeSats to enhance observations for Earth and space science. NASA GSFC has conducted research on future CubeSat constellations, including CubeSat swarms, daughter ship/mother ship constellations, NEN S- and X-band direct-to-ground links, TDRS Multiple Access (MA) arrays, and Single Access modes. The MA array requires the use of spread-spectrum to support multiple simultaneous communications links to increase coverage and link availability

As CubeSat missions employ more automation, constellations could exchange information to maintain precise positions without input from the ground. Radiometric ranging is a function recently incorporated into CubeSat transceivers. A timing signal is embedded into the radio signal and is used to determine the range to the spacecraft. Using this method along with directional vectors obtained from ground antennas allows for trajectory determination of satellites beyond low-Earth orbit. Spacecraft may relay data to increase the coverage from limited ground stations. Inter-CubeSat transponders may very well become a vital element of eventual deep space missions, since CubeSats are typically limited in broadcasting power due to their small size, and may be better suited to relay information to Earth via a larger, more powerful mothership.



Spacecraft routinely use transponders, however, networked swarms of CubeSats that pass information to each other and then eventually to ground, have not flown. Developing networked swarms is less of a hardware engineering problem than a systems and software engineering problem in that one must manage multiple dynamic communication links. As of 2023, only the two MarCO SmallSats and BioSentinel have operated beyond low-Earth orbit and both use the IRIS CubeSat Deep Space transponder. Both the MarCO satellites used a deployable reflectarray panel at X-band and were equipped with a full-duplex radio providing both UHF and X-band coverage (15). This allowed for near real-time updates of the InSight rover's landing. After this success, more SmallSats may be deployed beyond low-Earth orbit. The ability to provide crosslink relay hops for large spacecraft will prove to be critical for deep space missions.

Several projects funded via NASA's Small Spacecraft Technology (SST) program through the University Smallsat Technology Partnerships (USTP) initiative have begun advancing RF Communication systems. Listed below in table 9-2 are projects that focused on RF technology advancement, and further information can be found at the STP website:

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

Each presentation is from the USTP Technology Exposition that was held in June 2022.

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



Table 9-3: 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	Yagi antenna	Deployable	156.5-162.5	VHF	6.5	Dual Linear	<1kg	100 x 70	Y
Spacemanic	SAM_Antenna_Module	Dipole Cross Dipole	144 399 420	VHF, UHF	2.1	Linear/RHCP	120	9.8X9.8X0.56	Y
Haigh-Farr, Inc.	Part Number: 17100	Crossed Dipole	307	VHF, UHF	--	RHCP	267	32x8x1	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
NanoAvionics	CubeSat UHF Antenna System 2x2U	Turnstile	400-500	UHF	3.4	--	65	20x20x0.7	Y
EnduroSat	UHF Antenna III	Whip/Burn-wire	435-438 or 400-403	VHF, UHF	> 0	RHCP	85	10x10	Y
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



Table 9-3: Antennas (Continued)

Manufacturer	Product	Type	Min Frequency	Frequency Band	Gain	Polarization	Mass	Dimensions	Flight Heritage
---	---	---	[MHz]	--	[dBi]	--	[g]	[cm]	---
Oxford Space Systems	Helical antenna	Deployable	862-928	UHF	6.5-7.5	RHCP	~300	33	Y
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	4.6x4.3x1.0	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 Commercial Patch Antenna	Patch	2025-2110	S	7	Selectable Circular	64	9.8x9.8x0.6	Y
EnduroSat	S-band Wideband Patch Antenna	Patch	2025-2110 2200-2290	S	5	RHCP	115	9.8x9.8x0.7	Y
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



Table 9-3: Antennas (Continued)

Manufacturer	Product	Type	Min Frequency	Frequency Band	Gain	Polarization	Mass	Dimensions	Flight Heritage
---	---	---	[MHz]	--	[dBi]	--	[g]	[cm]	---
Haigh-Farr, Inc.	S-band Patch Antenna	Patch	2245-2245	S	--	RHCP	48	4.8x6.5x6.5	Y
EnduroSat	S-band ISM Patch Antenna	Patch	2400-2450	S	8	LHCP	64	9.8x9.8x0.6	Y
Oxford Space Systems	Deployable Parabolic Offset Reflector	Deployable	5310-5510	C	42	Linear	12kg to 21kg	350	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	(Single) Hinged Rib Metal Mesh	Deployable	7200-8500	X	30	RHCP/LHCP	5200	90	N
EnduroSat	X-band Patch Antenna	Patch	8025-8400	X	6	RHCP	2.2	2.4x2.4x0.2	Y
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
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 to 10000	X	29 – 42.5	Configurable	1300 to 11000	10 x 10 x 10 - 20 x 20 x 20 (stowed) Ø70-Ø200 (deployed)	N
Oxford Space Systems	Deployable Cassegrain Wrapped Rib Antenna	Deployable	9200-10400	X	46 - 49	Linear	25kg to 38kg	300 - 500	N



Table 9-3: Antennas (Continued)

Manufacturer	Product	Type	Min Frequency	Frequency Band	Gain	Polarization	Mass	Dimensions	Flight Heritage
---	---	---	[MHz]	--	[dBi]	--	[g]	[cm]	---
MMA Design	NeuSAR	Deployable Reflectarray	10000	X	>45.5	V+H Linear	16550	52 x 52 x 25 (stowed) Ø300 deployed	Y
EnduroSat	K-band Patch Antenna	Patch	17700-20200	K	18	RHCP	90	4.8x4.8x0.5	N
Oxford Space Systems	Deployable Hinged Rib Metal Mesh	Deployable	17700-20200 27700-30000	K,Ka	38/41	Linear	~2-3kg	60	N
Cesium Astro	Nightingale	Phased Array	27000-40000	Ka	30	Circular	1200	18x18x2	N
EnduroSat	W-band Patch Antenna	Patch	71000-75000	W	23-29	RHCP	37	8.7x8.1x2.0	N

Table 9-4: Radios

Manufacturer	Product	Type	Min Frequency	Frequency Band	Data Rate	Tx Power	Mass	Dimensions	Flight Heritage
---	---	---	[MHz]	--	[kbps]	--	[g]	[cm]	---
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

Table 9-4: Radios *Continued*

Manufacturer	Product	Type	Min Frequency	Frequency Band	Data Rate	Tx Power	Mass	Dimensions	Flight Heritage
---	---	---	[MHz]	--	[kbps]	--	[g]	[cm]	---
Alén Space	TREVO	SDR	70 - 6000	VHF, UHF, L, S	–	–	up to 714	9.33x8.93x27.88	N
Alén Space	TRISKEL	TTC	395 - 410, 430 - 440	UHF	2.2 - 1.9.2	30 dBm	200	9.33x8.93x126	N
SkyLabs	NANOcomm-2	Transceiver	130-470	VHF, UHF	Up to 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_trx_VHF	Transceiver	144	VHF, UHF	9.6	+30dBm	25	6.7x4.2x0.7	Y
LY3H	SatCOM TP0	FM Repeater	144-146, 430-440	VHF, UHF	--	217 mW	59	--	Y
ISISPACE	TRXVU	Transceiver	145.8-150.05, 400.15-440	VHF, UHF	9.6	27 dBm	75	9x9.5x1.5	Y
CeisumAstro	SDR-1001	SDR	300 – 6000	UHF, L, S, C	up to 62,500	-	100	5 x 8.4 x 1.3	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
Spacemanic	Murgas_trx_UHFlow	Transceiver	399	UHF	9.6	+30dBm	25	6.7x4.2x0.7	N
EnduroSat	UHF Transceiver Type II	Transceiver	400-403, 430-440	VHF, UHF	9.6	2 W	94	10x10x2	Y



Table 9-4: Radios (Continued)

Manufacturer	Product	Type	Min Frequency	Frequency Band	Data Rate	Tx Power	Mass	Dimensions	Flight Heritage
---	---	---	[MHz]	--	[kbps]	--	[g]	[cm]	---
Spacemanic	Murgas_trx_UHF	Transceiver	420 MHz	UHF	9.6	+30dBm	25	6.7x4.2x0.7	Y
L3 Communications, Inc. /SDL	Cadet	SDR	450	VHF, UHF	3,000	--	200	6.9x7.4x1.34	Y
NearSpace Launch	EyeStar-D2	Transceiver	1610-1625, 2484-2499	L	10,000	0.8 W	138	6.1x11.9x2.2	Y
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
NAL Research Corporation	NAL Iridium 9602-LP	Iridium Satellite Tracker	1616-1626.5	L	--	1 W	136	6.9x5.5x2.4	Y
NearSpace Launch	EyeStar-S3	Transmitter	1616.25	L	600	20 dBm	22	1.5x2.6x5.5	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 S/X Transceiver	Transceiver	2025-2110	S	100,000	27-33 dBm	400	9x9.6x3.9	Y



Table 9-4: Radios (Continued)

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	Tx: 2200-2290 Rx: 1760-1840 Rx: 2025-2110	Tx: S Rx: L/S	Tx: >4,500 Rx: 1000		250 - 290	8.2x8.2x2.5 9.8x8.2x3.3	Y
IQ Technologies for Earth and Space GmbH	HISPICO	Transmitter	2100-2500	S	1,000	27 dBm	100	9.5x4.6x1.5	Y
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	Request	3.3x8.6x0.8	Y
IQ Technologies for Earth and Space GmbH	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
Syrlinks	S-band Transponder	Transponder	2200-2290	S	8-2000	27-33 dBm	--	--	Y
EnduroSat	S-band Transmitter	Transmitter	2200-2290, 2400-2450	S	20000	0.5-2 W	250	--	Y
General Dynamics	S-Band TDRSS/DSN	Transponder	Tx: 2200-2300 Rx: 2025-2220	S	12,000	0.03 W	4900	19x23x15	Y
Microhard	Nano N2420	Modem	2400-2483.5	S	230	0.1-1 W	210	5x3x0.6	Y
Laboratory for Atmospheric and Space Physics (LASP)/Blue Canyon Technologies (BCT)	X-band Radio	SDR	Tx: 2200-2500, 8000-8500, 21000-33000 Rx: 1760-1840, 2000-2110, 21000-23000	Downlink: S, X, Ka Uplink: L, S, Ka	100000	30 dBm	--	4.5x4.35x1.25	Y



Table 9-4: Radios (Continued)

Manufacturer	Product	Type	Min Frequency	Frequency Band	Data Rate	Tx Power	Mass	Dimensions	Flight Heritage
---	---	---	[MHz]	--	[kbps]	--	[g]	[cm]	---
SkyLabs	NANOLink-base Gen2	SDR	2200-2300	S	Up to 4000	30 dBm	110	9.5x9.1x1.2	Y
SkyLabs	NANOLink-boost Gen2	SDR	2200-2300	S	Up to 4000	37 dBm	250	9.5x9.1x2.2	Y
SkyLabs	NANOLink-boost-dp Gen2	SDR	2200-2300	S	Up to 4000	31.5 dBm	385	9.5x9.1x3.2	Y
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	Transponder	7145, 8400	X, Ka, S, UHF	0.1 - 5313	3.8	875	10.1 x 10.1 x 5.6	Y
Innoflight, Inc.	SCR-106	SDR with AES-256 Encryption	Tx: 7800-8500 Rx: 1760-1840 Rx: 2025-2110	Tx: X Rx: L/S	Tx: 20,000 Rx: 1,000	0.02-2.5 W	250 - 290	8.2 x 8.2 x 2.5 9.8 x 8.2 x 2.8	Y
Innoflight, Inc.	SCR-108	SDR with AES-256 Encryption	Tx: 19200-21200 Rx: 29000- 31000	Tx: Ka Rx: Ka	Tx: 100,000 Rx: 20,000	0.02-3 W	404	9.8x8.7x3.9	Y
EnduroSat	X-band Transmitter	Transmitter	7900-8400	X	150,000	27-33 dBm	270	9x9.6x2.6	Y
EnduroSat	UHF/VHF Transceiver	Transceiver	137-150, 400-403, 430-44	VHF, UHF	19.2	0.5-1 W	< 150	9.6x9.0x1.9	N
EnduroSat	S-band Transceiver I	Transceiver	2200-2290 (downlink)	S	100	0.5-2 W	195	9.6x9.0x1.9	Y



Table 9-4: Radios (Continued)

Manufacturer	Product	Type	Min Frequency	Frequency Band	Data Rate	Tx Power	Mass	Dimensions	Flight Heritage
---	---	---	[MHz]	--	[kbps]	--	[g]	[cm]	---
IQ Technologies for Earth and Space GmbH	XLINK	Transceiver	8025-8500 7145-7250	X	64-25,000	30 dBm	--	<1 U	Y
Syrlinks	EWC27	Transmitter	8025-8500	X	140,000	27-33 dBm	235	9x9.6x2.6	Y
Syrlinks	EWC27 + OPT27-SRX	Transceiver	Rx: 2025-2110 Tx: 8025-8500	X/S	RX: 256 TX:100000	33 dBm	320	9.6x9x3.9	Y
Syrlinks	EWC31	Transceiver	Rx: 2025-2110 Tx: 2200-2290	S	RX: 256 TX: 2,000	33 dBm	405	9.5x9.5x5.3	Y
Syrlinks	EWC31-NG	Transceiver	Rx: 2025-2110 Tx : 2200-2290	S	RX: 512 TX: 2,000	33 dBm	360	9.5x9x3.2	N
Syrlinks	N-XONOS	Transmitter	Rx: 2025-2110 Tx: 8025-8400	X/S	RX: 256 TX:400000	33 dBm	385	9.5x9x3.1	Y
Syrlinks	EWC15-NG	Transceiver	Rx: 2025-2110 Tx: 2200-2290	S	RX: 512 TX: 2,000	33 dBm	1280	17.2x12x6.7	N
Syrlinks	XONOS	Transmitter	Rx: 2025-2110 Tx: 8025-8500	X/S	RX: 256 TX: 628,000	40 dBm	2400	20,6x15,2x6,9	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	1,000,000	2	1000	10x10x8	Y
AAC Clyde Space	PULSAR-DATA XTX X-Band Transmitter	SDR	--	X	50,000	2 W	130	9.6x9x1.1	Y



Table 9-4: Radios (Continued)

Manufacturer	Product	Type	Min Frequency	Frequency Band	Data Rate	Tx Power	Mass	Dimensions	Flight Heritage
---	---	---	[MHz]	--	[kbps]	--	[g]	[cm]	---
AAC Clyde Space	PULSAR-DATA STX S-Band Transmitter	SDR	--	S	7,500	1 W	100	9.6x9x1.7	Y
AAC Clyde Space	PULSAR-VUTRX	SDR	--	VHF, UHF	9.6	1.5 W	100	9.6x9x1.6	Y
Honeywell	STC-MS03	Transceiver	--	S	6,250	3.16 W	1000	16x11x4.4	Y
Innoflight, Inc.	SCR-106HDR	SDR with AES-256 Encryption	Tx: 7,800-8,500 Rx: 1,760-1,840 Rx: 2,025-2,110	Tx: X Rx: L/S	Tx: 100,000 Rx: 20,000		250 - 290	8.2 x 8.2 x 2.5 cm (CubeSat) 9.8 x 8.2 x 2.8 cm (SmallSat)	Y
EnduroSat	Versatile Wideband SDR (VW-SDR)	Transceiver	75 - 6000	VHF, UHF, L, S, C	982,000	-10 dBm	<1500	9.8x9.8x7.5	N
Trident	RDRT	SDR – RF System on Chip (RFSoc)	100	L/S	8-channels 250MHz – 6554MHz TX, 8-channels 250MHz – 4096MHz RX	-1 dBm Full-scale	571	10 x 14.6 x 2.54	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	10 x 14.6 x 2.54	N



9.3 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 rapidly changing, and optical communication is becoming a more common wireless communication technology for small satellites.

Due to the higher frequencies used in lasercom, the amount of bandwidth available for communicating is much larger compared to 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 a RF link (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 the wavelength of the transmitted energy is orders of magnitude smaller than RF systems. These small wavelengths mean 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 similar 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 which require a licensing process to be able to communicate with a spacecraft. Lasercom is not without its disadvantages, which include the required pointing of the beam and the impact weather has on the signal. The small beam divergence of lasercom systems means that the acceptable pointing error is much smaller. 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 that have infrequent cloud cover.

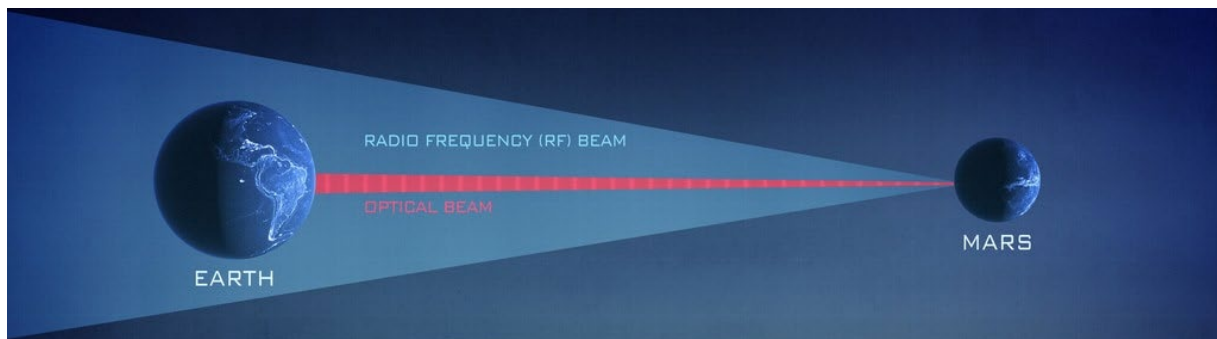


Figure 9.7: Laser vs RF link and data downlink. Credit: NASA.

While larger mission such as Geosynchronous Lightweight Technology Experiment (GeoLITE), Near Field Infrared Experiment (NFIRE), and Lunar Laser Communication Demonstration (LLCD) have demonstrated laser communications downlinks and crosslinks for over a decade, small satellites and CubeSats have also now successfully demonstrated laser communication downlinks from space. For example, the Aerospace Corporation, in cooperation with NASA ARC, launched three CubeSats in its AeroCube Optical Communication and Sensor Demonstration (OCSD) series (figure 9.8). OCSD-B & C demonstrated a 200 Mbps

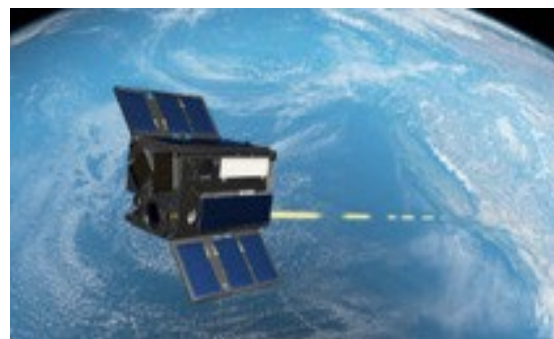


Figure 9.8: An artist rendering of laser communications for the OCSD. Credit: NASA.

downlink from a 1.5U CubeSat satellite 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 laser terminal system diagram). As with radio terminals, component locations in optical terminals can vary; for example, the modulator may not be located proximal to the optical front end. Also, the pointing mechanism might differ from the one shown in figure 9.9.

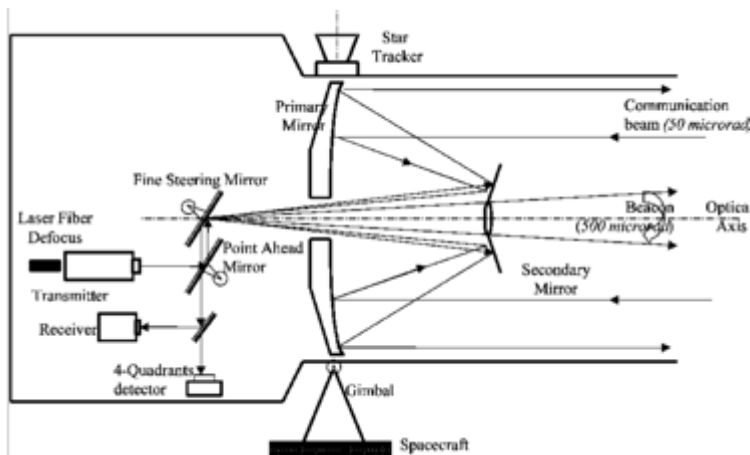


Figure 9.9: Laser terminal architecture diagram. Credit: M. Guelman et al. (2004).

The key parameters of an optical communication system are frequency, modulation, aperture size, and range. Successful optical communications links typically 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. In order 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. 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 to have the receiving aperture (typically a mirrored telescope) 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 located in favorable environments. Optical ground stations are typically mounted inside protected domes or other structures to cover them during bad weather. These structures 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 proximity to airports. Typical ground-to-space beacons are 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 has been recent development in commercial optical ground stations. For a more detailed outline 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 power draw compared to an RF terminal. However, lasercom pointing requirements are significantly tighter. One of the largest challenges to mainstream implementation is the required pointing for the LCT. To manage this, each system architecture will describe the specific system of pointing used. 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, SmallSat LCTs usually do not use mechanical gimbals. SmallSat lasercom systems solely or largely rely on the body pointing of the satellite to point the LCT at the ground station and may use an internal fine pointing mechanism to achieve the required 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 with 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, precise three-axis reaction wheels and attitude determination from one or more star trackers is necessary.

While RF bands with high frequency and bandwidth are affected by clouds and rain, cloud cover can prove difficult or even insurmountable for optical communications due to the high levels of attenuation by water vapor. 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. 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. The correction of the wavefront is required because of the lack of power that would 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 and measure the aberration to feed into the control of the adaptive optics system acting on the received light.

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 helps with data routing and can reduce how long it takes to route data to the end use. Lasercom crosslink systems are now in use for both commercial and government missions. Lasercom crosslink demonstrations have been performed from GEO-LEO, LEO-GEO, and LEO-LEO, and are operational as part of the European Data Relay Service (37)(38), but these LCTs were developed for much larger spacecraft (19)(20). 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. The challenges facing inter-satellite optical communications also centers 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 modifications to the receive optics may be required to manage high Doppler shift.



9.3.4 Policies and Licensing

Given the early stages of development for optical communication systems, both policy and regulatory approaches are still evolving. In the policy realm, there is an initial draft 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 communication working group with NASA and ESA participation.

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) 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 laser communications systems currently deployed doesn't warrant a complex coordination body like the ITU.

However, in the US there are three regulatory entities that are concerned with aspects of outdoor laser operations: The FAA, 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. 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 (39).

9.3.5 Mission Examples

Missions demonstrating lasercom terminals on small satellite and CubeSat platforms have shown viable pathways for overcoming the challenges associated with lasercom to enable high bandwidth communications. Please refer to table 9-5 for more information on lasercom missions.

The Small Optical Transponder (SOTA) was developed by the National Institute of Information and Communications Technology (NICT) in Japan and launched in 2014. This LCT is capable of up to 10 Mbps and has successfully demonstrated a laser space-ground link from a 50 kg microsatellite (21). 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 (22).

The German Aerospace Center (DLR) has been developing LCTs as part of its Optical Space Infrared Downlink System (OSIRIS) program to support lasercom from small satellites. The first, OSIRISv1 is capable of 200 Mbps downlinks and is integrated into the University of Stuttgart's Flying Laptop satellite. This LCT uses a body pointing-only approach. The OSIRISv1 LCT, launched in 2017, has completed commissioning and is being used by DLR to test their optical ground stations. The OSIRISv2 LCT, launched in 2016, is capable of 1 Gbps and is integrated into the BiROS satellite from DLR Berlin. This LCT uses closed-loop body pointing with a beacon reference. The OSIRISv2 LCT has been undergoing commissioning with parts of the terminal having been commissioned (23)(24)(25).

The Aerospace Corporation completed the first demonstration of optical communication from a CubeSat platform with the NASA-sponsored Optical Communication and Sensor Demonstration (OCSD) mission. These terminals were integrated into a 1.5U CubeSat and rely only on body pointing. The use of body pointing-only comes from using high optical power amplifiers with a larger beam divergence tuned to the pointing performance capability of their spacecraft. The terminals achieved a 200 Mbps downlink data rate to a 40 cm ground station and do 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).

As part of NASA's CLICK mission, MIT developed the 1.2U CLICK-A terminal. The first phase of the mission is flying 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 the spacecraft 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 is integrated into a Blue Canyon Technology's XB1 spacecraft bus and was launched to and deployed from the ISS in 2022. CLICK-A ultimately serves as a risk-reduction phase for the CLICK-B/C phases of the mission described later in this section (26).

DLR has also been developing their OSIRIS4 CubeSat transmitter. This optical communication terminal is designed to demonstrate an optical downlink in a 0.3U package. This transmitter also uses a MEMS FSM fine pointing mirror and was launched on the PIXL-1 mission in 2021. A beacon is used for fine pointing reference with this terminal. This terminal is designed to be used with a 60 cm optical receiver and has been commercialized through TESAT with the product name CubeLCT (27).

Sony Computer Science Lab and the Japanese Aerospace Exploration Agency (JAXA) jointly developed a LCT called Small Optical Link for ISS (SOLISS). This LCT is capable of bidirectional 100 Mbps links and was launched to and mounted on the ISS in 2019. This LCT has been successfully demonstrated with NICT's ground station (28)(29).

MIT Lincoln Laboratory developed the TBIRD terminal, which supports 200 Gbps downlinks. The transmitter uses commercial fiber telecommunication components to support very high data rates. This project is planned to downlink to 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 a fiber transceiver card. This terminal development was sponsored by NASA and was launched on the PDT-3 6U CubeSat mission in June of 2022 (30).

Future mission launches include the CLICK-B/C terminals. 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 & C will each be integrated into its 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 2024 and fly in the same orbital plane (26).

While results have not been shown on a flown mission, the CubeCat LCT is a commercial product by AAC Clyde Space that offers a bidirectional space-to-ground communication link between a CubeSat and an optical ground station. This LCT offers downlink speeds of up to 1 Gbps and an uplink data rate of 200 Kbps (31).

9.3.6 Future Technologies

While free space optical communication technology development has been making strides towards fielding operational systems, other avenues of research have also been explored. Quantum key distribution is a protocol that shares a secret cryptographic key through entangled photons. Sources and optical front ends have been developed for transmitting these keys from small satellite spaceborne platforms (32)(33). The Deployable Optical Receiver Aperture (DORA) project, which is developing a 1 Gbps crosslink LCT (34), is a novel approach to deploying large apertures in space. The inter-spacecraft optical communicator (ISOC), which includes arrays of fast photodetectors and transmit telescopes to provide full-sky coverage, gigabit data rates and multiple simultaneous links, was initially developed at NASA's Jet Propulsion Laboratory with funding from NASA's Small Spacecraft Technology (SST) program from 2018 to 2020. An advanced version of the ISOC is currently being developed by Chascii Inc. with funding from NASA Small Business Innovation Research Program for cislunar applications. There are currently several ISOC versions for short-, mid-, and long-range applications that use appropriate levels of power and aperture size, respectively, to achieve gigabit connectivity (35). Another approach to expanding the communication windows for small satellites in low-Earth orbit is to form an intersatellite link to geosynchronous orbit. Major programs, such as the previously mentioned European Data Relay System use this type of link. NICT is looking to establish this type of link with a CubeSat through the CubeSOTA program (36). In addition to CubeSat terminals, larger terminals for larger SmallSats are under development by Tesat, Mynaric (26), SpaceMicro (27), and SA Photonics. DARPA has funded the Space-BACN program that seeks to develop a reconfigurable and multi-protocol inter-satellite LCT that can be supported on small satellites.



Table 9-5: LCT Technologies									
Vendor/Developer	Terminal	Platform	Data Rate	Mass	Power	Wavelength	Modulation	Launch Date	Reference
---	---	---	[Mbps]	[kg]	[W]	[nm]	---	---	---
NICT	SOTA	SOCRATES	10	5.9	16	976/800/1549	OOK	5.2014	21
DLR	OSIRISv2	BiROS	1000	1.65	37	1550	OOK	6.2016	24
DLR	OSIRISv1	Flying Laptop	200	1.3	26	1550	OOK	7.2017	23, 24, 25
Aerospace Corporation	OCSD-B&C	AeroCube-7	200	<2.3	20	1064	OOK	12.2017	16
NICT	VSOTA	RISESAT	1	<1	4.33	980/1550	OOK/PPM	1.2019	22
Sony/JAXA	SOLISS	ISS	100	9.8	36	1550	OOK	7.2019	28, 29
DLR	OSIRIS4CubeSat	PIXL-1	100	0.4	10	1550	OOK	1.2021	27
MIT Lincoln Labs	TBIRD	PDT-3	200,000	<3	100	1550	QPSK	5.2022	30
MIT	CLICK-A	CLICK	10	1.2	15	1550	PPM	7.2022	26
MIT	CLICK-B/C	CLICK	20	1.5	30	1537/1563	PPM	Est. 2024	26
AAC Clyde Space	CubeCat	---	1000	<1.33	15	1550	OOK	---	31



9.4 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 and laser communication already have CubeSat flight heritage, but with limited (or yet to be demonstrated) performance. 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 a CubeSat platform, this is still not yet considered to be established technology on spacecraft. More demonstrations are in development, with some already launched and operating, to show 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 business email for further contact.

References

- (1) J.N Pelton. "The Basics of Satellite Communications." s.l.: Professional Education International, Inc., 2006.
- (2) NASA "Integrated Solar Array and Reflectarray Antenna (ISARA) for High Bandwidth CubeSats." [Online] July 26, 2016. Available at: https://www.nasa.gov/sites/default/files/atoms/files/isara_fact_sheet-26july2016.pdf
- (3) JPL. Mars Cube One (MarCO). Jet Propulsion Laboratory California Institute of Technology | CubeSat. [Online] Available at: <https://www.jpl.nasa.gov/cubesat/missions/marco.php>
- (4) S. Xie et al. "Wireless Sensor Network for Satellite Applications: A Survey and Case Study." Unmanned Systems, Vol. 2, pp. 261-277, 2014.
- (5) R. Schoemaker and J. Bouwmeester. "Evaluation of Bluetooth Low Energy Wireless Internal Data Communication for Nanosatellites." Small Satellites Systems and Services Symposium. pp. 1-15, 2014.
- (6) P.G. Farrell and A.P. Clark. "Modulation and coding." International Journal of Satellite Communications, 1984.
- (7) A. Datta. "New FCC rules make small satellite licensing easier, faster, and cheaper. Geospatial World | Advancing Knowledge for Sustainability." [Online] August 22, 2020. Available at: <https://www.geospatialworld.net/blogs/new-fcc-rules-make-small-satellite-licensing-easier-faster-and-cheaper/>
- (8) J. Buxton and D. Glasbrenner. "AMATEUR RADIO AND EXPERIMENTAL LICENSING FOR CUBESATS."
- (9) CalPoly. "CubeSat Licensing Support." [Online] Available at: <https://www.cubesat.org/cubesatlicensingupport>
- (10) National Institute of Standards and Technology. "Security Requirements for Cryptographic Modules, Federal Information Processing Standard (FIPS). ISO/IEC 19790:2012; ISO/IEC 24759:2014
- (11) 47 CFR Part 97 - AMATEUR RADIO SERVICE. [Online] Available at: <https://www.law.cornell.edu/cfr/text/47/part-97>
- (12) J.R. Wertz, D.F. Everett, and J.J. Puschell. "Space Mission Engineering: The New SMAD." Microcosm Press, Hawthorne, CA, 2015.
- (13) S.K. Johnson, R.C. Reinhart, and T.J. Kacpura. "CoNNeCT's approach for the development of three Software Defined Radios for space application." IEEE Aerospace Conference. pp. 1-13, Big Sky, MT, 2012.



- (14) Y. Wong et al. "NASA Near Earth Network (NEN) DVB-S2 Demonstration Testing for Enhancing Data Rates for CubeSats." 31st Annual AIAA/USU Conference on Small Satellites, Logan, UT, 2019.
- (15) JPL. "Iris V2 CubeSat Deep-Space Transponder (IRIS)." [Online] Available at: <https://www.jpl.nasa.gov/cubesat/missions/iris.php>
- (16) [101] T.S. Rose, D.W. Rowen, S.D. LaLumondiere, N.I. Werner, R. Linares, A.C. Faler, J.M. Wicker, C.M. Coffman, G.A. Maul, D.H. Chien, A.C. Utter, R.P. Welle, and S.W. Janson. "Optical communications downlink from a low-earth orbiting 1.5U CubeSat," *Opt. Express* 27, 24382-24392, 2019.
- (17) D.W. Pack, G. Kinum, P.D. Johnson, T.S. Wilkinson, C.M Coffman, J.C. Mauerhan, B.S. Hardy, R. Russell, and K. Mercy. "Landsat Imagery from a CubeSat: Results and Operational Lessons from the R3 Satellite's First 18 Months in Space." Small Satellite Conference, Logan UT, 2020.
- (18) D.W Pack, B.S Hardy, J.R. Santiago, D. Pietrowski, J.C. Mauerhan, P.F. Zittel, D.W. Rowen, C.R. Purcell, P. Thiyannaratnam, L.J. Gelinis, P.K. Su, J. Gussy, and J.M. Santiago. "Flight Operations of Two Rapidly Assembled CubeSats with Commercial Infrared Cameras: The Rogue-Alpha,Beta Program." Small Satellite Conference, Logan UT, 2021.
- (19) T. Jono, Y. Takayama, N. Kura, K. Ohinata, Y. Koyama, K. Shiratama, Z. Sodnik, B. Demellenne, A. Bird, and K. Arai. "OICETS on-orbit laser communication experiments. Page 610503, San Jose, CA, February 2006.
- (20) R. Fields, D. Kozlowski, H. Yura, R Wong, J Wicker, C. Lunde, M. Gregory, B Wandernoth, and F. Heine. "5.625 Gbps bidirectional laser communications measurements between the NFIRE satellite and an Optical Ground Station." International Conference on Space Optical Systems and Applications (ICSOS), pages 44–53, Santa Monica, CA, USA, May 2011. IEEE.
- (21) H. Takenaka, Y. Koyama, M Akioka, D. Kolev, N. Iwakiri, H. Kunimori, A. Carrasco-Casado, Y. Munemasa, E. Okamoto, M. Toyoshima. "In-orbit verification of small optical transponder (SOTA): evaluation of satellite-to-ground laser communication links." *Proc. SPIE* 9739, Free-Space Laser Communication and Atmospheric Propagation XXVIII, 973903, March 15, 2016.
- (22) H. Tomio, T. Kuwahara, S. Fujita, Y. Sato, M. Sakal, H. Kunimori, T. Kubooka, H. Takenaka, Y. Saito, M. Toyoshima. "Assembly and integration of optical downlink terminal VSOTA on microsatellite RISESAT." *Proc. SPIE* 11180, International Conference on Space Optics — ICSO 2018, 111805Z, July 12, 2019.
- (23) C. Schmidt, C. Fuchs, ""The OSIRIS program at DLR,"" *Proc. SPIE* 10524, Free-Space Laser Communication and Atmospheric Propagation XXX, 105240R, 5 February 15, 2018.
- (24) C. Fuchs, C. Schmidt, J. Keim, F. Moll, B. Rödiger, M. Lengowski, S. Gaißer, and D. Giggenbach. "Update on DLR's OSIRIS program and first results of OSIRISv1 on Flying Laptop." *Proc. SPIE* 10910, Free-Space Laser Communications XXXI, 109100S, March 4, 2019.
- (25) D. Giggenbach, C. Fuchs, C. Schmidt, B. Rödiger, S. Gaißer, S. Klinkner, D. Phung, J. Chabé, C. Courde, N. Maurice, H. Mariey, E. Samain, and G. Artaud. "Downlink communication experiments with OSIRISv1 laser terminal onboard Flying Laptop satellite." *Appl. Opt.* 61, 1938-1946, 2022.
- (26) W. Kammerer, P. Grenfell, L. Hiest, P. Serra, H. Tomio, N. Belsten, C. Lindsay, O. Čierny, K. Cahoy, M. Clark, D. Coogan, J. Conklin, D. Mayer, J. Stupl, J. Hanson. "CLICK Mission Flight Terminal Optomechanical Integration and Testing." International Conference on Space Optics — ICSO, 2022.



- (27) Tesat. "SMALLEST LASER COMMUNICATION TRANSMITTER WORLDWIDE." Technical Datasheet. [Online] 2022. Available at: https://www.tesat.de/images/tesat/products/220607_DataSheet_CubelCT100M_A4.pdf
- (28) K. Iwamoto, H. Komatsu, S. Ohta, Y. Kubo, T. Nakao, H. Yamazoe, T. Kamata, Y. Munemasa, H. Kunimori, M. Toyoshima, D. Koda, H. Sawada, T. Ikeda. "Experimental results on in-orbit technology demonstration of SOLISS." Proc. SPIE 11678, Free-Space Laser Communications XXXIII, 116780D, March 5, 2021.
- (29) H. Komatsu, S. Ohta, H. Yamazoe, Y. Kubo, T. Nakao, T. Ito, D. Koda, H. Sawada, T. Ikeda, Y. Munemasa, H. Kunimori, T. Kubooka, M. Toyoshima, K. Iwamoto. "The pointing performance of the optical communication terminal, SOLISS in the experimentation of bidirectional laser communication with an optical ground station." Proc. SPIE 11678, Free-Space Laser Communications XXXIII, 116780F, March 5, 2021.
- (30) Curt M. Schieler, Kathleen M. Riesing, Andrew J. Horvath, Bryan C. Bilyeu, Jesse S. Chang, Ajay S. Garg, Jade P. Wang, Bryan S. Robinson, ""200 Gbps TBIRD CubeSat downlink: pre-flight test results,"" Proc. SPIE 11993, Free-Space Laser Communications XXXIV, 119930P, March 4, 2022.
- (31) AAC Clyde Space. "LASER COMMUNICATIONS CUBECAT." Technical Datasheet. [Online] 2022. Available at: <https://www.aac-clyde.space/wp-content/uploads/2021/10/CUBECAT.pdf>
- (32) R. Bedington, J.M. Arrazola, and A. Ling. "Progress in satellite quantum key distribution." Npj Quantum Information Vol. 3, 30, 2017.
- (33) P. Serra, O. Čierny, W. Kammerer, E.S. Douglas, D.W. Kim, J.N. Ashcraft, G. Smith, C. Guthery, T. Vergoossen, A. Lohrmann, R. Bedington, C. Perumangatt, A. Ling, K. Cahoy. "Optical front-end for a quantum key distribution cubesat." Proc. SPIE 11852, International Conference on Space Optics, 118523C, June 11, 2021.
- (34) D. Jacobs, J. Bowman, M. Patterson, M. Horn, C. McCormick and M. Adkins. "Plan for On-Orbit Demonstration of the Deployable Optical Receiver Array." IEEE Aerospace Conference (AERO), pp. 1-8, 2022.
- (35) J.E. Velazco and J.S. de la Vega. "Q4 – A CubeSat Mission to Demonstrate Omnidirectional Optical Communications." IEEE Aerospace Conference, pp. 1-6, 2020.
- (36) A. Carrasco-Casado et al., ""Intersatellite-Link Demonstration Mission between CubeSOTA (LEO CubeSat) and ETS9-HICALI (GEO Satellite)." IEEE International Conference on Space Optical Systems and Applications (ICSOS), pp. 1-5, 2019.
- (37) European Space Agency. "European Data Relay Service." [Online] Available at: https://www.esa.int/Applications/Telecommunications_Integrated_Applications/EDRS
- (38) F. Heine, P. Martin-Pimentel, N. Höpcke, D. Hasler, C. Rochow, and H. Zech. "Status of tesat lasercomms activities." Free-Space Laser Communications XXXIII, vol. 11678, pp. 45-50. SPIE, 2021.
- (39) R. Lafon, J. Wu, B. Edwards. "Regulatory Considerations: Laser Safety and the Emerging Technology of Laser Communication." Commercial Laser Communications Interoperability and Regulatory Workshop, Washington, DC, June 12, 2017.