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Small Spacecraft Antenna Selection Tutorial[1]

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[1] A paper presented to the AIAA Conference on Small Satellites, August 23, 1999, Utah State University, Logon, Utah when Dr. Blevins worked for the Electromagnetic Systems Branch (EMSB), Physical Science Laboratory, New Mexico State University.

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Introduction

This paper will discuss some of the key parameters used to specify small spacecraft antennas and rules of thumb to calculate their performance. It will also present typical values for several antenna types. The paper will be available on our web pages at **http://www.AntDevCo.com .**

The tutorial assumes that the reader is familiar with certain aspects of microwave antennas. For instance, I assume the reader is knowledgeable about the differences between directivity and gain, the characteristics of polarized waves, and the concepts associated with transmission lines such as impedance, insertion loss and standing wave ratios. Further, I assume that the reader is comfortable with other associated antenna terms such as beamwidth, bandwidth, and freespace wavelength. For detailed definitions and a more general discussion of small spacecraft antennas, please refer to the paper **"Small Spacecraft Antennas", (ADC-0807201320).**

Artificial satellites often use the NASA Ground Spaceflight Tracking and Data Network (GSTDN) or the US Air Force Space-Ground Link System (SGLS), both of which operate in the S-band microwave range [1]. The TDRSS (Tracking and Data Relay Satellite System) also provides user services in the Ku, Ka, and S-band frequency regions. The Deep Space Network (DSN) operates in the X-band frequency region of the spectrum and individual investigators have used other higher and lower frequency space to ground links.

Most small spacecraft cannot afford the complexity and cost of mechanical or electronic pointing mechanisms for high gain (on the order of 30 dB or more) antennas. This article will therefore concentrate on antennas with reasonably low gains, 15 dB or less.

Detailed mission requirements for satellite tracking, telemetry and control (TT&C), for payload communications, and spacecraft orbits set the detailed parameters and requirements for antennas. This paper first reviews the two most important antenna specifications and provided some example antenna performances. It then reviews other critical considerations.

Antenna Gain and Beamwidth:

Two of the most basic specifications for small satellite antennas are the antenna gain and beamwidth. Sometimes system engineers forget that the beamwidth and gain are intimately linked by physical (and therefore mathematical) relationships. More than once people have requested omni-directional antennas with high (more than 0 dB) gain. System designers also tend to ask antenna suppliers for physically small high gain antennas regardless of the frequency of operation. This request may not be explicit - the system designer may attempt to limit the physical space available on the satellite for the antenna irrespective of the wavelength and the required gain.

Antenna gain can be viewed as consisting of two major components - the radiation pattern shape and the electrical Ohmic efficiency. The radiation pattern shape (with the associated pattern beamwidth a constituent part of the shape) is related to the gain by an explicit formula that also involves the efficiency. The relationship also includes an intermediate quantity called the beam solid angle.

The operant equations are:

(1) $$\Omega_A = \int_{\phi=0}^{\phi=2\cdot\pi} \int_{\theta=0}^{\theta=\pi} P_n(\theta,\phi)\cdot\sin(\theta)\cdot d\theta\, d\phi$$

Ω_A = the beam solid angle, steradians

P_n = the normalized antenna power pattern, linear and unit-less

(2) $D = \frac{4\cdot\pi}{\Omega_A}$ directivity, unit-less and linear

(3) $G = D\cdot\varepsilon$ gain, unit-less and linear

The satellite system designer should use these equations to check the reasonableness of proposed gain and beamwidth requirements. Given a proposed normalized antenna power pattern, one can easily evaluate the beam solid angle integral equation. This can be performed analytically or by using one of the mathematical analysis programs such as MathCAD or Matlab. The proposed antenna power pattern will necessarily include the designer's specification for the antenna half power beamwidth. The directivity can then be calculated and from that, knowing typical efficiencies for the class of antenna under consideration, the gain. The gain computed from the proposed radiation power pattern shape can then be compared to the proposed gain specification. If the gain computed from the pattern shape and efficiency is significantly lower than the proposed specified gain there may be a potential problem and the antenna may not be physically realizable.

From the antenna designer's point of view, it is desirable to use conservative efficiencies when calculating the gain. There are many contributing factors all conspiring to make the gain lower and frustrate the antenna builder.

Remember also that high gain antennas require significant areas (aperture) measured in units of square wavelengths. Careful attention must therefore be paid to physics and the limits imposed by nature when specifying antennas. I will now review several classes of antennas, list some rule of thumb equations associated with those antennas, and present some example antenna performance.

Antennas with High Gains (> 6 dBi)

Antennas with "high" gains are sometimes required for small spacecraft applications. High data rate links may demand higher gain antennas in order to realize positive link margins. The spacecraft system designer must perform tradeoffs between the disadvantages of the narrow antenna beams and increased link margins associated with higher gain antennas.

Aperture-type antennas:

The system designer should remember one of the most powerful and important antenna formulas:

Aperture area and antenna gain relationship

(4) $G = \frac{4 \cdot \pi \cdot A_e}{\lambda^2}$ (unitless, linear)

The antenna's gain is equal to 4π times the "effective" area of the antenna divided by the square of the free space wavelength. (Here the effective area compensates for the effects of Ohmic efficiency, impedance mismatch losses, and all other loss mechanisms).

This equation is most directly applicable to aperture-type antennas like reflector (dish) antennas, planar antennas (microstrip patch arrays), and horn antennas. In most cases the effective aperture is approximately 50% of the physical area.

There are pros and cons associated with these various types of aperture antennas. Reflector antennas are somewhat pesky in that they require an illumination arrangement - offset, prime-focus, or Cassegrain configurations for example. Reflector antennas, however, have many potential advantages - they can be high gain, light weight and broad band.

Horn antennas can also be troubling because they may require long length if the gain is high. On the other hand, horn antennas can have many advantages like broad bandwidth, high power, and simple light weight structures.

Microstrip patch array antennas can be advantageous since their structure nearly a true two dimensional form. Microstrip antennas have large effective areas (about 80% of the physical area) but suffer from higher losses (losses can be on the order of 3 dB for a 34 dB gain X-band antenna, for example). Therefore, the microstrip antennas may require about the same aperture as a reflector antenna even though the microstrip antenna has a larger effective area.

Some useful rules of thumb and performance characteristics for these antennas are:

Reflector antenna height, beamwidth, and gain:

The height of a reflector antenna with a prime focus feed is about

(5) $f \cong 0.3 \cdot D$ (meters)

The half power beam width can be very symmetric about the axis and is given by:

(6) $HPBW \cong \frac{72 \cdot \lambda}{D}$ (degrees)

D = the diameter of the antenna's reflector.

The gain is approximated by:

(7) $G \cong \frac{27000}{HPBW^{2}}$ (linear)

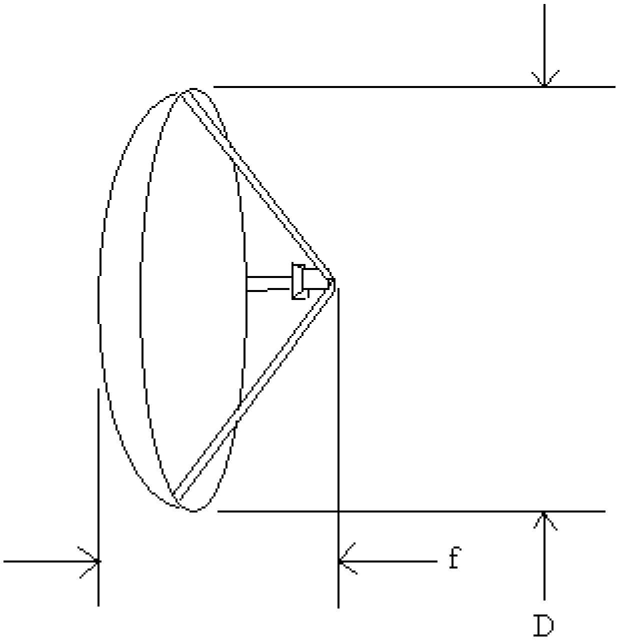


Figure 1. Prime focus fed parabolic reflector antenna.

Horn antenna length, beamwidth, and gain:

Rectangular Horn Antenna:

A typical rectangular linearly polarized horn antenna will have a length given by:

(8) $L_{\lambda} \cong 0.036 \cdot 10^{\frac{G_{dB}}{9.245}}$ (linear, wavelengths)

(developed from Figure 13-25a in [2])

L_{λ} = the length of the horn in units of wavelengths.
G_{dB} = the gain of the antenna in dBiL (deci Bells with respect to an isotropic linearly polarized antenna).

The half power beam widths for a linearly polarized rectangular horn are

(9) $HPBW_e \cong 56 \cdot \frac{\lambda}{D_e}$ (degrees)

(10) $HPBW_h \cong 67 \cdot \frac{\lambda}{D_h}$ (degrees)

De = the width of the horn in the electric field direction, same units as λ
Dh = the width of the horn in the magnetic field direction, same units as λ

And the gain is

(11) $G \cong \frac{32000}{HPBW_e \cdot HPBW_h}$ (unitless, linear)

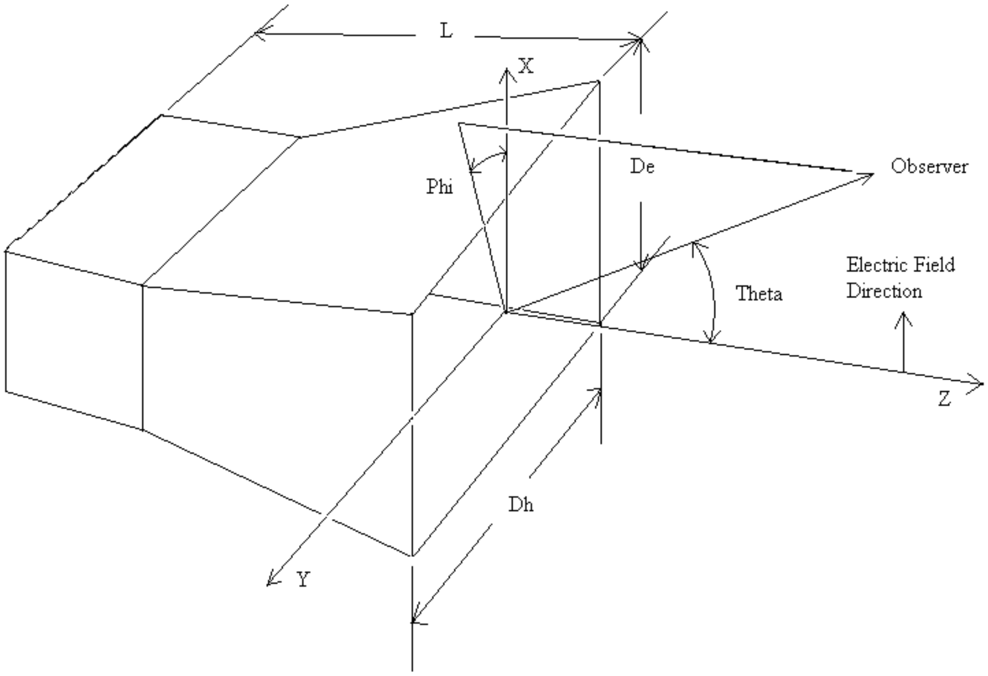


Figure 2. Linearly polarized rectangular horn antenna.

Conical Horn Antenna:

Horn antennas can also be constructed in a cylindrically symmetric conical shape and can receive and radiate circularly polarized radiation. Again, the gain can be approximated from the formula:

(12) $G = \frac{4 \cdot \pi \cdot A_e}{\lambda^2}$ (unitless, linear)

The effective area (including Ohmic efficiency) is very close to 50% of the physical aperture area. The length of a conical horn is given by :

(13) $L_\lambda \cong 0.06 \cdot 10^{\frac{G_{dB}}{10}}$ (linear, wavelengths)

and the aperture diameter is

(14) $D_\lambda \cong 0.423 \cdot 10^{\frac{G_{dB}}{19.9}}$ (linear, wavelengths)

(Both equations were developed from Figure 13-25b in [2].)

An example of a conical horn antenna is shown in Figure 3 (The Stardust spacecraft's medium gain antenna, designed and built by the Physical Science Laboratory, New Mexico State University). This antenna operates at about 8.4 GHz and is designed for spaceflight operation. The antenna has a gain of about 22 dB, a 7 inch aperture, and operates at a wavelength of about 1.406 inches. The equation (13) gives a length of about 9.5 wavelengths or 13.4 inches. The actual antenna length is about 10 wavelengths or 14.3 inches. This is reasonably close. Equation (14) predicts a diameter of 5.39 wavelengths or 7.5 inches - also very close to the dimension actually used. The length and diameter of these types of antennas can also be played off each other to satisfy form factor requirements imposed on the designer.

The radiation patterns for the antenna are shown in Figure 4 and illustrate the high degree of symmetry characteristic of an antenna of this type.

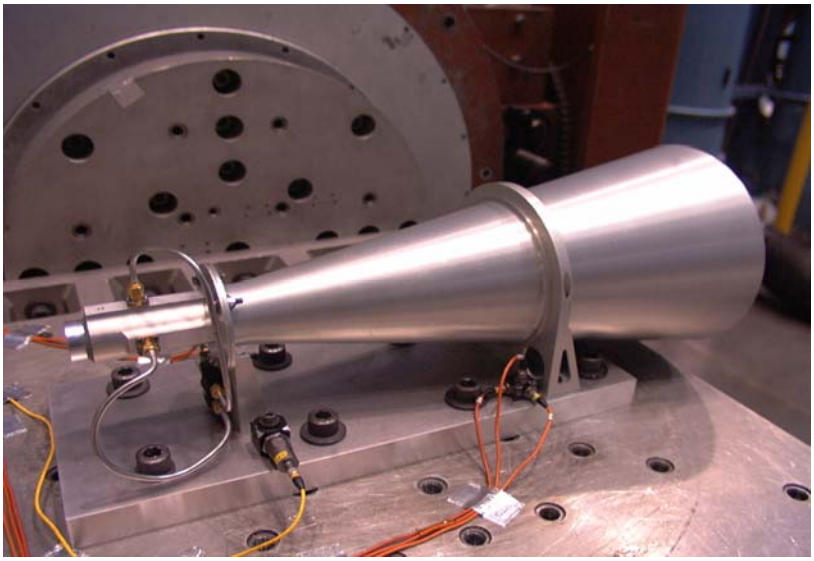
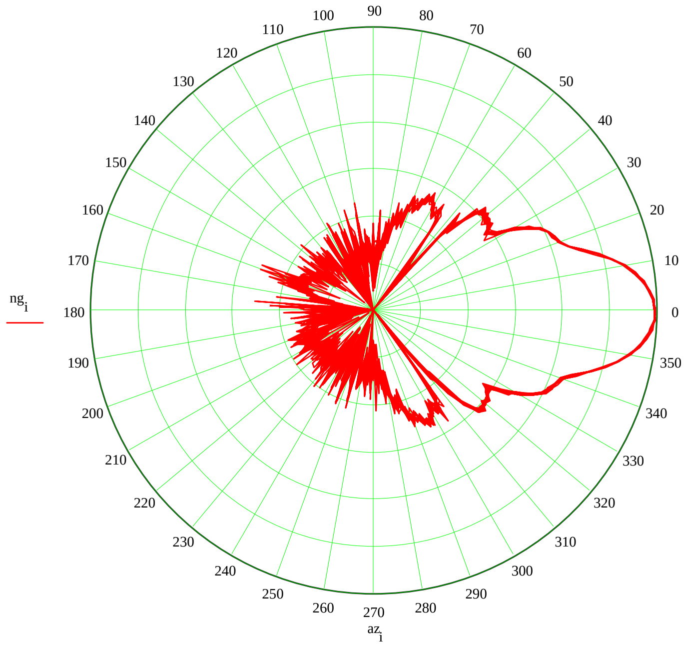


Figure 3. Stardust Medium Gain Antenna.



This plot has all phi cuts from 0 to 180 deg in 10 deg increments.
At each phi, theta is rotated from 0 to 358 deg in 2 deg steps.

Figure 4. Conical Horn Radiation Pattern.

The antenna has a full scale gain of 22 dBic. The plot scale is 10 dB per division and the antenna had RHCP polarization.

Microstrip Patch Array Antennas:

A microstrip patch array antenna can be a planer structure and is usually constructed with special low loss microwave-compatible printed circuit board material. Array antennas can have gains as small at about 10 dB and as high as 30 or 40 dB or even higher. The structures can be light weight and even electronically steerable (if you have enough money). The antennas tend to be narrow band (less than 20% bandwidth) and either linearly or circularly polarized. The gain and beamwidth are approximated by the following equations:

(15) $G = \frac{4 \cdot \pi \cdot A_e}{\lambda^{2}} \cdot \varepsilon$ (linear)

(16) $HPBW \approx 59 \cdot \frac{\lambda}{D}$ (degrees)

where ε is the Ohmic efficiency of the antenna and D is the diameter of the array. (Here the aperture's effective area does not include the Ohmic losses). The efficiency is dependent on the dissipative loss characteristics of the printed circuit board material dielectric and conductors and the details of the power distribution arrangement. Efficiency can be as low as 50% or so.

Microstrip patch arrays have structural shapes that are almost always very simple like represented below in Figure 5:

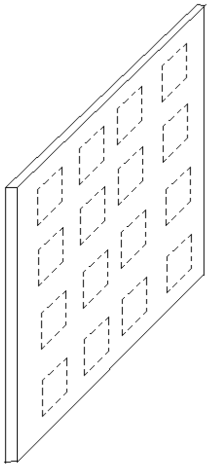


Figure 5. Rectangular Microstrip Patch Array Antenna.

Linear Array Antennas:

Antenna elements can be arrayed in one dimension to attempt to minimize the use of valuable satellite real estate. Linear array antennas like the log periodic, Yagi, and helix antennas have form factors dominated by one dimension - their long length.

Helix Antennas

For example, a helix antenna requires a smaller physical area than an equal gain aperture-type antenna. However, the helix has a much larger depth (length). Usually the length of the antenna is much larger than its diameter. The applicable equations for the gain are related to both the antenna area and the antenna length

(17) $$A \cong \frac{\lambda^2}{4 \cdot \pi}$$ (square wavelengths)

(18) $$G \cong 4 \cdot N$$ (linear)

(19) $$L_\lambda \cong \frac{N \cdot \lambda}{4}$$ (wavelengths)

where N = the number of turns in the helix and A is the physical area of the antenna.

An example of a typical small spacecraft helix antenna is shown in Figure 6.

Table 1. Helix antenna specifications.

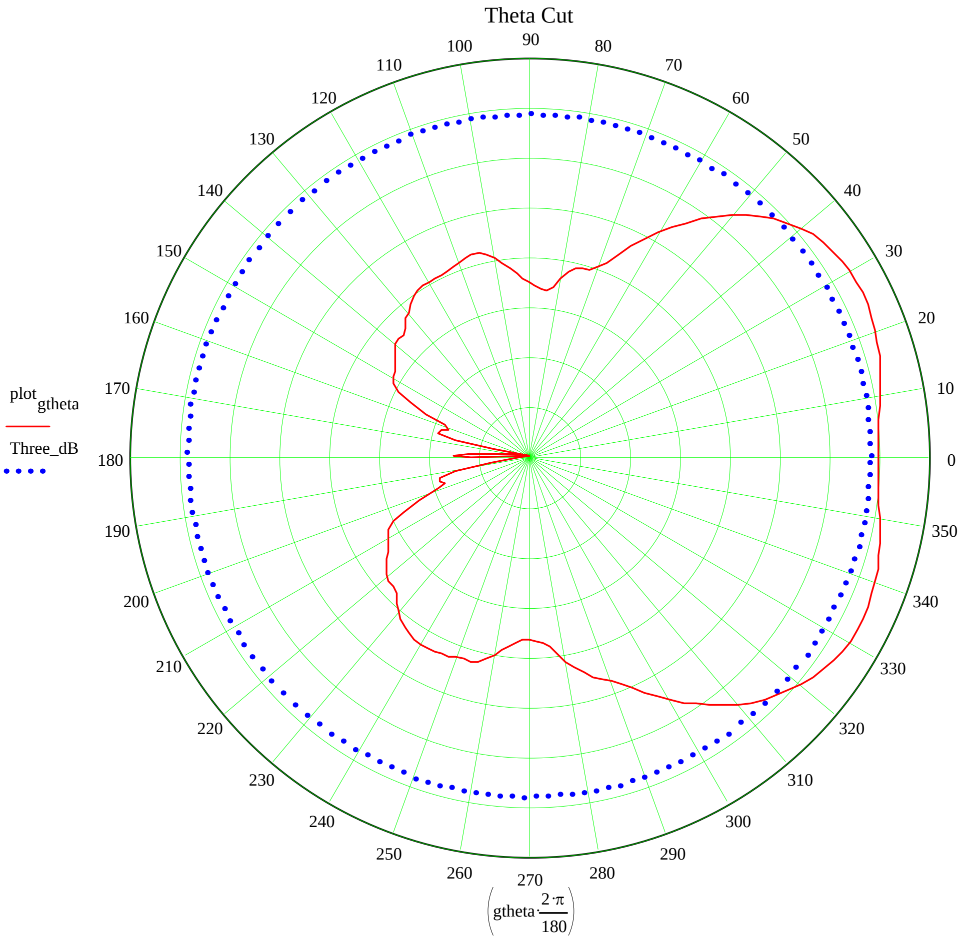
Frequency:	Receive 2056 - 2066 MHz (center = 2060.8250 MHz) Transmit 2233 - 2243 MHz (center = 2238.0000 MHz)
VSWR:	< 2:1 over band
Axial Ratio:	< 1.8 dB on axis (θ = 0) at 2060.8250 MHz < 4.7 dB on axis (θ = 0) at 2238.0 MHz
Gain:	Receive > +4.4 dBic for 6 ° < θ < 36 ° Transmit > +5.5 dBic for 6 ° < θ < 36 °
Polarization:	RHCP
Mass:	< 110 grams
Envelope:	5.7" (H) x 4.0" (base diameter)
Thermal:	-150° C to +85° C

Figure 6. Genesis Spacecraft Medium Gain Antenna.

Like the conical horn, helix antennas also produce cylindrically symmetric circularly polarized radiation patterns as shown by Figure 7.

Right Hand Circular Polarization Gain

phi = 0 degrees



ring_step = 5 dB Plot_max = 10 dB max phi = 0

serial = 592 f = 2238 MHz RHCP_max = 7.418 dBic efficiency·100 = 95.976

Figure 7. Helix antenna radiation pattern.

Antennas with Low Gains (< 6 dBi)

Antennas with "low" gains are often required for small spacecraft applications. Low data rate links may have to communicate with the spacecraft irrespective of the spacecraft attitude. Usually the spacecraft system designer would prefer a low gain antenna with true omni-directional performance - a practical impossibility. Due to the limits of physics, the designer must perform tradeoffs between actual practical antenna performance and the unattainable ideal.

This section of this article will consider several popular low gain antenna types and will provide representative radiation patterns and gain performances.

Microstrip Patch Antennas

Single patch microstrip antennas have been used as broad beam, low gain units on many small spacecraft. Microstrip patch antenna technology has been used in the various bands, VHF through K band and higher. Even though antennas can be constructed for operation at many frequencies, the beamwidth and gains are not subject to large modification. Generally speaking, the gain of a single patch antenna is on the order of 5 to 7 dB, linear or circular. The 3 dB full angle beam width is about 100 degrees. Small fine-tuning adjustments can be made by modifications of the dielectric material and patch shape. A typical microstrip patch antenna shares its simple external appearance with the patch array - an example is shown in Figure 8 below:

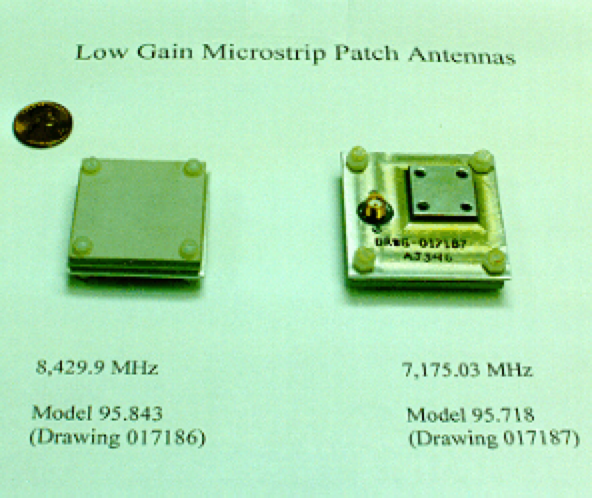


Figure 8. Single element microstrip patch antennas, Physical Science Laboratory.

For scale, the coin on the upper left of the photograph is a US penny. These antennas were used on the STARDUST spacecraft, currently on its way to its rendezvous with a comet. Another example is an S-band patch antenna shown in Figure 9.

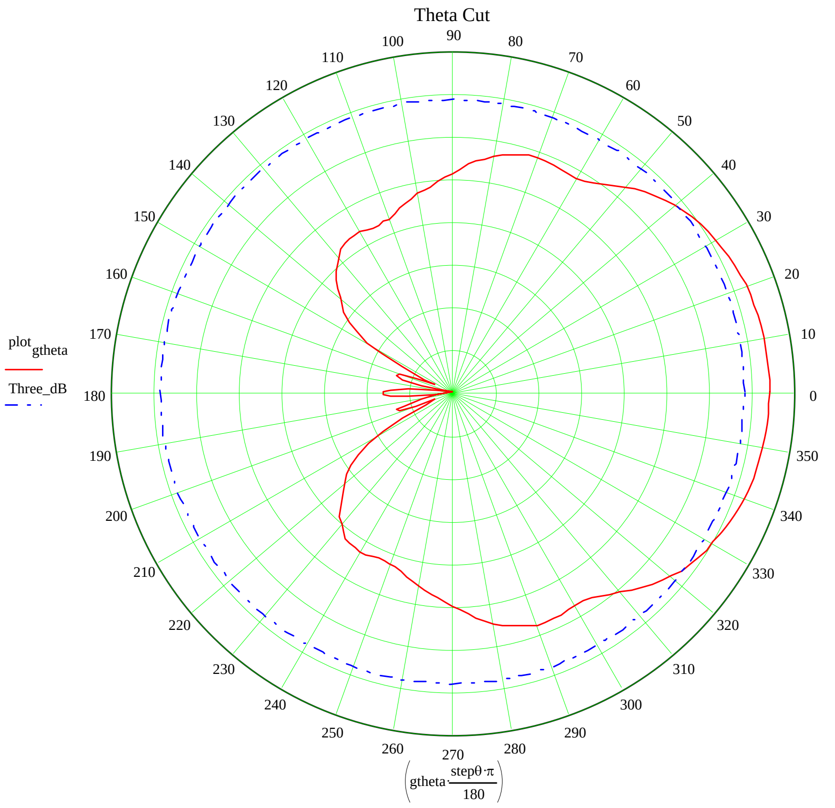
Figure 9. Single frequency Microstrip Patch Antenna.

This is a 2040 MHz telemetry antenna with dimensions of 4 x 4 x 0.120 inches. The antenna is to be used on the HESSI spacecraft. These types of antennas have patterns shown in Figure 10.

Dual frequency microstrip patch antennas are also available. Such antennas can be designed to operate at both the uplink and downlink frequencies used by NASA or the Air Force. The external appearance of S-band versions of this type of antenna is almost identical to the single frequency unit shown in Figure 9 - the only difference is that the antenna is 3/16 inch thick instead of 1/8 inch. The radiation patterns for each frequency are essentially identical with the one shown in Figure 10.

Right Hand Circular Polarization Gain

phi = 0 degrees



Radial_scale = 5 dB Plot_max = 10 dB max phi = 0

serial = 731 f = 1575.5 MHz RHCP_max = 7.281 dBic efficiency·100 = 97.786

Figure 10. Typical GPS microstrip patch radiation pattern.

Other popular low gain, broad beam antenna types are Quadrifilar Helix, Lindenblad, crossed dipole, small waveguide horn, conical spiral, cavity backed planar spiral, rampart, and the dipole and monopole antennas. Each of these antennas has specific advantages and disadvantages with respect to gain and beamwidth and other parameters. The references provide more information on each of these antenna types.

Polarization Mismatch

Spacecraft systems designers frequently specify the polarization mismatch loss allowed for a spacecraft telemetry link by restricting the allowable axial ratio. The polarization state of an antenna can be described by the so called polarization ellipse or by the location of the antennas response on the Poincare sphere (see for example [3]). The axial ratio is a measure of the relative magnitudes of the major and minor axes of the polarization ellipse. The ground station typically has a very good, low axial ratio, circularly polarized antenna for communications with the spacecraft. The spacecraft most often has a like-polarized or sometimes linearly polarized antenna. If the spacecraft antenna is not perfectly circularly polarized or is linearly polarized, there will be a mismatch loss between the spacecraft and ground antennas. The graph shown in Figure 11 quantifies the polarization mismatch between an ideal circularly polarized ground antenna and an imperfect, elliptically polarized, spacecraft antenna.

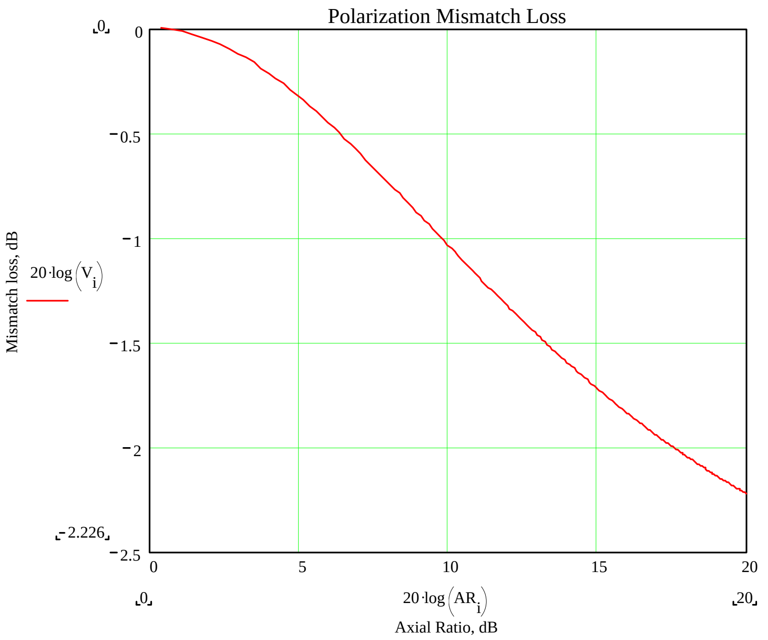


Figure 11. Polarization Mismatch Loss.

A major point to note here is that an axial ratio of 3 dB does not correspond to a polarization loss of 3 dB - rather, the polarization mismatch loss is only about 0.125 dB. An antenna must be nearly linearly polarized (which has an infinite axial ratio) to have a 3 dB polarization mismatch to a perfectly circularly polarized system. The polarization purity of an antenna depends on the physical arrangements of the conductors and the currents carried by the conductors. The distribution of the current is dependent on the frequency of operation. Therefore, as with the impedance bandwidth discussed below, antennas can be specified with a polarization bandwidth. For example, a spacecraft designer might specify that the polarization mismatch loss must be less than 0.5 dB over the entire 3 dB beamwidth and over a frequency band of operation.

Antenna Impedance Bandwidth

The impedance bandwidth of an antenna is determined by the details of the physical structure of the radiator. Some types of structures are inherently broad band like the monofilar helical and conical spiral. Others tend to be narrower band like the microstrip patch and the simple dipole. Typical impedance bandwidths and other parameters for the various popular small spacecraft antenna classes are summarized in Table 2.

Table 2. Antenna Summary.

Antenna Type	Impedance Bandwidth	Gain (dB)	3 dB Beamwidth (degrees)	Polarization
Reflector	≈ 40 %	15 - 35	25 - 2	linear or circular
Simple Horn	≈ 40 %	3 - 25	120 - 8	linear or circular
Patch Array	2 - 20 %	15 - 35	25 - 2	linear or circular
Helix	≈ 40 %	5 - 20	100 - 15	circular
Single Patch	2 - 20 %	5 - 8	~ 100	linear or circular
Quadrifilar	15 to 400 %	3 - 6	100 - 200	circular
Lindenblad	5 %	~ 3	~ 100	circular
Crossed Dipole	5 %	6	~ 70	circular
Conical Spiral	~ 8:1 or wider	5	~ 80	circular
Planar Spiral	~ 8:1 or wider	~ 4	~ 90	circular
Dipole	5 %	1.64	~ 78	linear
Monopole	5 %	3	~ 39	linear

Other Concerns

There are many other concerns that the spacecraft system designer must worry about and must be given serious attention by the antenna designer/supplier. Some of these concerns are:

- CVCM (collected volatile condensable materials), TML (total mass loss), WVR (water vapor regained), and particle shedding
- Antenna electrostatic charging and discharge
- Power breakdown and cooling - multipaction
- PIM (passive intermodulation products)
- Thermal expansion
- Infrared Emissivity
- Solar Absorptivity
- Mass
- Reliability
- Coupling and EMC/EMI
- Gain variation with temperature
- Nuclear radiation degradation of materials
- Atomic oxygen degradation of materials.

Entire careers have been spent investigating and worrying about each of these subjects. References for some of these subjects are included in the bibliography.

Conclusions

There are a multitude of considerations and design approaches for small spacecraft antennas. These multiple choices are complicated by the many performance requirements for the antennas and a desire to limit the cost of the units. This paper barely scratches the surface of this interesting and complex engineering discipline.

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