Small Satellite Antennas

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Abstract

Antennas are an integral part of the satellite radio communication and navigation system that enables the transmission and reception of electromagnetic energy through free space. The small satellite size, volume, thermal, and material constraints pose a special challenge to the antenna system, and the antenna design is as much a challenge for radio engineering as it is for mechanical/structural engineering. Many new techniques including novel packaging solutions, deployment structures, 3D printing, and advances in the commercial printed circuit board technology have helped to tremendously reduce the volume and mass of antenna structures so they can be integrated on small satellites. Over the last decade, many novel and compact antenna solutions have been developed for small satellites that have enabled the small satellite radio communication systems to compete with much larger class satellites. This chapter presents an overview of the antennas that are most commonly used on small satellites and presents some recent examples of commercial small satellite antennas.

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Gain · Beamwidth · Bandwidth · Cross polarization · Axial ratio · Omnidirectional · Isoflux · Tracking · Telemetry · Command (TTC) · Monopole · Dipole · Patch · Helical · Reflectarray

1 Introduction

Over the last 20 years, mission enabling technologies such as radio systems and antennas have become mainstream, and there has been a surge of activity in various types of small satellite missions – including Earth Observation satellites (such as Planet Labs Inc., Spire, Iceye, Capella Space), communication satellites (such as Starlink, Oneweb, Kepler communication, Lynk), and Internet of Things (IoT) satellites (such as Myriota, Astrocast, Fleet Space, Eutelsat, Swarm Technologies). The capabilities and performance of some of these small satellite communication systems are on par with larger form factor satellites.

Recent advances in 3D printing/additive manufacturing, material science, and commercial printed circuit technology have yielded a number of compact and highly performing antenna solutions that enable these newer classes of missions from a very small form factor platform. Some of these small satellite antennas have flown on over 300 satellites and established contact reliability on Planet's Dove satellites (https://www.planet.com/pulse/planet-openlst-radio-solution-for-cubesats/). Some other antennas have demonstrated impressively high gain, such as JPL's ISARA reflectarray with 33 dBi gain (Hodges et al. 2018). One of these antennas has even made it to deep space orbiting Mars and relaying data back to Earth on the MarCO satellite (Hodges et al. 2017).

1.1 Antenna Requirements

The requirements posed on the antenna subsystem can be split into internal performance requirements and external system requirements.

1.1.1 Performance Requirements

Frequency of Operation

Frequency of operation is set domestically in the USA by Federal Trade Commission (FCC) and internationally by the International Telecommunication Union (ITU) regulations.

Bandwidth.

Antennas need to maintain their performance (gain, beamwidth, and axial ratio) over a specific bandwidth. The actual use case will dictate whether a wideband or narrowband antenna is used. For instance, Tracking, Telemetry, and Command (TTC) radios traditionally are low data rate. Because of this, a narrowband antenna such as a dipole or patch antenna with ~1–3% fractional bandwidth is adequate. The payload radio, however, typically needs a high data rate. Depending on the fractional bandwidth requirements, which may be higher than 10%, broadband antennas such as deployable reflectors, horn antennas, or helical antennas are used.

Polarization

Radio waves passing through the Earth's ionosphere are subjected to Faraday rotation effects where the left and right hand circularly polarized waves propagate at slightly different speeds. Since a linear polarized wave is made up of two equal-amplitude left and right circular polarized components, a relative phase shift is introduced which ends up rotating the orientation of linear polarization. This effect is proportional to the square of the wavelength. While this effect is pronounced with very-high-frequency (VHF) and ultra-high-frequency (UHF) bands, it rapidly diminishes at higher frequencies such as X-band and above. Second, if a linear polarized antenna were to be used on a satellite, the satellite antenna orientation would need to constantly be maintained with respect to the ground antenna orientation during a ground station pass. This would add additional complications to the pointing and tracking requirements of the satellite.

To avoid the complications that linear polarized antennas pose, most satellites use left or right hand circular polarized antennas. These circularly polarized antennas need good cross polarization (cross-pol) discrimination between the two polarizations. Cross-pol is nominally specified as the Axial Ratio (AR) – which is the ratio between the semi-major and semi-minor axis of the polarization ellipse. A rule of thumb is for a single transmit system to have cross-pol levels of about 15 dBc (AR ~3 dB). Some special dual polarization transmit/receive systems that need a high signal to noise ratio for high order modulation (like 32APSK or higher) will need very high cross-pol discrimination of 25 dBc (AR ~ 1 dB), which helps improve the signal to noise ratio.

Efficiency

Satellite antennas require high efficiency so as to optimally utilize the radiation aperture. This requires, depending on the type of the antenna, a combination of the following:

- Low loss tangent materials
- Low surface roughness
- Low loss feed networks
- Optimal taper
- High cross polarization isolation
- Low spillover

Beamwidth and Gain

The mission system needs imposed on the antenna subsystem affect whether a broad beamwidth antenna with low gain, or high gain antenna with narrow beamwidth, is chosen. TTC antennas need wide coverage, so low/medium gain antennas such as dipoles or monopoles, and sometimes patch antennas are used. Payload antennas need high gain, so narrow beamwidth is acceptable since the satellite is either mechanically or electronically steering and continuously pointing and tracking the ground station during a pass.

1.1.2 External System Requirements

Some external requirements are imposed by the fact that these antennas are integrated on a small satellite platform. They also need to survive launch, operate in a space environment, and operate with other subsystems. These subsystems include:

High Reliability and Robustness

- The antennas need to survive the shock and vibrations of the launch environment.
- The antenna deployment mechanism, if any, should work with very high reliability since deployment failure could mean the end of a mission.
- Space poses extreme thermal and vacuum challenges and the antenna performance should not degrade under vacuum conditions or repeated extreme thermal cycling.
- The antenna should withstand space environmental effects including surface erosion from ultraviolet radiation and atomic oxygen, surface charging from space plasma, and structural damage from micrometeoroids. Active antennas should also withstand total ionizing dose and single event upsets from radiation.

Low SWaP (Size, Weight, and Power)

- Size: Small satellites have a very small volume available, so antennas are typically small form factor or need to be packaged in a small volume and deployed on orbit.
- Weight: Along with size, mass is also a limiting factor on small satellites because launch costs are constrained by mass and volume. Using light weight material is key to reducing total antenna mass.
- Power: For small satellite antennas, power is another constraint and certain steps could be taken to reduce total power consumption. For instance, a high efficiency power amplifier could be placed very close to the antenna or integrated into the antenna feed structure so as to avoid long cables and associated losses. The RF power could be reduced and a higher gain antenna could be used or vice-versa so that the effective isotropic radiated power (EIRP) stays constant.

Location Constraints

- Physical location: Antennas need to be physically located on the body of the satellite such that they are optimally utilized. For instance, on a low-Earth orbit (LEO) satellite, the GPS antenna should be mounted on the zenith facing side and the payload antenna should be mounted on the nadir facing side.
- Radiation surface: Depending on the frequency of operation, the entire satellite could become a radiator or ground plane, so antenna analysis and measurements should be done on the integrated spacecraft structure.

Other Constraints

- Multipaction: Under vacuum conditions, an electron avalanche effect called multipaction (multiple + impact) can occur, leading to intermittent disruption in communication subsystems and added noise. This occurs primarily in resonant structures such as cavity filters due to very high voltages of hundreds of thousands of volts in those structures. However, at RF frequencies, depending on the geometry of the structure and frequency of operation, this effect can occur at power levels as low as 5 W.
- EMI: In small satellites, electromagnetic interference (EMI) and self-interference issues need to be considered to ensure that one transmit antenna does not interfere with a sensitive receive system.

1.1.3 Feed Network

The feed network is an integral part of the antenna design, especially for high gain antennas that use antenna arrays. The feed network ensures that the electromagnetic signal is directed to and from the antenna with low attenuation and low phase mismatch. An ideal antenna design will incorporate broadband feed networks so that bandwidth is limited by antenna radiation patterns or gain variations and not by the resonant behavior of feed network. Several impedance matching and bandwidth enhancement techniques are available to enhance the fractional bandwidth of the feed network, which is limited theoretically by Fano's broadband matching theory (Fano 1948). Appropriate phase matching of the feed elements is also required to ensure the antenna meets the cross polarization requirements. For example, aperture coupling for patch antennas improves the bandwidth. For antenna arrays, quadrature hybrids and wilkinson power dividers provide phase matching as well as improved bandwidth.

When an antenna is chosen for a specific mission, its feed network should also be considered, such that the combined antenna/feed network pair maximizes the radiation efficiency and meets all the other performance and external requirements provided above. For instance, a large passive patch array might be less efficient compared to a passive reflect array if the dielectric transmission line losses dominate compared to reflectarray aperture losses. A reflectarray may be less efficient compared to a waveguide slot array, especially at high frequencies such as Ka-band, since the effects of feed positional or angular misalignments are more pronounced at higher frequencies. Some antenna arrays, such as radar antennas, may require specific amplitude and phase weighting to the individual elements so a very specific beam tapering or side lobe level can be achieved.

1.2 Antenna Types

A typical small satellite requires multiple antennas including Tracking, Telemetry, and Command (TTC) antennas, payload antennas, and Global Navigation Satellite System (GNSS) antennas. Additional antennas may be needed for certain missions like radar antenna for radar missions or antennas for intersatellite links. Each of these

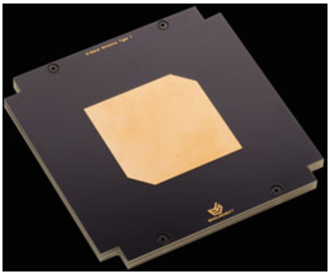
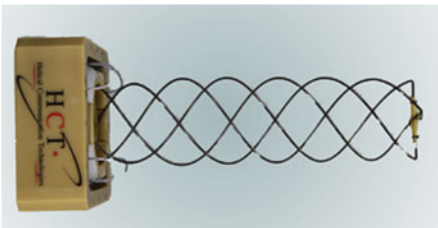
 Figure 1a: Monopole antenna. Graphics courtesy of ISIS.	ISIS Monopole Antenna [5] Four monopole tape spring antennas with a phasing network tying the antennas together in a monopole configuration ● Operating frequency: VHF or UHF ● Beamwidth: Omnidirectional ● Polarization: Linear ● Gain: 0 dBi
 Figure 1b: UHF turnstile antenna. Graphics courtesy of GOMSpace.	GOMSpace Turnstile UHF Antenna [6] The turnstile antenna consists of four monopole antennas combined in a phasing network. ● Operating frequency: 435 +- 5 MHz ● Beamwidth: Omnidirectional ● Polarization: Circular ● Gain: 1.5 dBi to -1 dBi
 Figure 1c: Patch antenna. Graphics courtesy of Endurosat.	Endurosat Patch Antenna [7] S-band medium gain patch antenna with good cross polarization ● Operating frequency: 2400-2450 MHz ● Half power beamwidth: 71 degrees ● Polarization: Left hand circular ● Gain: 8.3 dBi
 Figure 1d: Deployable helical antenna. Graphics courtesy of Helical communication technologies.	HCT Helical Antenna [8] Deployable quadrifilar helical antenna occuputing 5 cm x 5 cm x 10 cm volume ● Operating frequency: 450 MHz, 1.3 GHz or 2.3 GHz ● Half power beamwidth: Can be configured to be isoflux, hemispherical or narrow beamwidth ● Polarization: Right or left hand circular ● Gain: 3 dBi

Fig. 1 Four types of small satellites used on commercial satellites for the TTC systems

antennas has very different sets of requirements from each other. The TTC antennas are typically omnidirectional so that communication can be established with the satellite at all satellite attitudes or pointing modes. The GNSS antennas are typically hemispherical beams that allow for maximizing the number of available GNSS satellites. The payload antennas by contrast are narrow beam antennas with very high gain.

1.2.1 TTC Antennas

TTC radios and antennas need to possess very high reliability since their malfunction could mean the end of a mission. TTC antennas are typically omnidirectional so communication can be established with a satellite under all attitudes or pointing modes. If a single antenna cannot provide near spherical beam coverage, multiple spatially separated antennas are combined or switched to provide an omnidirectional pattern. The TTC frequency bands include VHF, UHF, S, X, Ku, and Ka bands. The data rates of a TTC radio are very low and bandwidth or cross-polarization requirements are not very demanding. At VHF and UHF bands, monopole and dipole antennas are typically used. At S, X, Ku, and Ka bands, patch, helical, horn antennas are used for TTC. Some examples of commercial TTC antennas used on small satellites are given in Fig. 1.

1.2.2 GNSS Antennas

GNSS antennas typically have hemispherical beam patterns. On LEO cubesats, GNSS antennas are mounted on the zenith facing direction so as to maximize the number of GNSS satellites in view of the antennas. Many small satellites have two GNSS antennas (which are most typically GPS antennas). They are often mounted

 Figure 2a: Dual band GPS antenna. Graphics courtesy of Taoglass.	Taoglass GPS Antenna [9] Dual band single feed stacked patch based GPS antenna covering GPS L1+L2 bands • Operating frequency: 1575 MHz (L1) and 1227 MHz (L2) • Beamwidth: Hemispherical • Polarization: Right hand circular with axial Ratio 1.69 dB (L1) and 2.70 dB (L2) • Gain: 5 dBi (L1), 3 dBi (L2)
 Figure 2b: Multiband GNSS antenna. Graphics courtesy of Maxtenna.	Maxtenna GPS/GLONASS Antenna [10] Multiple band Iridium/GPS/GLONASS passive embedded antenna • Operating frequency: 1616-1626 MHz (Iridium), 1575 MHz (GPS) 1602 MHz (GLONASS) • Beamwidth: Hemispherical • Polarization: Right hand circular • Gain: 2.8 dBic (Iridium), -3 dBic (GPS), 0 dBic (GLONASS)

Fig. 2 Two types of GPS antennas used for position determination

on opposite sides of the spacecraft, to get positional and timing knowledge under all spacecraft attitudes. Recently, commercial multiple-band GNSS antennas have been made readily available and provide improved positioning accuracy as well as redundancy in frequency. Two examples of GNSS antennas used on small satellites are provided in Fig. 2.

1.2.3 Payload Antennas

High gain antennas have a narrow beamwidth and require accurate pointing. When tight pointing requirements cannot be met, like with cubesats, a medium gain antenna with ~10–12 dB gain is used for downlinking payload data and high rate telemetry. Some medium gain antennas have an isoflux pattern to compensate for

 Figure 3a: 4x4 patch array antenna. Graphics courtesy of Endurosat.	Endurosat Patch Array [11] • Operating Frequency: 8.025-8.4 GHz • Half power beamwidth: 18 deg • Polarization: Right hand circular • Gain: 16 dBi
 Figure 3b: Lens corrected horn antenna. Graphics courtesy of Sage millimeter.	Sage Millimeter Horn [12] K-band low loss lens mounted on a horn antenna to provide high aperture efficiency and low sidelobe levels • Operating Frequency: 25-27 GHz • Half power beamwidth: ~5 deg • Polarization: Linear or circular • Gain: 30 dBi
 Figure 3c: Slot array antenna designed for a SAR payload. Graphics courtesy of JAXA [13]	Slot Array Antenna [13] X-band compact, passive, low-mass honeycomb panel antenna with slot array fed with non-contacting choke flanges at deployable hinges • Operating Frequency: 9.5-9.8 GHz • Polarization: Linear • Gain: 36.6 dBi

Fig. 3 (continued)

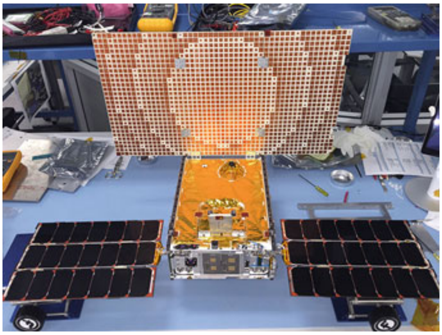
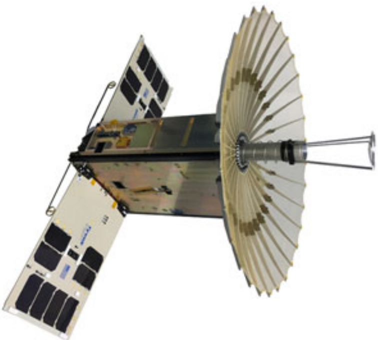
 Figure 3d: Reflectarray that flew on the MarCO mission to Mars. Graphics courtesy of NASA JPL.	MarCo Reflectarray Antenna [3] Ka band folded, three panel reflectarray antenna fed with a microstrip patch antenna, which consumes ~4 percent of the usable spacecraft payload volume with a mass of <1 kg ● Operating Frequency: 8.4 GHz ● Polarization: Right hand circular ● Gain: 29 dBi
 Figure 3e: Membrane reflectarray. Graphics courtesy of DARPA/MMA Design.	DARPA's Radio Frequency Risk Reduction Deployment Demonstration (R3D2) [14] A membrane reflectarray that deploys to 2.25 m in diameter, built by MMA design [15] ● Operational frequency: UHF-Ka band ● Fractional bandwidth: 5-10 percent ● Antenna aperture: 2.25 m diameter ● Aperture efficiency: ~50% ● Polarization: Circular
 Figure 3f: Reflectarray that flew on the Raincube satellite. Graphics courtesy of NASA JPL.	Raincube deployable mesh cassegrain reflector antenna [16] ● Operating Frequency: 35.75 GHz ● Antenna aperture: 0.5 m diameter ● Aperture efficiency: > 50 percent ● Polarization: Right hand circular ● Gain: 42.6 dBi
 Figure 3g: Planar patch array that flew on Iceye X1 satellite. Graphics courtesy of Iceye.	Iceye's Radar Antenna [17] Iceye's radar antenna array deploys to 3.25 m in length and operates at X-band.

Fig. 3 Seven types of antennas used for payload-related services on small satellites

slant range variations. NASA satellites Aqua, Terra, and Aura have isoflux payload antennas. On satellites that have very high data rate and bandwidth needs, it is necessary to use high gain, narrow beamwidth antennas as payload antennas. Whereas big satellites have been historically using large parabolic dish antennas, Fig. 3 provides recent examples of very compact, high gain payload antennas that have flown recently on small satellites.

2 Summary

Any small satellite antenna design should first and foremost start with the mission and satellite requirements. The system link budgets need to be appropriately allocated between the RF power amplifiers, satellite antenna, and the ground station. The satellite attitude control system, timing precision, and ground station tracking systems need to be designed appropriately to meet the pointing and tracking of the antenna beam. Once the antenna design requirements like frequency, bandwidth, gain, beamwidth, cross polarization, and sidelobe levels are established for the mission, an appropriate antenna type is chosen in collaboration with mechanical, structural, and reliability teams. Appropriate electromagnetic solvers such as ANSYS high frequency structure simulator (HFSS), Keysight Advanced Design Systems (ADS), TICRA GRASP, or CST should be used to simulate the antenna performance as a standalone unit and integrate on the satellite structure. The feed network needs to be co-designed with antenna to ensure appropriate impedance and phase matching to the antenna's elements. During fabrication, a good understanding of the material properties and the implications of manufacturing tolerances, stackup issues, and alignment errors will reduce mistakes and the need for multiple manufacturing iterations of the design. Some of these issues such as dielectric tolerances and surface roughness can be simulated a priori, and their effects can be understood before manufacturing begins. After fabrication, antenna characterization is done by measuring return loss with a vector network analyzer, while the antenna beam pattern is measured with a far-or near-field chamber. Gain, cross-polarization, and side lobes should also be measured for the antenna as a stand-alone unit, and after integration on a satellite. For deployable antennas, multiple deployment tests should be conducted and any variations in antenna performance should be measured. If there are large variations during the multiple deployment test, mechanical design tolerances should be revisited. Finally, the satellite should be operated under different operational modes by turning on various subsystems there no longer have EMI implications for the radio.

In conclusion, a broad overview of small satellite antenna design guidelines and recommendations are provided in this chapter, along with some recent examples of small satellite antennas that have flown on recent missions. Small satellite antennas represent both a strong mechanical and structural engineering challenge as well an electromagnetic engineering challenge.

3 Cross-References

- ▶ Flight Software and Software-Driven Approaches to Small Satellite Networks
- ▶ High Altitude Platform Systems (HAPS) and Unmanned Aerial Vehicles (UAV) as an Alternative to Small Satellites
- ▶ Hosted Payload Packages as a Form of Small Satellite System
- ▶ Network Control Systems for Large-Scale Constellations
- ▶ Overview of Small Satellite Technology and Systems Design
- ▶ Power Systems for Small Satellites
- ▶ RF and Optical Communications for Small Satellites
- ▶ Small Satellite Radio Link Fundamentals
- ▶ Small Satellite Constellations and End-of-Life Deorbit Considerations
- ▶ Small Satellites and Structural Design
- ▶ Spectrum Frequency Allocation Issues and Concerns for Small Satellites
- ▶ Stability, Pointing, and Orientation

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