Chapter Contents

Chapter Glossary

(ADCS)	Attitude Determination and Control System
(BPF)	BandPass Filters
(CDH)	Command and Data Handling
(COTS)	Commercial-off-the-Shelf
(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
(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
(ISS)	International Space Station
(JPL)	Jet Propulsion Laboratory
(LADEE)	Lunar Atmosphere and Dust Environment Explorer
(Lasercom)	Laser Communications
(LCH)	Laser ClearingHouse
(LCT)	LaserCom Terminals
(LDPC)	Low-Density Parity-check Code
(LLCD)	Lunar Laser Communications Demonstration
(LNA)	Low Noise Amplifier
(MA)	Multiple Access
(MarCO)	Mars Cube One
(MEMS)	Micro-Electro-Mechanical
(MRR)	Modulating Retro-Reflector

(NEN)	Near Earth Network
(NICT)	National Institute of Information and Communications Technology
(NOAA)	National Oceanic and Atmospheric Administration
(NTIA)	National Telecommunications and Information Administration
(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
(WFF)	Wallops Flight Facility

9.0 Communications

9.1 Introduction

The communication system is an essential part of a spacecraft, enabling spacecraft to transmit data and telemetry to Earth, receive commands from Earth, and relay information to one another. A communications system consists of the ground segment: one or more ground stations located on Earth, and the space segment: the spacecraft(s) 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). There are two types of communication systems: radio frequency (RF) and free space optical (FSO) also referred to as laser communications (lasercom).

Most spacecraft communications systems are radio frequency based. They are conducted in the Institute of Electrical and Electronics Engineers (IEEE) radio bands of 300 MHz to 40 GHz. A RF system communicates by sending data over electromagnetic waves to and from antennas. Information is encoded onto radio frequency waves using modulation and sent to the receiving system where it is demodulated and decoded.

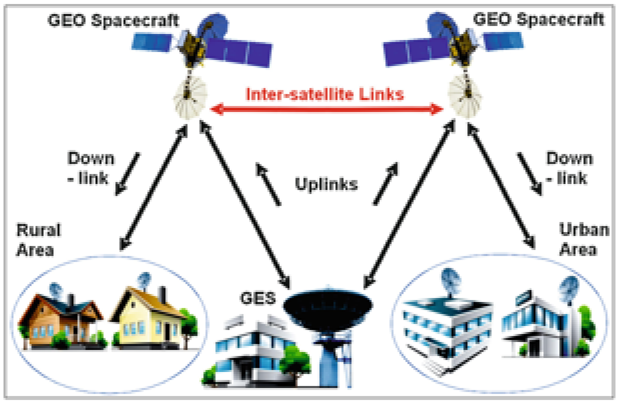

Figure 9.1: Satellite uplink, downlink, and crosslink. Credit: D. Stojce (2019).

Recent development in FSO communications has made it a strong alternative to RF systems. FSO systems consist of a transmitting terminal and receiving terminal. Much like an RF system, information is encoded onto electromagnetic waves using modulation and sent to the receiving system. FSO links operate at a much higher frequency than RF links, generally at infrared or visible bands. Higher frequencies result in wider bandwidths which result in higher data rates.

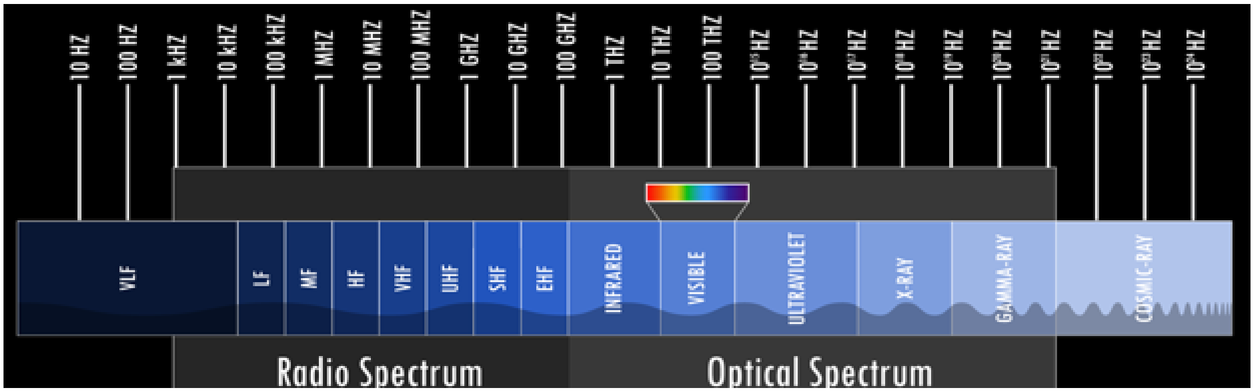

Figure 9.2: Radio and optical spectrum used by spacecraft for communication. Credit: NASA.

9.1.1 Document Organization

This chapter organizes the state-of-the-art in small spacecraft communications hardware into the following categories:

1. Radio Frequency Communications (9.5)
2. Optical Communications (9.6)

Each of these categories is further subdivided by the system background and prevailing technology types. The subsections organize data as follows:

a. System Introduction
    i. Frequency Bands
    ii. System Architecture
    iii. Design Considerations
    iv. Policies and Licensing
b. Hardware
    i. Device Introduction
    ii. Device Tables
c. On the Horizon

9.2 Public Data Sources and Disclaimers

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.

9.3 Definitions

- Device refers to a component, subsystem, or system, depending on the context.
- Technology refers to a broad category of devices or intangible materials, such as processes.
- System refers to the integration of components from a multitude of manufacturers, which may be mixed-and-matched to create a unique mission-appropriate subsystem solution.

9.4 Technological Maturity

9.4.1 Application of the TRL Scale to SmallSat Communications Systems

NASA has clear guidelines for Technology Maturity Assessments (TMA) outlined in the NASA SP-2016-6105 NASA Systems Engineering Handbook Appendix G: Technology Assessment/Insertion. An assessment determines a device’s maturity level, and the Technology Readiness Level (TRL) as the frequently used system of measure. The TRL scale is defined in NASA Procedural Requirements (NPR) 7123. In general, technologies rated TRL 5 have been demonstrated in a laboratory, TRL 7 has been demonstrated in a flight-like environment, and TRL 9 is flight ready and space-qualified. TRL is used to communicate the maturity and risk levels associated with a particular technology. TRLs are applied across all technology categories, resulting in broad definitions for each level. Assessment of a device’s TRL level requires the consideration of a subject matter expert (SME). Without the in-depth technical knowledge of the specific subject, the TRL level could be applied incorrectly.

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 particular small spacecraft subsystems. It should be noted that TRL designations may vary with changes specific to payload, mission requirements, reliability considerations, and/or the environment in which performance was demonstrated. This chapter will be reviewing state-of-the-art technology on the order of TRL 7-9, spanning early flight testing to production flight hardware. Due to the limited technical knowledge of the reviewer(s) about specific hardware, TRL assessment for RF hardware and lasercom terminals will not be provided. The technology reviewed for this chapter will all be at a certain threshold of development; therefore, it can be assumed by the reader that it is at minimum TRL 7. Hardware used in notable missions will be identified, and those devices can be assumed to be TRL 9. Technology characterized as On-the-Horizon will be included at the end of each chapter. These devices will be on the order of TRL 4-6.

Readers are highly encouraged to reach out to companies for further information regarding the performance and TRL of described technology. There is no intention of mentioning certain companies and omitting others based on their technologies or relationship with NASA.

9.5 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 and filters are sometimes employed to reduce signal noise in certain frequency bands 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 are typically more mature for SmallSat usage, 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 require higher power due to increased atmospheric attenuation at those frequencies and the higher free space loss that is directly proportional to frequency.

9.5.1 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 being NASA's intended band for 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 greater atmospheric and rain attenuation adding to increased free space loss. This needs to be 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.

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 Earth Network (NEN) at no charge. 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).

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).

9.5.2 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. Modulation and coding are added to achieve communication efficiency and adequate performance under the conditions imposed by the satellite transmission path (6). 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 increase it while reducing interference noise using a bandpass filter. 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.

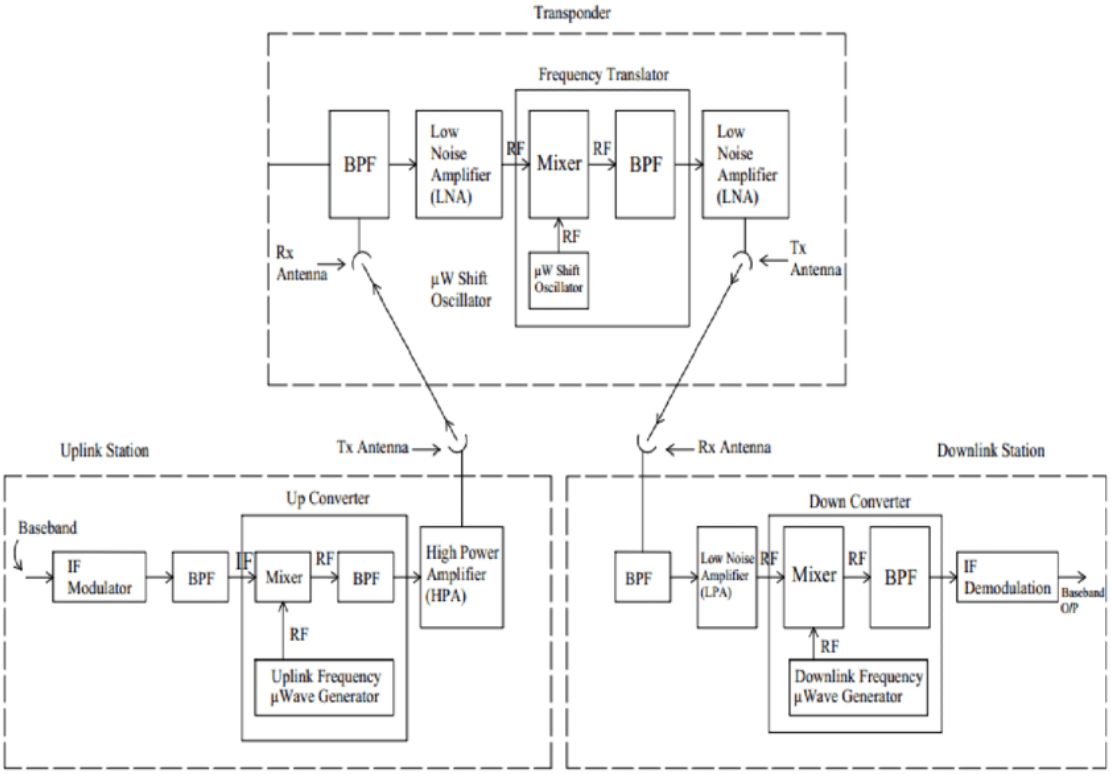

Figure 9.2: Transmit and receive block diagram. Credit: Karim et al. (2018). http://creativecommons.org/licenses/by/4.0/

9.5.3 Definitions

- Radio or Modulator: 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.
- Filters and mixers: Bandpass filters (BPF) and 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 be used to convert the signal to a higher frequency for transmit. Similarly, the downconverter will down convert a receive frequency to a lower one for processing.
- Amplifier: For a transmit system, a power or gain amplifier is required. For a receive system, a low noise amplifier (LNA) is required.
- Antenna: Increases the strength of a signal in a specific direction, relative to the same signal strength without directionality. Receives signals sent towards it by the transmitter.
- 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 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.

9.5.4 Design Considerations

The communications subsystem is an essential part of every spacecraft. It is required to transmit important health and telemetry data down to Earth, as well as receive commands from ground operators. Additionally, the communications system is critical to transporting mission data back to Earth. 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 a RF comm 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 UL/DL or XL, 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.

9.5.5 Policies and Licensing

Any non-Federal 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).

9.5.6 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. Additionally, the improvement in propulsion technology for small satellites creates a potential collision threat for other low-Earth orbit spacecraft. 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).

9.5.7 Antennas

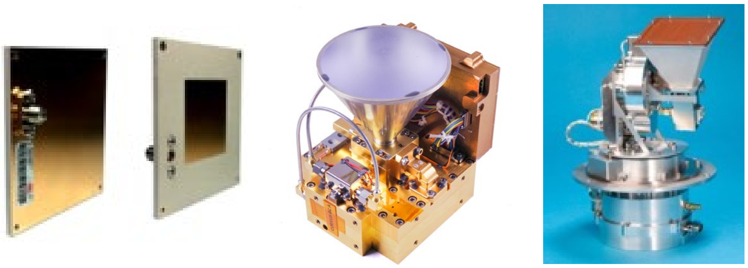

Figure 9.3: (from left to right) CubeSat-compatible S-band patch antenna (IQ Wireless), X-band high-gain antenna and pointing mechanism (Surrey Satellite Technology, Ltd.), and Ka-band transmitter with a horn antenna (Astro Digital).

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.

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 9.3. 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 9.4.

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. By increasing the aperture or diameter of an antenna it inceases the link margin, which can allow designers to increase the data rate of the system or reduce the necessary transmit power.

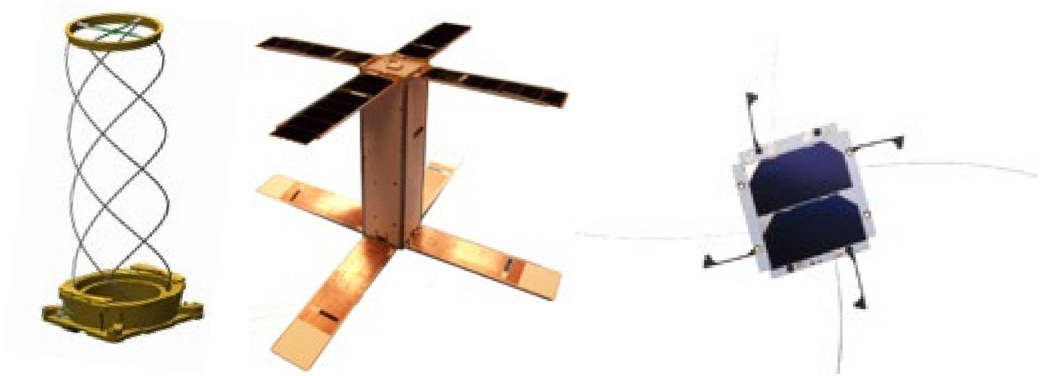

Figure 9.4: (from left to right) Example of deployable quadrifilar helical antenna. (Helical Communication Technologies), SNaP spacecraft with Haigh-Farr's deployable UHF Crossed Dipole antenna (Space Missile and Defense Command), and EnduroSat UHF antenna with EnduroSat solar panels (EnduroSat).

9.5.8 Radios

Figure 9.5: Example of software defined radio, tunable in the range 70 MHz to 6 GHz. Credit: GomSpace.

Radios for small sat 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 to be low data-rate, 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, see figure 9.5 for an example of an SDR. 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. Since 2012, NASA has been operating the Space Communications and Navigation (SCaN) Testbed on the International Space Station 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.

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 tradeoffs 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, along with size, weight, and power (SWaP). DVB-S2 uses power and bandwidth efficient modulation and coding techniques to deliver performance approaching theoretical limits of RF channels. NASA's NEN 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).

9.5.9 On the Horizon RF Communications

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 will 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.

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 CubeSat may be mother ship-capable while the others may be subordinate (e.g., daughterships), however, multiple CubeSats may have the ability to fulfill the role of a mothership.

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. This includes 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.

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 this 2021 edition, only the two MarCO SmallSats have operated beyond low-Earth orbit. Both satellites used a deployable reflectarray panel at X-band and were equipped with a full-duplex radio providing both UHF and X-band coverage. 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.

IRIS Version 2 is a CubeSat/SmallSat compatible transponder developed by NASA Jet Propulsion Laboratory (JPL) as a low volume and mass, lower power and cost, software/firmware defined telecommunications subsystem for deep space technology demonstration missions (15). IRIS is designed to be radiation-hardened for deep space missions and interoperable with the NASA Deep Space Network (DSN). Launch date is currently TBD.

9.6 Optical Communications

Optical communications or lasercom, is the use of optical wavelengths of electromagnetic radiation to transmit messages wirelessly between user terminals. Optical communication is the forefront of current wireless communication technologies for small satellites. The technology is relatively new, and as such few proven optical communications terminals exist. Most available data is produced by government laboratories.

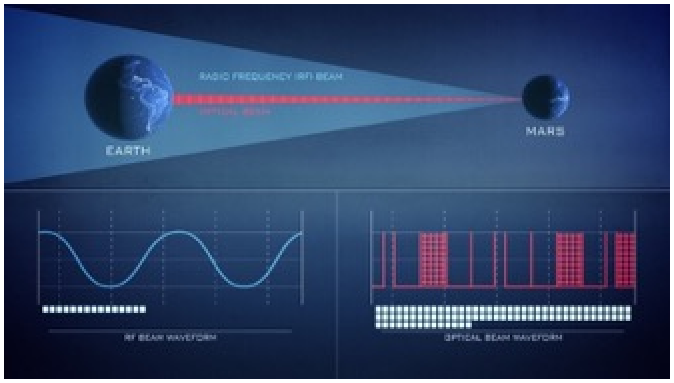

Figure 9.6: Laser vs RF link and data downlink. Credit: NASA.

Optical communications offer better performance than RF systems due to larger bandwidths available at sub-millimeter wavelengths. Laser communications have a low probability of intercept, are difficult to jam and encounters very little interference because of its narrow beamwidth. At the present, optical frequencies are unregulated and allow for large bandwidths and high channel throughput. Figure 9.6 displays the differences between Laser and RF link and data downlink.

CubeSats have successfully demonstrated laser communication in space, and the technology is quickly maturing. The Aerospace Corporation, in cooperation with NASA ARC, launched three CubeSats in its AeroCube Optical Communication and Sensor Demonstration; see figure 9.7. In March 2018, a systems checkout was completed, and the mission entered the operational phase. AeroCube's optical system successfully transmitted in mid-2018.

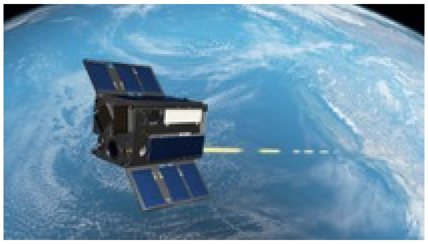

Figure 9.7: An artist rendering of laser communications for the OCSD. Credit: NASA.

9.6.1 System Architecture

Lasercom terminals (LCT) are comprised of an optical modem, optical amplifier, and optical head, see figure 9.8 for a laser terminal diagram. This is not always the case, as the Lunar Laser Communications Demonstration (LLCD) on NASA's Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft had the modem separated from the optical head (16). The key parameters of an optical comm system are frequency, aperture size, and range. Successful optical communications links require extremely high pointing accuracy; thus the system relies heavily on the attitude determination and control system (ADCS). Optical modems may be software defined and can support multiple modulation and coding schemes, similar to RF. The optical head is very similar to a RF

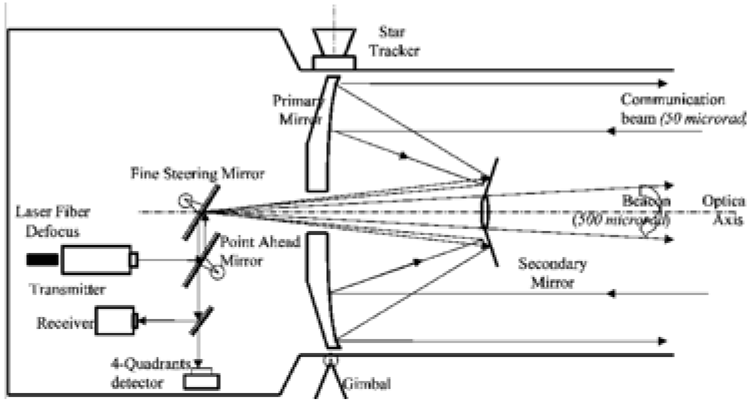

Figure 9.8: Laser terminal architecture diagram. Credit: M. Guelman et al. (2004).

antenna, it uses optics to concentrate energy through an aperture to form a very narrow beam. The narrower the beam, the higher the power density and the higher the data rate or range of the link.

9.6.2 Design Considerations

Lasercom terminals offer a smaller footprint and power draw compared to the RF alternative. However, the pointing requirements are much more difficult to achieve. Current ADCS for SmallSats do not quite meet the needs of LCT pointing. This is the greatest challenge to mainstream implementation. Generally, an optical comm system on a spacecraft can provide both coarse and fine pointing. After slewing as accurately as ADCS is able, the LCT will use both fast-steering mirrors used for fine pointing. Some systems also use gimbals for coarser pointing if the spacecraft ADCS cannot provide sufficient accuracy.

Much like rain attenuation at higher bands, for optical communications cloud cover can prove difficult, even insurmountable. 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. Some optical ground stations have sophisticated adaptive optics to accommodate atmospheric spreading and diffusion caused by turbulence.

Lasercom crosslink development is a field of great interest for both commercial and government customers. In the past, building a high-speed crosslink space network has proven nearly impossible (18). The challenges facing inter-satellite optical communications links primarily lies with the pointing accuracy, acquisition, and tracking requirements. Satellites in orbit are traveling at high speeds and experience jitter and vibration. This poses an extreme challenge and necessitates an advanced mechanical optical system to overcome. In the last few years, impressive progress has been made in the civilian and government non-classified arenas to make inter-satellite optical links a reality (18).

9.6.3 Policies and Licensing

Currently there are no licensing requirements for spacecraft laser communications. As the technology is still in development, there is minimal regulation of the few terminals in use. For commercial applications, the regulatory agency that will have to be dealt with the most is the FAA. FAA coordination is relevant to lasercom only if ground terminals are transmitting. Given that the transmit or crosslink vehicles are hundreds of miles above the highest-flying aircraft, it is not necessary to coordinate with the FAA, as beam dispersion is so great it doesn’t represent a risk. The American National Standard documents serve as the guiding basis from which many of the FAA requirements were derived. From ANSI Z136.6 “American National Standard for Safe Use of Lasers Outdoors”: Operators of lasers that have a divergence less than 10 µrad, or that exceed a peak irradiance greater than 1 mWcm-2 above 18 km (60,000 feet) in altitude above sea level, should contact U.S. Space Command regarding “Laser Clearinghouse” screening. When transmitting through navigable airspace, coordination with the FAA may be required to prevent damage to eyesight or distraction to pilots (19).

The laser clearinghouse (LCH) is tasked with ensuring orbital assets are not negatively impacted by lasers. However, the LCH only considers DoD laser programs to be required to coordinate laser activities with them. Many non-DoD projects volunteer to coordinate with LCH to ensure no damage to satellites. The process of coordinating with LCH can take many months and should be started as early as possible. Establishing a new account with LCH may involve significant lead time but submitting Predictive Avoidance Requests to run a pass is only 7 days. When designing a lasercom link, ensuring that the laser system can quickly autonomously shutter itself if laser pointing drift occurs could allow for the request of a smaller Keep Out Cone from the LCH. This will reduce the number of predictive avoidance outages your mission will have during operations.

9.6.4 Missions

The first attempt to demonstrate laser communication on a CubeSat was on-board FITSAT-1, a 1U system developed at the Fukuoka Institute of Technology in Japan. The satellite carried two arrays of high-power LEDs along with an experimental RF transceiver. The robotic arm of the International Space Station (ISS) deployed FITSAT-1 in October 2012. The German Aerospace Center is currently flying two lasercom terminals as part of its OSIRIS program. The Small Optical Transponder (SOTA) developed by the National Institute of Information and Communications Technology in Japan (NICT) has successfully demonstrated a laser space-ground link from a 50 kg microsatellite (20). Tesat-Spacecom offers the CubeLCT laser communication terminal (0.3U, 0.4 kg, 8 W), also known as OSIRIS4 CubeSat (21) and offers high bandwidth space-to- ground data transmissions of up to 100 Mbit/s. CubeLCT was launched in January 2021 as part of SpaceX's first SmallSat rideshare program, Transporter-1, aboard a Falcon 9 (22).

There are several up and coming laser communications technologies, all lower TRL than existing missions. Future endeavors include the NASA-sponsored Miniature Optical Communication Transmitter (23) and the CLICK mission (24). CLICK is a two-part mission, sponsored and overseen by NASA's SST Program and involving MIT, and University of Florida for the payload and BCT for the bus. CLICK-A will demonstrate a laser downlink, CLICK-B/C a laser cross-link. All CLICK spacecraft are 3U spacecraft and the payload occupies approximately 1.5U.

9.6.5 On the Horizon Optical Communications

Spacecraft parameters like power, mass, and volume are constrained by cost and current capability. Ground operations, on the other hand, are not subject to the same limitations. Asymmetric laser communications leverage this imbalance. Asymmetric laser communication uses a remotely generated laser (e.g., does not require an on-board signal carrier) and Modulating Retro-Reflector (MRR) to reflect and modulate a laser beam (encoding it with spacecraft data) back to Earth. The laser is located on Earth, where power and volume constraints are not as tight, while the communications payload on the spacecraft is limited to only a few watts for operation, see figure 9.9. NIWC is developing this technology using a MEMS-based MRR (20), The Navy has funded Boston Micromachines via small business innovative research (SBIR) to develop a Large Aperture Micro-Electro-Mechanical (MEMS) MRR. The goal of the project is to develop MRRs with a clear aperture of 25.4mm with packaging to survive the launch environment and operate in the vacuum of space.

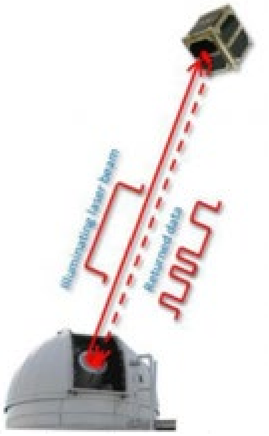

Figure 9.9: Scheme for using land-based laser to transmit data from CubeSat using on-board MRR. Credit: Salas et al. (2012).

Fibertek developed a 2U CubeSat lasercom system in 2018 based on work performed under a NASA ARC SBIR and continues to make substantial progress in lasercom and LiDAR technologies. Sinclair Interplanetary is developing the DCL-17 (TRL 5), a self-contained optical communications terminal that incorporates a built-in star tracker and a 1 Gbps laser downlink. CubeSat LCT are also in development by General Atomics and Hyperion Technologies. The CubeSat lasercom module by Hyperion Technologies enables a bidirectional space-to-ground communication link between a CubeSat and an optical ground station, with downlink speeds of up to 1 Gbps and an uplink data rate of 200 Kbps. In addition to CubeSat terminals, larger terminals for SmallSats are under development by Tesat, Mynaric (26), SpaceMicro (27), and SA Photonics.

9.7 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. On the other hand, laser communication is a spaceflight-ready technology that should see future onboard laser systems with increased performance. Alternatively, a few groups are working on asymmetric laser communication, but this is still a relatively low TRL technology. 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.

Table 9-1: Antennas

Manufacturer	Product	Type	Min Frequency	Frequency Band	Gain	Polarization	Mass	Dimensions	Flight Heritage
---	---	---	[MHz]	--	[dBi]	--	[g]	[cm]	---
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	Turnstile	400-500	VHF, UHF	1.37	--	33	10x10x0.7	
EnduroSat	UHF Antenna III	Whip/Burnwire	435-438	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
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
Flexitech Aerospace	2-2.5GHz Turnstile Antenna	Turnstile	2000-2500	S	5	Circular	173	--	N
Vulcan Wireless	ANT-S/S Unified S-Band Antenna	Patch	2025-2300	S	6.5	Circular	76	8x8x1	Y
EnduroSat	S-band Patch Antenna	Patch	2025-2110	S	7	Circular	64	10x10	Y
Syrlinks	SPAN-S-T3	Patch	2025-2290	S	4.8	Circular	117	8x8x11	Y
IQ Spacecom	S-band Patch Antenna	Patch	2100-2500	S	6	Circular	49	7x7x1	Y
ISISPACE	S-Band Patch Antenna	Patch	2200-2290	S	6.5	RHCP	50	8x8x1	N

Haigh-Farr, Inc.	S-band Patch Antenna	Patch	2245-2245	S	--	RHCP	48	4.8x6.5x6.5	Y
EnduroSat	X-band Patch Antenna	Patch	8025-8400	X	6	RHCP	2.2	--	Y
Syrlinks	SPAN-X-T2	Patch	8025-8450	X	7.6	RHCP	68	10x10x7	Y
Syrlinks	SPAN-X-T3	Patch	8025-8400	X	11.5	Circular	65	7.3x7.3x11	Y
Cesium Astro	Nightingale	Phased Array	27000-40000	Ka	30	Circular	1200	18x18x2	N
Oxford Space Systems	Helical antenna	Deployable	--	862 – 928 MHz	6.5	RHCP	~300	33	Y
Oxford Space Systems	Yagi antenna	Deployable	--	156.5 -162.5 MHz	6.5	Dual Linear	<1kg	100 x 70	Y
Oxford Space Systems	Deployable Cassegrain Wrapped Rib Antenna	Deployable	--	X-band	46 - 49	Linear	25kg to 38kg	300 - 500	N
Oxford Space Systems	Deployable Parabolic Offset Reflector	Deployable	--	C-band	42	Linear	from 12kg to 21kg	200 - 600	N
Oxford Space Systems	Deployable Hinged Rib Metal Mesh	Deployable	--	K/Ka-band	41	Linear	~2-3kg	~60	N
Redwire Space	Narwhal Antenna	Helical	100 – 4 GHz	L	6-18	Circular	0.0032	1.25U x 1.25U x 2U	N

Table 9-8: 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
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
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
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
SpaceQuest	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	19.2	2 W	94	10x10x2	Y
L3 Communications, Inc./SDL	Cadet	SDR	450	VHF, UHF	3,000	--	200	6.9x7.4x1.34	Y
AAC Clyde Space	PULSAR-TMTC	SDR	--	VHF, UHF	9.6	1.5 W	100	9.6x9x1.6	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
SpaceQuest	TX-2400	Transmitter	2000 to 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
Innoflight, Inc.	SCR-104	SDR	Tx: 2200-2300 Rx: 1760-1840 2025-2110	L, S	4500	1	290	9.8x8x3	Y
IQ Wireless 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 Wireless GmbH	SLINK-PHY	Transceiver	2200-2290 2025-2110	S	64-4,000	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 EWC31	Transponder	2200–2290 2025–2110	S	8-2,000	27-33 dBm	--	--	Y
EnduroSat	S-band Transmitter	Transmitter	2200-2290 2400-2450	S	20,000	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
Honeywell	STC-MS03	Transceiver	--	S	6,250	3.16 W	1000	16x11x4.4	Y
AAC Clyde Space	PULSAR-DATA S-Band Transmitter	SDR	--	S	7,500	1 W	100	9.6x9x1.7	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	100,000	30 dBm	--	4.5x4.35x1.25	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
JPL/SDL	IRIS V2	Transponder	7200-8400	X, Ka	--	3.8 W	1200	10x10x5.6	Y
Innoflight, Inc.	SCR-106	SDR	Tx: 7900-8500 Rx: 1760-1840 2025-2110	X	150,000	0.02-2.5 W	290	9.8x8.2x2.8	N
EnduroSat	X-band Transmitter	Transmitter	7900 to 8400	X	150,000	27-33 dBm	270	9x9.6x2.6	Y
IQ Wireless GmbH	XLINK	Transceiver	8025-8500 7145-7250	X	64-25,000	30 dBm	--	<1 U	Y
Syrlinks	X-band Transmitter EWC27	Transmitter	8025-8400	X	140,000	27-33 dBm	225	9x9.6x2.6	Y
AAC Clyde Space	PULSAR-DATA X-Band Transmitter	SDR	--	X	50,000	2 W	130	9.6x9x1.1	Y
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	1,000,000	35 dBm	1,000	16x9.6x6	N
SpaceMicro	microKaTx-300	Transmitter	25250-27250	K	1,000,000	2	1000	10x10x8	Y

Table 9-9: Optical Communications Terminals

Vendor/Developer	Program	Platform	Downlink Data Rate	Range	DC Power	Mass	Launch Date	Reference
---	---	---	[Mbps]	[km]	[W]	[kg]	---	---
The Aerospace Corporation	Optical Communications and Sensor Demonstration (OCSD)	Aerocube-7	200	1,000	2.3	30	11.2017	Datasheet
The Aerospace Corporation	Testbed for Optical Missions Satellite (TOMSat)	Aerocube-11	200	1,000	4.2	25	12.2018	Datasheet
Fibertek	WeatherSat AgileSat	MORPHEUS Cubesat	1,000	4,000	2.5	30	2020	Datasheet
MIT-LL	NODE (Nanosatellite Optical Downlink Experiment)	NODE (Nanosatellite Optical Downlink Experiment) Cubesat	20	2,000	1.0	15	2018	Datasheet
TESAT	NFIRE	NFIRE	n/a	4,900	30.0	130	4.2007	Datasheet
German Aerospace Center (DLR)	OSIRIS	Flying Laptop	200	600	1.3	26	7.2017	Datasheet
German Aerospace Center (DLR)	OSIRIS	BiROS	1,000	1,000	5.0	50	6.2016	Datasheet

References

(1) Pelton, J.N.: "The Basics of Satellite Communications." s.l.: Professional Education International, Inc., 2006.

(2) National Aeronautics and Space Administration. Integrated Solar Array and Reflectarray Antenna (ISARA) for High Bandwidth CubeSats. NASA. [Online] 2016.

(3) JPL. Mars Cube One (MarCO). *Jet Propulsion Laboratory California Institute of Technology | CubeSat.* [Online] https://www.jpl.nasa.gov/cubesat/missions/marco.php.

(4) Xie, Shuanglong, et al. "*Wireless Sensor Network for Satellite Applications: A Survey and Case Study."* 2014, Unmanned Systems, Vol. 2, pp. 261-277.

(5) Schoemaker, R. and Bouwmeester, J.: "*Evaluation of Bluetooth Low Energy Wireless Internal Data Communication for Nanosatellites.*" 2014. Small Satellites Systems and Services Symposium. pp. 1-15.

(6) Farrell, P. G. and Clark, A. P.: *"Modulation and coding.*" 1984, International Journal of Satellite Communications.

(7) Datta, Anusuya. New FCC rules make small satellite licensing easier, faster, and cheaper. Geospatial World | Advancing Knowledge for Sustainability. [Online] August 22, 2020. https://www.geospatialworld.net/blogs/new-fcc-rules-make-small-satellite-licensing-easier-faster-and-cheaper/.

(8) Buxton, Jerry and Glasbrenner, Drew. AMATEUR RADIO AND EXPERIMENTAL LICENSING FOR CUBESATS.

(9) CalPoly. CubeSat Licensing Support. CubeSat. [Online] https://www.cubesat.org/cubesatlicensingsupport.

(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 https://www.law.cornell.edu/cfr/text/47/part-97

(12) Wertz, James R., Everett, David F. and Puschell, Jeffery J.: "*Space Mission Engineering: The New SMAD."* Hawthorne, CA : Microcosm Press, 2015.

(13) Johnson, S.K., Reinhart, R.C. and Kacpura, T.J.: "CoNNeCT's approach for the development of three Software Defined Radios for space application.*"* Big Sky, MT : s.n., 2012. 2012 IEEE Aerospace Conference. pp. 1-13.

(14) Wong, Yen, et al. "*NASA Near Earth Network (NEN) DVB-S2 Demonstration Testing for Enhancing Data Rates for CubeSats."* Logan : 31th Annual AIAA/USU Conference on Small Satellites, 2019.

(15) JPL. "Iris V2 CubeSat Deep-Space Transponder (IRIS)." *Jet Propulsion Laboratory California Institute of Technology | CubeSat.* [Online] https://www.jpl.nasa.gov/cubesat/missions/iris.php

(16) NASA. Lunar Laser Communication Demonstration NASA's First Space Laser Communication System Demonstration. *NASAfacts.* [Online] https://www.nasa.gov/sites/default/files/llcdfactsheet.final_.web_.pdf.

(17) Kogan, A. and Guelman, Mauricio Moshe. Acquisition and pointing control for inter-satellite laser communications. 2004, IEEE Transactions on Aerospace and Electronic Systems

(18) Panahi, Allen and Kazemi, Alex A. Optical Laser Cross-Link in Space-Based Systems used for Satellite Communications. [book auth.] Alex A. Kazemi. *Photonics in the Transportation Industry: Volume III: Auto to Aerospace.* s.l. : SPIE Press, 2010.

(19) American National Standard for Safe Use of Lasers Outdoors”: ANSI Z136.6 (2015) - Safe Use Of Lasers Outdoors (Electronic Version)

(20) National Institute of Information and Communications Technology. World's First Demonstration of Space Quantum Communication Using a Microsatellite. *NICT.* [Online] 2017.

(21) Tesat. CubelC: "SmalleSt laSer CommuniCation tranSmitter" WorldWide datasheet. *Products.* [Online] 2020. https://www.tesat.de/images/tesat/products/CubeLCT_Data-Sheet.pdf.

(22) Exolaunch. "DLR mission PIXL-1 is integrated by Exolaunch for SpaceX’s Falcon 9 upcoming launch from Cape Canaveral." *Exolaunch.* [Online] https://exolaunch.com/news-block-23.html.

(23) Serra, P., et al.: "*Deep Space Laser Communication Transmitter and High Precision Timing System for Small Satellites."* Logan, UT : s.n., 2016. 30th Annual AIAA/USU Conference on Small Satellites.

(24) NASA. CubeSat Laser Infrared CrosslinK. [Online] 07 31, 2020. https://www.nasa.gov/directorates/spacetech/small_spacecraft/cubesat_laser_infrared_crosslink/

(25) Mynaric. Mynaric on track to become industry-first supplier of satellite constellation-grade laser communication. [Online] 04 03, 2020. https://mynaric.com/news/mynaric-on-track-to-become-industry-first-supplier-of-satellite-constellation-grade-laser-communication/) .

(26) SpaceMicro. Laser Communication Terminals. [Online] 2020. https://www.spacemicro.com/products/lasercom.html.

(27) Wayne, D., et al.: "*Design and Testing of a CubeSat-Sized Retroreflector Payload ."* 2015. 29th Annual AIAA/USU Conference of Small Satellites.

(28) Salas, A.G., Stupl, J. and Mason, J.: "*Modulating retro-reflectors: technology, link budgets and applications."* 2012. 63rd International Astronautical Congress.

(29) Ilčev, Stojče Dimov. Ground Communication Segment. Global Aeronautical Distress and Safety Systems (GADSS). s.I.: Cham Springer, pp. 227-313.