

# Koch Snowflake Fractal Antenna Design in the Deep Space Bands for a Constellation of Cubesat Explorers

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**Abstract.** This paper presents the design and simulation of a Koch curve fractal antenna, developed according to the second iteration of the Koch snowflake fractal for S-band, C-band, X-band and Ku-band. The simulated antenna shows good performance for the operating frequencies and desirable gain, bandwidth and VSWR parameters. Being a compact antenna, it has a size, geometry and characteristics that go in accord with the CubeSat's structure standards. The antenna was fabricated on a 1.5 mm thick FR-4 substrate. The VSWR achieved values are lower than 1.4 for the frequencies used (2.1 GHz to 2.4 GHz and 7.4 GHz to 8.9 GHz) with a simulated omnidirectional radiation pattern. A maximum **gain of 6.8 dBi** was achieved. As this antenna works optimally in the S, C and X bands, it is adequate for deep space applications, especially in low-power consumption systems. This approach would be ideal for constellations of Cubesat explorers.

**Keywords.** Antenna, microstrip, fractal, S-band, C-band, X-band, Ku-band, deep space, cubesat, constellation, swarm, communication

## 1. Introduction

Aerospace technology in recent years has advanced exponentially, but it continues to present new challenges that stimulate human ingenuity. In the next decade, we will face the new challenge that is the colonization of the Moon and Mars. This boom in space exploration requires new design alternatives that meet the demands of increasingly complex aerospace standards. NASA is committed to landing American astronauts on the Moon by 2024, through the Artemis lunar exploration program [1], new technologies and innovative systems will be used for deep exploration of the Moon and deep space.

Possible applications on deep space exploration as the case of a “mothership” spacecraft carrying multiple Cubesats with multiple targets as an objective, such as an asteroid belt [2], or areas of phenomena of interest where multiple simultaneous observations are required are discussed in this paper. Within the communication group,

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a simple TCP/IP protocol could be used between the mothership and the various explorer Cubesats [2]. The mothership serves as an in-situ store-and-forward communication node.

Contributing to these technological innovations, this scientific article works on the design of a Koch snowflake fractal antenna that works in the S-band, C-band and X-band, which will be used in a constellation of CubeSats or small satellites to carry out scientific investigation in deep space. The communication capabilities (hardware and software) of the CubeSat satellite standard allow the transmission of data and telemetry for missions in LEO. However, interplanetary communications with 1 to 3 U Cubesats remain a challenge due to the limited size and power of these spacecrafts [3]. Recent advances in antenna and amplifier designs have expanded the communication possibilities for the Cubesat standard, although more research work is still needed on Cubesat communication systems. However, the simplicity and low cost of CubeSats make them attractive candidates for scientific missions to the Moon [4] and study experimental payloads such as this “Koch Snowflake Fractal Antenna” [5].

## **2. Deep Space Cubesat Constellation Application**

### *2.1. Cubesat Satellites*

A Cubesat is a small and affordable satellite that can be developed and launched by colleges, high schools, and even individuals. The specifications were developed by California Polytechnic State University (Cal Poly) and Stanford University in 1999. The basic structure is a 10-centimeter cube, weighing less than 1.33 kilograms [6]. This allows multiple of these standardized packages to be launched as secondary payloads on other missions [7].

The Cubesat design specification, developed by Cal Poly, defines the physical and interface specifications for Cubesats, and gives testing requirements for vibration, thermal-vacuum and shock tests, as well as safety tests [7]. Since a Cubesat flies along with other Cubesats in a deployment device, and with a primary payload, safety is a key concern.

### *2.2. Constellation Systems*

Constellations are groups of satellites operating together to observe a single target. A constellation allows simultaneous observations of one target from multiple locations, or multiple targets simultaneously [8]. The step beyond constellation systems is a swarm architecture. In swarm robotics, the key issues are the communication between units, and cooperative behavior. The fractal antenna for this constellation of satellites is designed to primarily serve small satellites using UHF and VHF, as they are the most popular bands in nano and microsatellite standards. The capability of individual units does not matter much; what matters is the strength in numbers, and for this reason the given approach is applicable to groups of explorers arranged as constellations, clusters, and swarms.

### 2.3. Relay Constellation Orbital Design

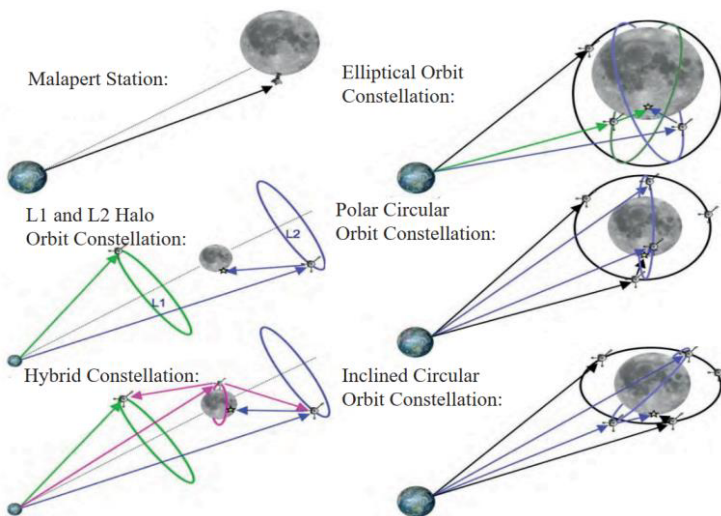
A relay satellite constellation that orbits on a low altitude orbit will allow us to establish an autonomous communication network that provides connectivity between the surface nodes, satellite constellations and base stations on Earth. Some orbit options for this configuration are the following: Malapert station [9], L1 & L2 halo constellation [10], hybrid constellation, elliptical orbit constellation, polar circular orbit constellation and inclined circular orbit constellation [11]. These orbital alternatives are depicted on Figure 1.

### 2.4. Communication within collection of Cubesats (relay communication)

The Cubesat's small antennas, and relatively low power (1W) means we have to get clever with communications. One approach is to have the dispenser or mothership handle communications with Earth, and have short-range communication with the Cubesats using the store-and-forward technique [12]. A relay communication constellation system for low lunar orbits is proposed to be used in conjunction with the fractal antenna presented in this paper. As low-orbit relay satellites will pass over the surface sites relatively quickly, a high-orbiting mothership is needed to provide near-continuous communication support [13].

### 2.5. The Mothership

The mothership would also support point to multipoint communications between the various units of Cubesats or units on the surface. The protocol for communication between Cubesats and the mothership could be as simple as TCP/IP [12]. It would be ideal to consider the Autonomous Space Communications Technology (ASCoT) [14]. Since it nimbly executes a media access control (MAC) scheme, it simultaneously drives electronically directed arrays and switches communication links between multiple nodes separated in space or on the surface.



**Figure 1.** Relay Constellation Orbital Design configurations studied by the SCAWG [11]

3. Antenna Design

The proposed antenna must cover the S-band, C-band and X-band for deep-space communication standards [15]. 1U Cubesat standard states a satellite’s dimension must be 10x10x10cm, therefore the antenna is constrained by this requirement to avoid the implementation of complex deployment systems. A fractal pattern antenna easily complies with these two requirements, due to its characteristic antenna miniaturization and broad bandwidth, multi band coverage. Since the antenna will be used for a low power application, the radiating pattern will be printed as a microstrip on a FR-4 substrate [16].

3.1. Fractal Design

Fractal patterns are self-contained and self-similar; thus, a fractal shape replicates itself as a fraction of the original shape with each iteration. As the fractal keeps self-replicating limited to a certain space, with a space-filling behavior, the Chu limit for small antennas is approached with higher iterations [17]. Among fractal patterns, Koch snowflake is generated using an iterative function system on an equilateral triangle [18]; thus, the perimeter of the Koch loop curve is [19]:

$$P_n = 3\sqrt{3} r \left(\frac{4}{3}\right)^n$$

Where  $r$  is the radio of the circle that circumscribes a Koch snowflake, and  $n$  is the number of iterations. Two iterations have been chosen as further iterations will resolve in smaller details which complicate the antenna fabrication [20]. The monopole and snowflake lengths have been calculated for the chosen fractal radius, as shown on Table 1.

Table 1. Monopole, snowflake and iteration lengths according to fractal radio.

Fractal radius (cm)	Iteration	Monopole length (cm)	Snowflake length (cm)	Segment length (cm)
1.767	0	3.061	9.18	3.06
1.767	1	4.081	12.24	1.02
1.767	2	5.442	16.33	0.34

3.2. Microstrip Antenna Parameters

This microstrip antenna is mounted on a 1.5mm FR-4 substrate and follows the electrical length correction procedures presented on [18]. The Koch snowflake fractal loop is imprinted as a microstrip line on the substrate, thus the dimensions shown on Table 1. have to be tuned to match substrate electromagnetic parameters. The results of these recalculations are shown on Table 2. where  $L$  is the pattern base length and  $L_n$  is the  $n$ -th iteration length ( $n=2$ ), while  $Loop\_w$  is the pattern microstrip width. Antenna is fed by a 50 Ohms microstrip line with a  $Feed\_w$  width [5]. Final design of the antenna front and rear views along with its parameters are depicted in Figure 2.

Table 2. Antenna dimensions for bandwidth coverage optimization in the X-Band

Parameter	Dimensions (mm)	Parameter	Dimensions (mm)
$L$	30.61	$Subs\_w$	44
$L_n$	3.4	$Subs\_h$	42
$Feed\_w$	2.9	$Gr\_w$	6.00
$Loop\_w$	6	$Gr\_h$	26.30

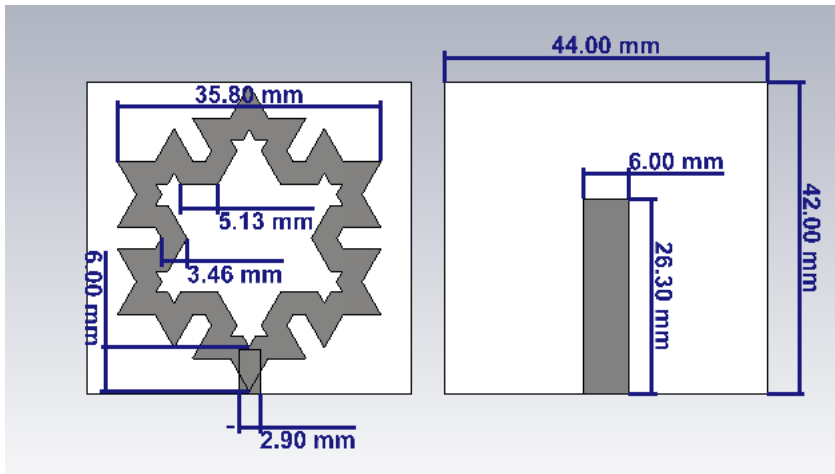


Figure 2. Koch snowflake fractal antenna dimensions

#### 4. Simulation and Results

The dimensions of the substrate, fractal geometry and ground plane previously calculated are now optimized with computational electromagnetic finite element modeling. The proposed antenna modeling and X-band focused optimization have been carried out using EM CAD Microwave Studio by Computer Simulation Technology (CST®). The dimensions we obtained after the optimization are shown in Section 3.2 and the antenna performance evaluation in the sections below. This setting achieves a maximum gain of 6.8 dBi for the X-band uplink channel.

##### 4.1. Bandwidth: $S_{11}$ Parameter & VSWR

An antenna bandwidth is calculated according to its wave reflection parameters when matched to a load; these values can be presented as voltage standing wave ratio (VSWR) or as input reflection coefficient ( $S_{11}$ ). Fractal pattern design allows the antenna to have a broad bandwidth and thus it has multiple working frequency bands: S-band working frequency is from 2.0 GHz to 2.5 GHz, C-band working frequency from 7.1 GHz to 8 GHz, X-band working frequency from 8 GHz to 9.3 GHz and Ku-band working frequency from 13.8 GHz to 18 GHz. The antenna's  $S_{11}$  and VSWR parameters when matched to a 50 Ohm load are shown on Figure 3 and Figure 4, these results cover the whole S-Band and X-Band Deep-Space communication standards frequencies and broaden the possible applications for this antenna.

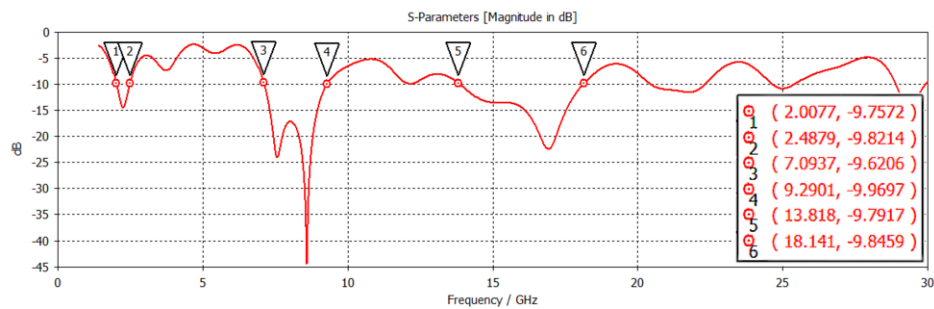


Figure 3. Antenna S11 parameters in S-Band, C-band, X-band and Ku-band (50 Ohms).

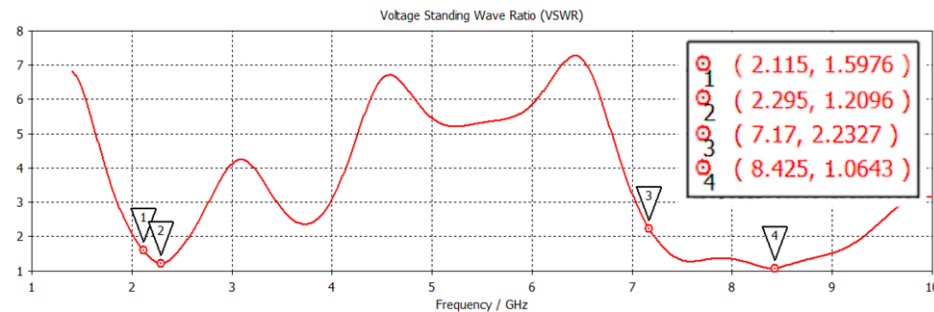


Figure 4. Voltage standing wave ratio values in S-Band, C-band and X-band (50 Ohms).

4.2. Radiation Pattern

Radiation pattern is expected to be that of an omnidirectional antenna, with its maximum along the fractal loop perpendicular axis. While effective aperture is low on S-band, due to the antenna’s effective length, the antenna performs better for X-band [21]. Since Deep-space communications standards make no use of Ku-band, we’ll present the antenna S, C and X bands gain radiation patterns in Figure 5 and Figure 6 respectively. X-Band uplink radiation pattern presents a 6.8 dBi gain, while C-Band downlink has the maximum gain of 4.37 dBi, this result is optimal as transmission requires more power than reception.

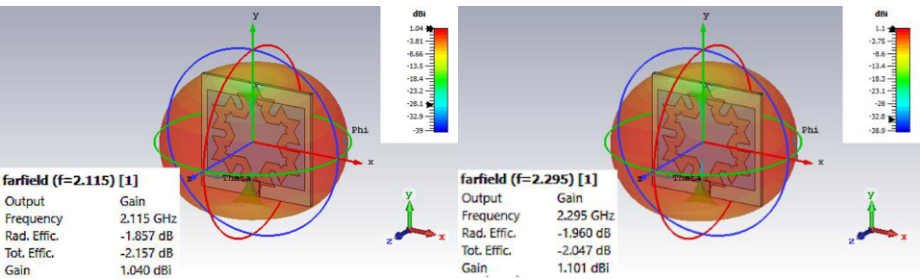


Figure 5. Deep space S-band 2110-2120 MHz up-link and 2290-2300 MHz down-link radiation patterns.

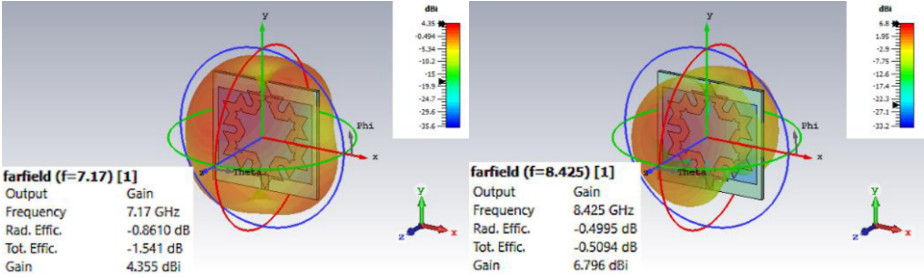


Figure 6. Deep space C-band 7145-7190 MHz up-link and X-band 8400-8450 MHz down-link radiation patterns.

Based on the previous radiation pattern figures and VSWR diagram, we can confirm the antenna optimized dimensions have been correctly tuned to the deep space bands working frequencies. The proposed antenna electromagnetic gain, S11 parameter and VSWR along each band are presented in Table 3.

Table 3. Antenna electromagnetic performance for S-band, C-Band, K-band and X-band

Center frequency (GHz)	Gain (dBi)	S11 (dB)	VSWR (-)
2.115	1.04	-12.765	1.598
2.295	1.1	-20.459	1.210
7.17	4.35	-8.374	2.233
8.425	6.8	-30.127	1.064

5. Conclusions and Future Works

The design of an antenna with a "Koch Snowflake" fractal geometry is introduced in this paper as a suitable candidate for deep space missions, as well as in various Cubesat applications which allow testing and developing technology at low cost.

The proposed antenna serves for dual-band communication since its working frequency band covers the entirety of S, C and X band up-link and down-link standard channels. The uplink gain is 6.8 dBi while the downlink gain is 4.37 dBi. The development of an omnidirectional radiation pattern allows CubeSats that use a passive magnetic attitude stabilization system to maintain a communication link with no need of an aiming system. This is ideal for low-power consumption space communication, as relay or store and forward systems, as a non-off-the-shelf alternative.

Applications such as the following could make use of this article: Deep-space missions such as asteroid exploration, investigation of the moons of Jupiter and Saturn.

We are currently working with the STK & Matlab Software for a complete simulation of the antenna constellation operation in deep space and need to further investigate the swarm system communication protocol and cooperative behavior.

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