

# **Applications of CubeSats for Astrophysics Research**

## **Detection of Radio Frequency Counterparts of High Energy Phenomena with Very Long Baseline Interferometry**

**Abstract** CubeSat systems have the potential to make significant contributions to multiple areas of astrophysics research, including detection of gravitational wave counterparts, Gamma Ray Bursts (GRBs) and GRB afterglow, X-ray and ultraviolet astrophysics, exoplanet studies, solar, ionospheric and space physics, and variable star astrophysics including pulsar detection, Active Galactic Nuclei (AGN) physics, transient, time domain, and multi-messenger astrophysics. Several of these areas of astrophysical research utilize the radio frequency (RF) spectrum between 10 MHz and 10 GHz. This spectrum accounts for significant opportunities for research with space-based CubeSat systems and networks. While other frequency ranges such as millimeter-wave bands are important for research, the 10 MHz to 10 GHz frequency bands are optimum for CubeSat applications. Given this wide frequency range, the question becomes how to incorporate this capability in small form factor CubeSats. Swarms or constellations of CubeSats can be configured to perform multi-aperture Very Long Baseline Interferometry (VLBI), which is a fundamental technique for radio astronomy. The applications of CubeSats for detection of radio frequency counterparts of high energy phenomena with VLBI will be the focus of this study.

This study is divided into two sections. Section 1 is a high level overview of the basic concepts, architectures, and technologies of a CubeSat system utilized for radio frequency counterparts of high energy astrophysical phenomena. This section was independently published in the Journal of the Society of Amateur Radio Astronomers (JSARA) and can be used as a standalone document for introduction to the subject discussed herein. Section 2 is the detailed analysis and design of the specific topics introduced in Section 1.

### **SECTION 1: OVERVIEW**

#### **1. Introduction**

A CubeSat is a class of miniaturized satellite based around a form factor of 10 cm x 10 cm x 10 cm of useful volume (denoted 1U) as well as a weight of no more than 2 kilograms (or 4.4 pounds). Other satellite classifications are based upon their mass, ranging from large satellites of greater than 1000 kilograms to femto-satellites of less than 0.1 kilograms. CubeSats fall in the general category of nano-satellites which range from 1 to 10 kilograms. [CubeSat](#) architecture consists of several specialized subsystems including:

- **Power:** the electrical power system encompasses electrical power generation, storage, and distribution. Power generation technologies include photovoltaic cells, fuel cells, panels and arrays, and radioisotope thermoelectric or other nuclear power generators.
- **In-space propulsion:** in-space propulsion includes chemical (hydrazine based, warm/cold gas systems, and solid propellants), electric (electrothermal, ion thruster, Hall-effect, pulsed plasma, and vacuum arc systems), and propellantless (solar sails, electrodynamic tethers, and aerodynamic drag devices) propulsion technologies.
- **Guidance, navigation, and control:** these include reaction wheels, magnetic torquers, thrusters, star trackers, magnetometers, sun sensors, earth horizon sensors, inertial sensors (gyroscopes/accelerometers), GPS receivers, deep space navigation, and atomic clocks.
- **Structures, materials, and mechanisms:** modular frames, card slot systems, thermoplastics, radiation shielding and mitigation, charge dissipation, composites.

- Thermal control: passive thermal control includes paints/coats/tapes, multilayer insulation, thermal straps, conductive gaskets, sunshields, thermal louvers, radiators and heat pipes, phase changing materials, and thermal switches and storage units. Active thermal control includes heaters, cryocoolers, thermoelectric coolers, and active thermal architectures.
- Spacecraft avionics: this includes command and data handling, avionics and on-board computing, highly integrated on-board computing, radiation hardened processors and Field Programmable Gate Arrays (FPGAs), memory, electronic functional blocks and components, bus electrical interfaces, and flight software.
- Communications: CubeSat transponder, uplink station, downlink station, antennas, radio frequency electronics, optical communications.
- Sensor payloads: Software Defined Radios (SDRs), optical sensors, radio frequency and microwave sensors, x-ray sensors, gamma ray sensors, infrared and ultraviolet sensors.

## 2. Background

CubeSat systems have the potential to make significant contributions to multiple areas of astrophysics research, including detection of gravitational wave counterparts, Gamma Ray Bursts (GRBs) and GRB afterglow, X-ray and ultraviolet astrophysics, exoplanet studies, solar, ionospheric and space physics, and variable star astrophysics including pulsar detection, Active Galactic Nuclei (AGN) physics, transient, time domain, and multi-messenger astrophysics. Several of these areas of astrophysical research utilize the radio frequency (RF) spectrum between 10 MHz and 10 GHz. This spectrum accounts for significant opportunities for research with space-based CubeSat systems and networks. While other frequency ranges such as millimeter-wave bands are important for research, the 10 MHz to 10 GHz frequency bands are optimum for CubeSat applications. Given this wide frequency range, the question becomes how to incorporate this capability in small form factor CubeSats. Swarms or constellations of CubeSats can be configured to perform multi-aperture Very Long Baseline Interferometry (VLBI), which is a fundamental technique for radio astronomy. The applications of CubeSats for VLBI will be the focus of this study. In particular, the emphasis will be on variable star astrophysics including pulsar detection, AGN physics, transient, time domain, and multi-messenger astrophysics (GRBs, gravitational wave counterparts, etc.). The 10 MHz to 10 GHz frequency bands are optimum for these CubeSat applications including:

2.1 Gravitational wave counterparts: Gravitational Wave (GW) radio frequency counterparts have been detected at approximately 150 MHz (Black Hole-Neutron Star mergers), 1.4 GHz/3 GHz (Double Neutron Star mergers), and 1-5 GHz (synchrotron radiation from post-merger events). Frequencies in the 10-240 MHz band are detected by LOFAR (Low Frequency Array) systems [Yancey, 2015; Hotokezaka, K., et al., 2016].

2.2 Pulsars: pulsars produce numerous radio frequencies, depending on the specific parameters of the pulsar. Frequencies in the 10-240 MHz band are detected by LOFAR systems while larger radio telescopes such as the JVLA (Jansky Very Large Array) detect pulsar emissions from approximately 1 GHz to 8.4 GHz [Tan, C.M, et al. 2018].

2.3 Active Galactic Nuclei: AGN activity has been detected by the JVLA at 610 MHz, 1.4GHz/L band, 5.0 GHz/C band, and 8.5 GHz/X band [Padovani, P., 2017; Padovani, P., et al. 2017].

2.4 Gamma Ray Burst afterglow and GRB jet RF signals span several bands including the 10-240 MHz LOFAR frequencies, 400 MHz, 1.5 GHz, 4.9 GHz, 8.5 GHz, and 0.7-1.8 GHz/0.58-14.5 GHz (GRB jets) [Hotokezaka, K., et al., 2016].

2.5 Transient, time domain, and multimessenger astrophysics radio frequency counterparts typically span the frequency range between 10 MHz and 10 GHz. The ground-based [Square Kilometer Array](#) (SKA),

currently being developed for multi-messenger observations, will operate from 70 MHz to 500 MHz, 500 MHz to 1.5 GHz, and 800 MHz to 10 GHz in three arrays. [Padovani, P., et al. 2017].

### 3. Methods and concept of operations

Swarms or constellations of CubeSats can be configured to perform multi-aperture Very Long Baseline Interferometry (VLBI), which is a fundamental technique for radio astronomy. Figure 1 shows a three element VLBI constellation and Figure 2 shows a CubeSat swarm. Figure 2 illustrates the ability to communicate and share their data as a network. Each of the satellites is capable of communicating with a ground station and can relay all of the information gathered from the entire network.

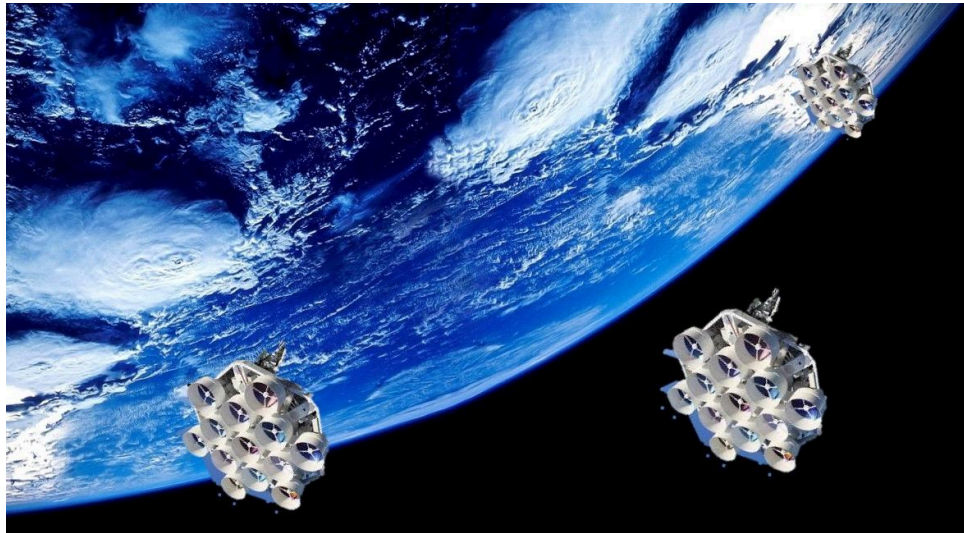


**Figure 1. A Three Element VLBI CubeSat Constellation  
(Courtesy ASTRON & Joint Institute for VLBI)**

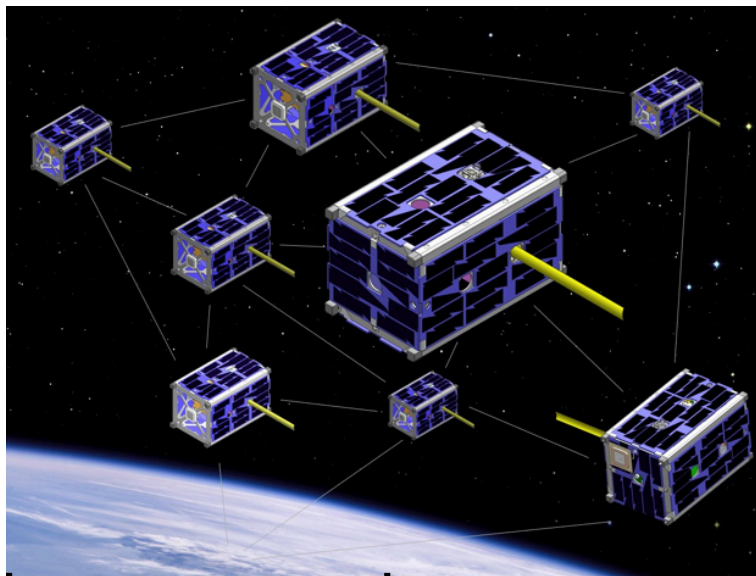


**Figure 2. A CubeSat Swarm (Courtesy NASA)**

CubeSat systems and networks can take advantage of their flexibility to dynamically configure the interferometer observing baseline length as well as network aperture geometry. For example, if the system is observing AGN activity at 1.4 GHz with the required baseline length and number of satellites and is retasked to

observe a pulsar at 240 MHz, the network can reconfigure its baseline and satellite geometry to optimize operation for the pulsar mission. The specific configuration for a target depends on the required resolution which is a function of frequency (wavelength) and baseline length.

Telescopes in a traditional ground based interferometer are connected via cables so that their signals can be combined in real time. For a CubeSat network, the individual CubeSat units can be phase synchronized for coherent operation across the entire array (or subarray) in several ways depending on where they are deployed. In a low earth orbit application, GPS can be the timing mechanism. Alternatively, a ground based timing and synchronizing network could be employed and signals uplinked to the array. For a deep space application such as around one of the LaGrange points, one or more of the CubeSat units would have to take on the role as the timing source. Another option is the use of pulsars themselves with the [International Pulsar Timing Array \(IPTA\)](#) which incorporates approximately 100 millisecond pulsars as a galactic system of highly accurate clocks. Each pulsar (a rapidly rotating neutron star) typically has a rotational period of less than 10 milliseconds with an accuracy of 100 nanoseconds.

### 3.1 Interferometry and aperture synthesis

Radio telescopes typically used in astronomical observations incorporate interferometry, specifically Very Long Baseline Interferometry, or VLBI. The resolving power of the interferometer (how small an object that can be seen) is a function of telescope size and wavelength of the electromagnetic energy. For a single telescope, the size is the diameter of the receiver dish while for an array of telescopes the size is the maximum distance between the individual telescope elements. VLBI provides high precision and good sensitivity (the weakest detectable radio emission) thereby making it an excellent tool for astrophysical objects such as AGNs, pulsars, and radio counterparts of gravitational wave events.

Important considerations for VLBI systems are sensitivity, type and length of the observing baseline, and the geometry of the VLBI array. For a single receiver antenna with a gain  $G$  and a system temperature  $T(\text{sys})$ , the overall antenna performance is defined as the System Equivalent Flux Density (SEFD)

$$\text{SEFD} = T(\text{sys})/G \text{ in units of Janskys or Jy} \quad \text{Equation (1)}$$

(1 Jy =  $10^{-26}$  Watts per meter squared per Hertz of bandwidth)

For a multielement interferometer with individual antenna performance as stated above, the sensitivity is

$$\Delta S(i,j) = 1/\eta \times \sqrt{[(\text{SEFD}(i) \times \text{SEFD}(j))/2 \times \Delta\nu \times \tau(\text{acc})]} \quad \text{Equation (2)}$$

Here  $\tau(\text{acc})$  is the accumulation time,  $\eta$  is the system or array efficiency, and  $\Delta\nu$  is the collecting bandwidth of each antenna [Rioja, M., 2002].

[Aperture Synthesis](#) or synthesis imaging is a type of interferometry that mixes signals from a collection of telescopes to produce images having the same angular resolution as an instrument the size of the entire collection. At each separation and orientation, the lobe-pattern of the interferometer produces an output which is one component of the Fourier transform of the spatial distribution of the brightness of the observed object. The image (or "map") of the source is produced from these measurements. A two-element interferometer

provides very limited information about the structure of a source unless the baseline is continually adjusted. However, if there are  $N$  telescopes, then their outputs can be combined to yield  $N(N-1)/2$  unique baselines with each baseline adding improved sensitivity as well as a wider operating frequency range. Figure 3 shows the aperture improvement achieved by adding antennas, from two in 3 (a) to four in 3 (e) [Condon, J. J., and Ransom, S. M., 2010].

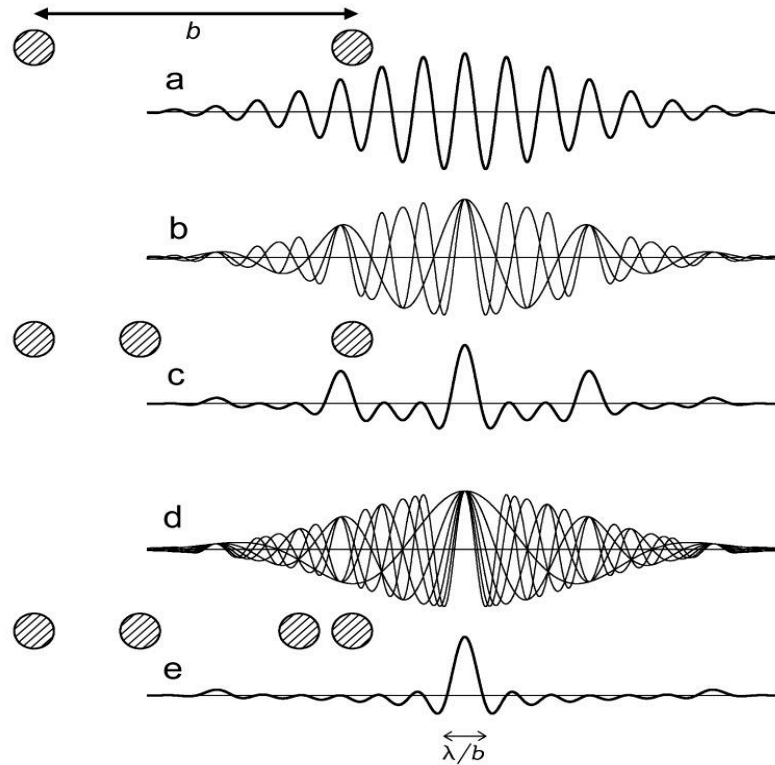


**Figure 3. Aperture Synthesis**

CubeSat systems and networks can take advantage of their flexibility to dynamically configure interferometer observing baseline length as well as network aperture geometry. Also, given the wide 10MHz-10GHz frequency range, the question becomes how to incorporate this capability in small form factor CubeSats. One approach is to apply the principles of fractal mathematics and geometry to both the individual CubeSat antennas and the overall array aperture of the antennas in the CubeSat constellation.

### 3.2 Fractal antennas and fractal arrays

Given the small form factor of CubeSat spacecraft, it is advantageous to keep the antenna structures similarly small. This runs counter to the requirements for a CubeSat system whose purpose is to study astrophysical phenomena that potentially covers a wide radio frequency spectrum. One solution to this is the use of fractal antennas on each CubeSat and fractal arrays of the CubeSat elements of the satellite constellation.

Fractal antennas have unique characteristics associated with the various geometries and mathematical properties of fractals. Fractals were first defined by Benoit Mandelbrot (1975) and published in his book (Mandelbrot, 1983) as a way of classifying structures whose dimensions were not whole numbers, but rather fractional dimensions (fractals). Application of fractal geometry to various antenna elements yields smaller antenna size, resonant frequencies that are wideband and multiband, and are optimized for antenna gain.

Applying fractals to entire network antenna arrays also results in multiband/broadband performance. Therefore, fractal geometries are highly advantageous to both individual antenna elements and entire antenna arrays.

The key feature of fractal systems is self-similarity, that is, different parts of the antenna or antenna array are similar to each other at different physical scales (scale invariance). This makes it possible to design antennas and arrays capable of wideband and multi-band frequency response at a fraction of the size of conventional antennas. Figure 4 is a Cantor slot patch antenna. This fractal antenna operates from frequency  $f$  to frequency  $32f$  all within one structure. Figure 5 is a Cantor linear fractal array and Figure 6 is the Cantor linear array factor. The array factor is a function of the positions of the individual antennas in the array and the relative weighting of each antenna. Figure 6 shows the various baselines that can be formed by combinations of the distances  $d$  ( $d_1$ - $d_4$ ) among the Cantor linear array elements shown in Figure 5. By varying the distances  $d$ , the beam can be steered over an angle  $\theta$  from approximately 0-180 degrees.

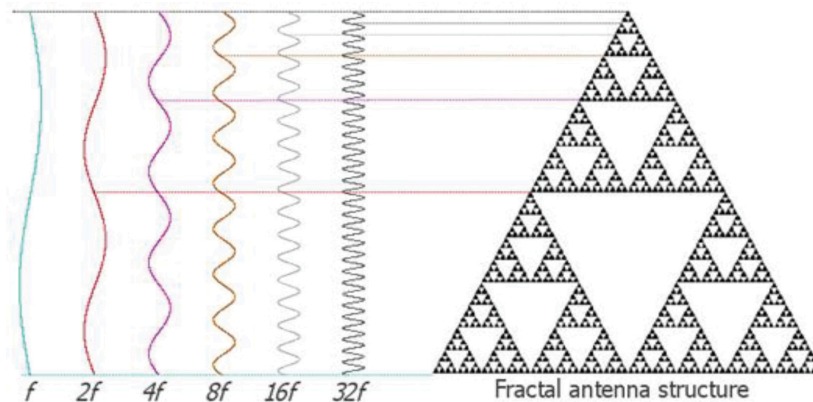


Figure 4. A Cantor Slot Patch Antenna



Figure 5. A Cantor Linear Fractal Array

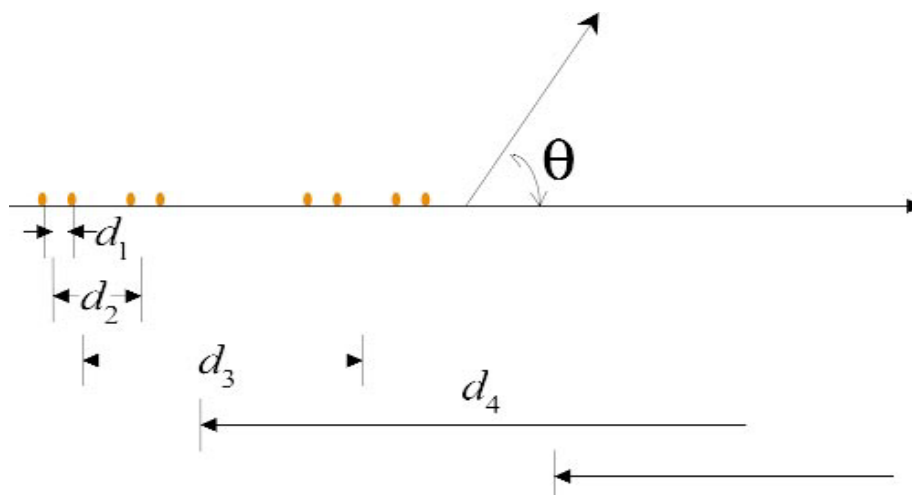


Figure 6. The Cantor Linear Array Factor  
(Courtesy Yang, et al; Ponnappalli, et al)

### 3.3 Instrumentation, methods, and technologies

#### 3.3.1 Software Defined Radios (SDRs)

The use of fractal-based antennas and antenna arrays as discussed above is a key consideration for CubeSat system flexibility in terms of wide frequency coverage and multi-aperture Very Long Baseline Interferometry. An additional degree of freedom for CubeSat operations is the implementation of Software Defined Radios (SDRs). A Software Defined Radio is a flexible technology that enables the design of adaptive communications systems. A generic hardware design can be used to address different communication needs, such as changing frequencies, modulation schemes and data rates. The hardware can be off-the-shelf technology, state-of-the-art technology, and a combination of the two. In its extreme, the entire CubeSat satellite could be considered to be a Software Defined Satellite. While the hardware remains essentially fixed, the flexibility is produced by the software that controls the hardware such that it can be rapidly reconfigured to meet the requirements of a particular mission. An example of an SDR is shown in Figure 7. The software functions are indicated as shown.

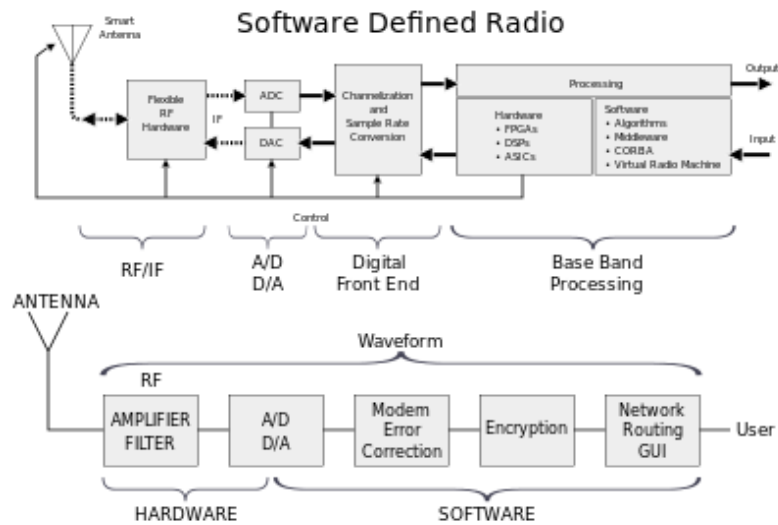


Figure 7. Software Defined Radio

#### 3.3.2 Tunable filters, phase shifters, and switching networks

The flexibility in the SDR hardware can be further improved with the use of tunable bandpass filters, phase shifters, and switching networks to realize frequency band selection, tuning, and beam steering as required for the specific astrophysical applications and targets. These devices, integrated within the SDR digital receiver architecture, utilize the technology of Micro-Electro-Mechanical Systems (MEMS). Advantages of MEMS technology in CubeSat systems is that it requires very little electrical power, has very small size and weight, and can be integrated into higher order assemblies at the device level [Goldsmith, C.L., et al., 1999; Hinzl, D., et al., 2003].

Figure 8 shows a MEMS tunable bandpass filter including the basic filter structures, top view and cross section of the basic MEMS switch element, and a single pole four throw switch network implemented with the MEMS switches outlined above. Figure 8(e) shows the tunability of a bandpass filter implemented with the highly integrated MEMS technology. This filter tunes from approximately 200 MHz to approximately 525 MHz.

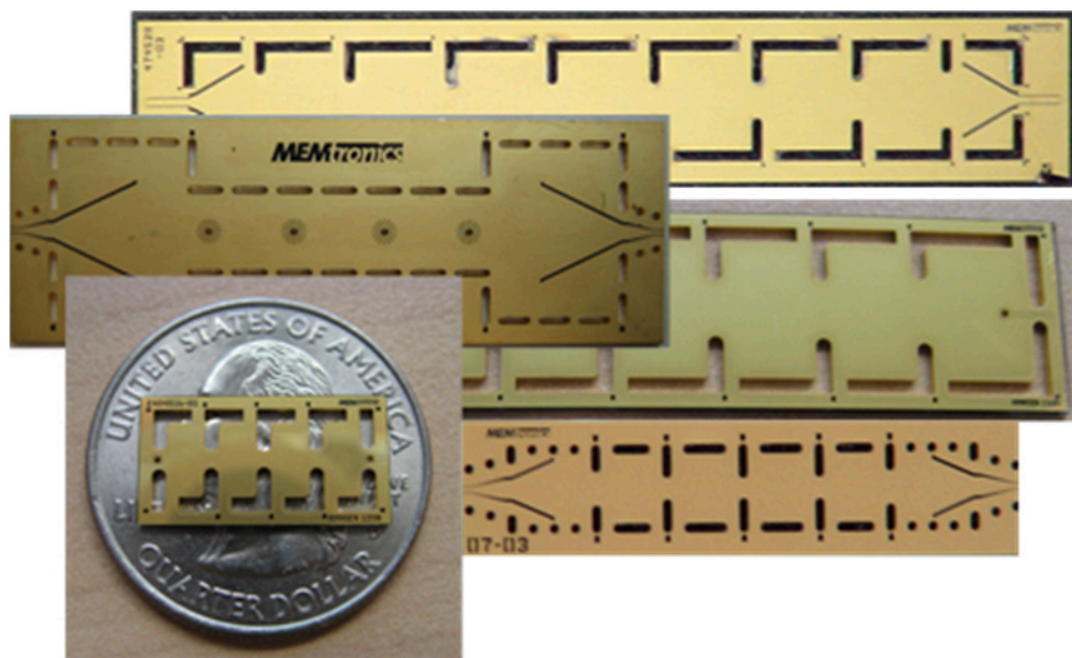


**Figure 8a: Tunable Bandpass Filter Basic Filter Structures**  
(Courtesy MEMtronics Corporation)

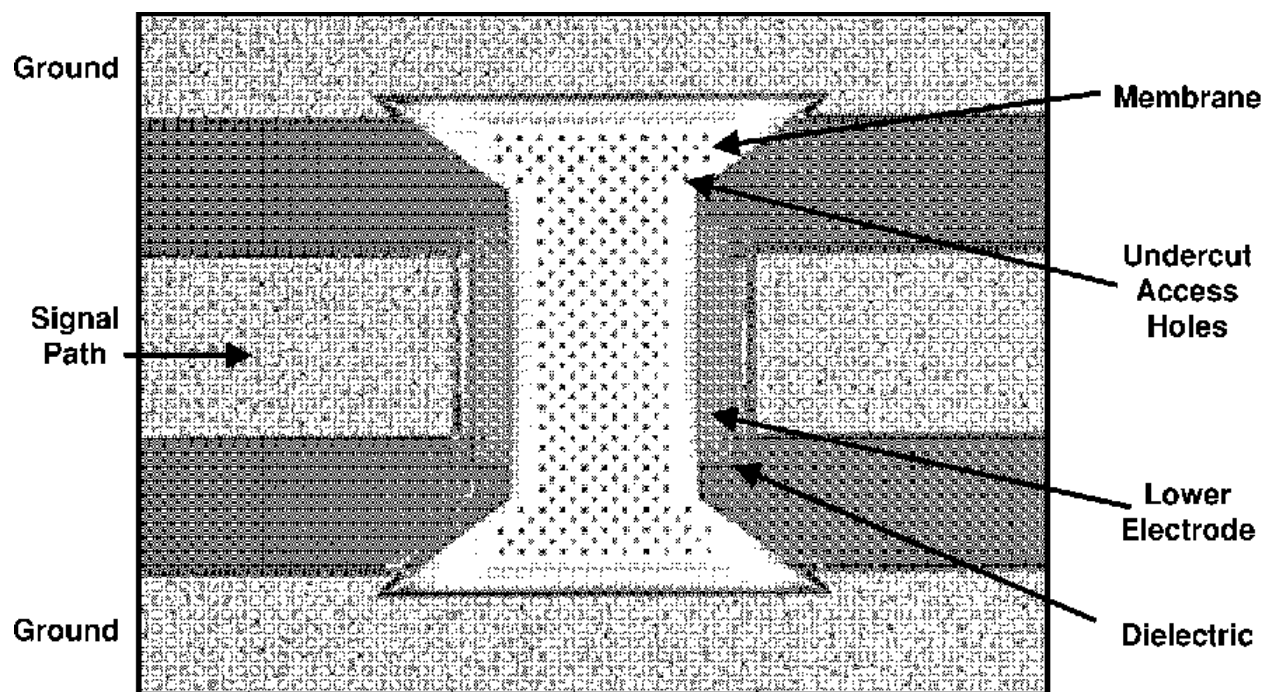


**Figure 8b: Tunable Bandpass Filter MEMS Switch Element Top View**  
(Courtesy MEMtronics Corporation)

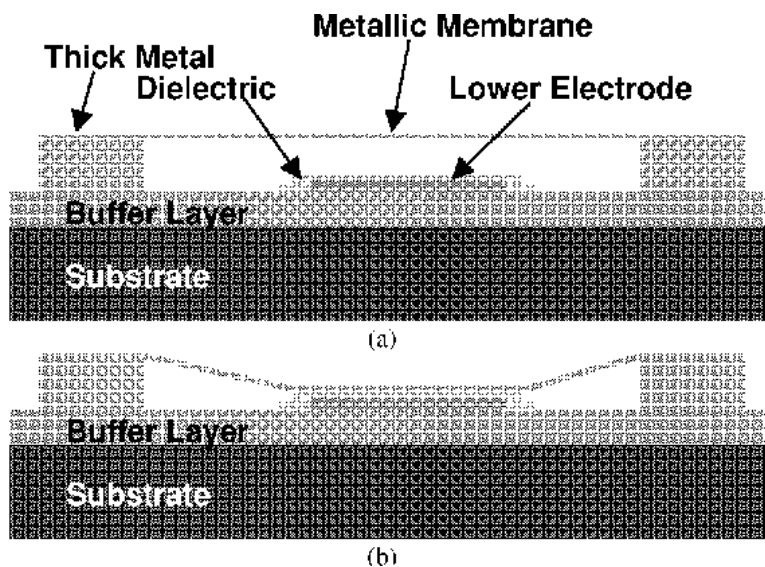


Figure 8c: Tunable Bandpass Filter MEMS Switch Element Cross Section  
(Courtesy MEMtronics Corporation)

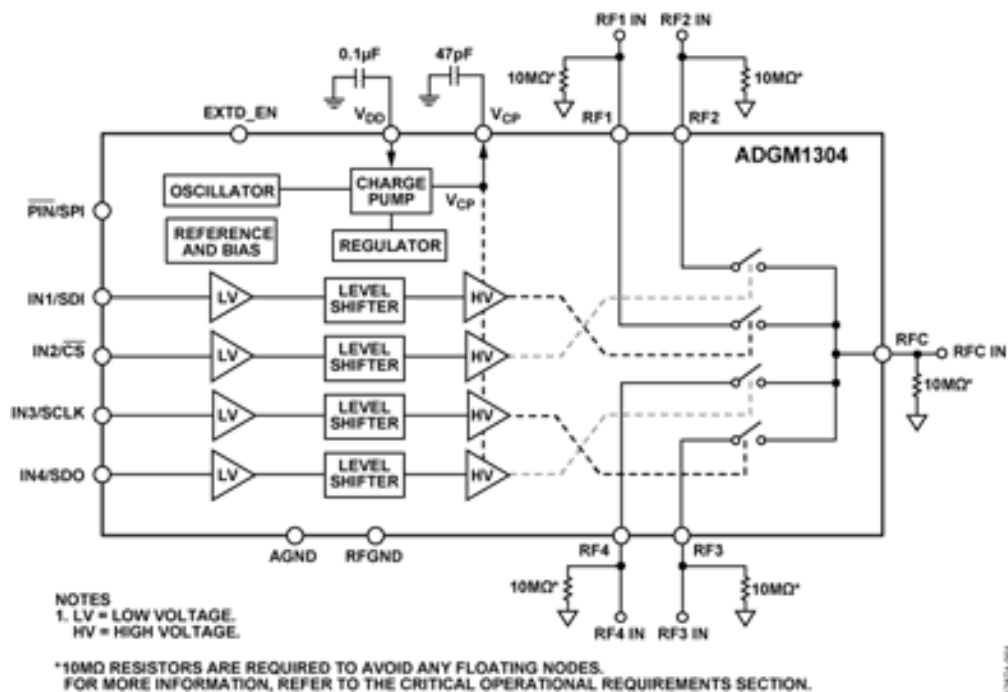


Figure 8d: Tunable Bandpass Filter MEMS Single Pole Four Throw Switch Network

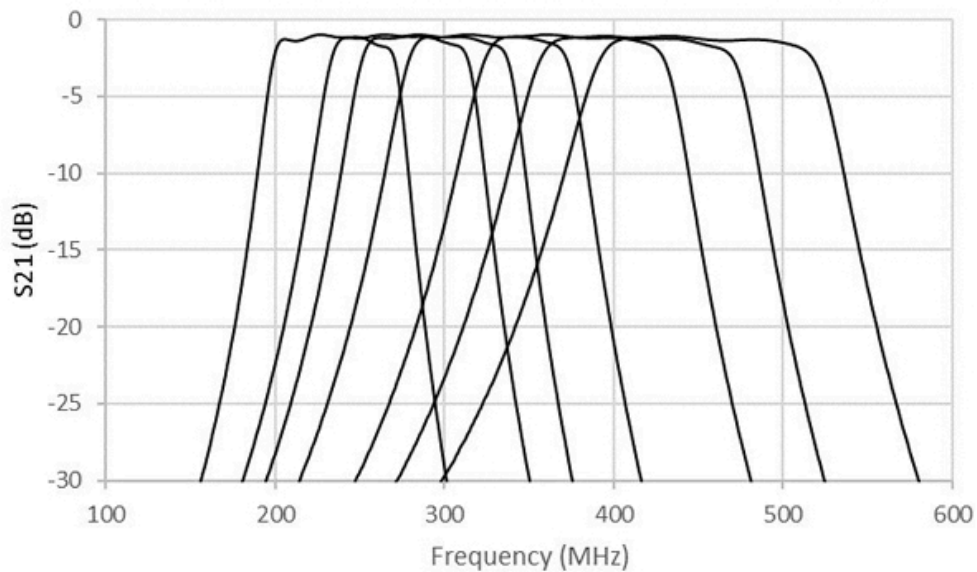


**Figure 8e: MEMS Tunable Bandpass Filter Frequency Range (200 MHz-525 MHz)**  
(Courtesy MEMtronics Corporation)

This same MEMS technology can also be used to implement phase shifting functions for the purpose of antenna beam steering. This is shown in Figure 9. By steering the antenna beam, the CubeSat system can move from target to target very quickly. Here, eight MEMS phase shifters, with appropriate phase weighting in each element, can steer or scan the antenna beam by adjusting the equiphase front of the radiation pattern.

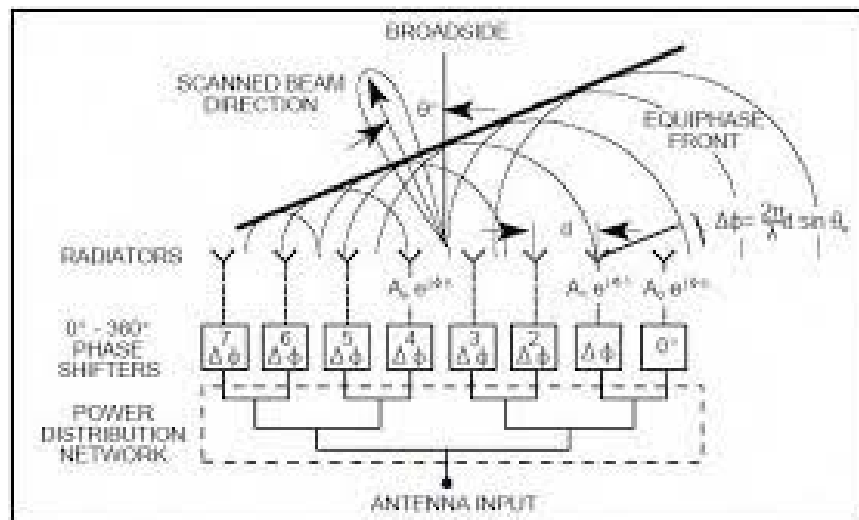


**Figure 9. CubeSat Antenna Beam Steering Utilizing MEMS Technology**  
(Courtesy Elbanna, H., et al.)

#### 4. Results

Figure 10 presents the results of implementing CubeSat systems for detection of the radio frequency counterpart of high energy events incorporating VLBI principles. It should be noted that Figure 10 is only a notional concept and not meant to represent an actual proposed system. Figure 10(a) indicates the notional

placement of the Software Defined Radio used for detection of radio frequency counterparts of events, the fractal antenna as discussed above, and an RF link to other satellites in the array. Figure 10(b) is the Cantor linear fractal array as discussed above showing the beam steered to an angle  $\Theta$ , and Figure 10(c) illustrates what a network of CubeSats in this type of array might look like on station.

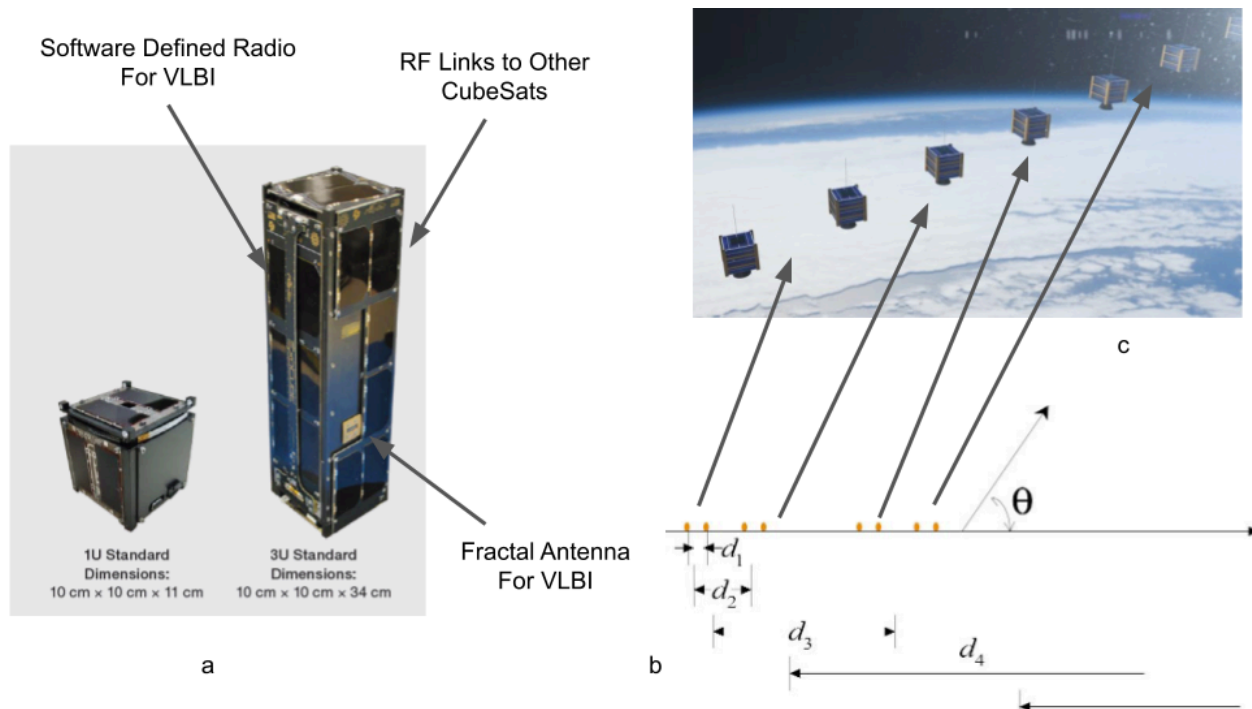


**Figure 10. Notional Concept for CubeSat Array incorporating VLBI**  
(Courtesy NASA)

## 5. Conclusions

CubeSat systems have the potential to make significant contributions to multiple areas of astrophysics research, including detection of gravitational wave counterparts, Gamma Ray Bursts (GRBs) and GRB afterglow, X-ray and ultraviolet astrophysics, exoplanet studies, solar, ionospheric and space physics, and variable star astrophysics including pulsar detection, Active Galactic Nuclei (AGN) physics, transient, time domain, and multi-messenger astrophysics. Several of these areas of astrophysical research utilize the radio frequency (RF) spectrum between 10 MHz and 10 GHz. This spectrum accounts for significant opportunities for research with space-based CubeSat systems and networks. Swarms or constellations of CubeSats can be configured to perform multi-aperture Very Long Baseline Interferometry (VLBI), which is a fundamental technique for radio astronomy. This can be achieved with the use of fractal antennas and fractal arrays, interferometry and aperture synthesis, Software Defined Radios, and MEMS tunable filters, switches, and phase shifters for agile frequency selection and antenna beam steering.

Researchers interested in CubeSat design, technology, and astrophysical applications should visit these links:

[CubeSats](#)

[NASA's CubeSat Launch Initiative](#)

[NASA: CubeSat 101](#)

[CubeSat.org](#)

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Wikipedia: [Software Defined Radios](#)

Wikipedia: [Square Kilometer Array](#)

Wikipedia: [Aperture Synthesis](#)

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## SECTION 2: DETAILED ANALYSIS AND DESIGN

This section describes the detailed analysis and design of the CubeSat concepts introduced in Section 1. In addition to realizing the ultimate goal of a deployed Cubesat system, this study will use the CubeSat as a technology development platform in which various technologies can be developed that may or may not be applied to the CubeSat concepts outlined above. In its extreme, the CubeSat should be considered to use Cognitive receivers and transmitters to achieve a fully functional Software Defined Satellite (SDS). This section discusses in detail orbital configurations, ground segment/ground station design, and space segment design.

### Candidate Orbital Configuration-Lagrange Points

There are two orbital configurations that should be seriously considered for CubeSat operation, near-earth orbits (low/medium/high/geosynchronous) and one of the five Lagrange Points. For the purpose of this study, only operation at one of the Lagrange Points will be considered, primarily in order to obtain a worst-case communications link range (uplink/downlink). In celestial mechanics [Lagrange Points](#) are points of equilibrium for small mass objects under the gravitational influence of two massive orbiting bodies. At the Lagrange Points, the gravitational forces of the two large bodies and the centrifugal force balance each other. This can make the Lagrange Points an excellent location for satellites since the requirements needed to maintain the desired orbit are kept to a minimum. For any combination of two orbital bodies, there are five Lagrange Points, L1 to L5, all in the orbital plane of the two large bodies. There are five Lagrange Points for the Sun–Earth system, and five different Lagrange Points for the Earth–Moon system. L1, L2, and L3 are on the line through the centers of the two large bodies, while L4 and L5 each act as the third vertex of an equilateral triangle formed with the centers of the two large bodies. For deep space exploration two important Lagrange Points in the Sun-Earth system are L1, between the Sun and Earth, and L2 on the same line at the opposite side of the Earth; both are well outside the Moon's orbit. Sun-Earth Lagrange Points are shown in Figures A1 and A2.

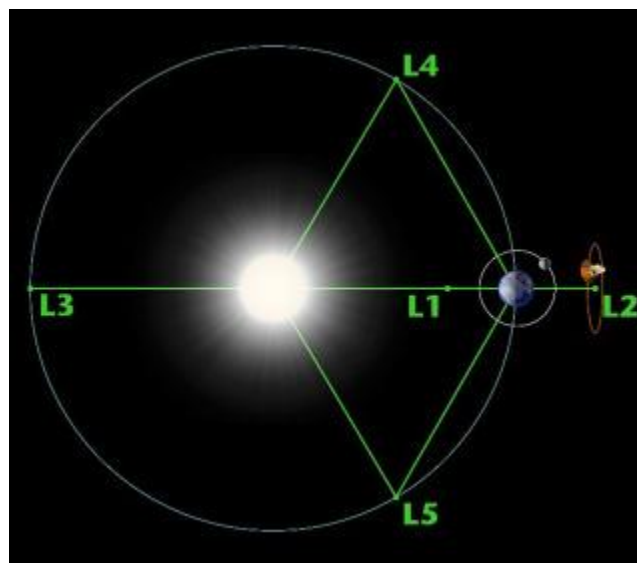


Figure A1: Earth/Sun Lagrange Points  
Courtesy NASA

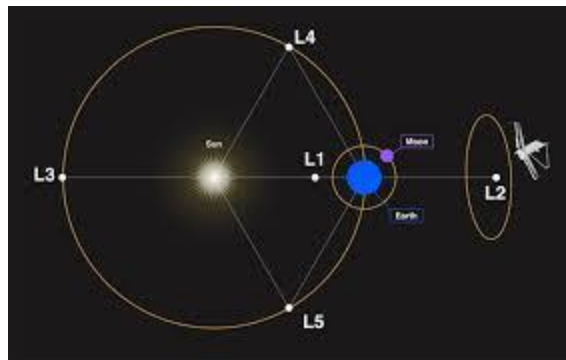


**Figure A2: Lagrange Point L2 for CubeSat Operation**  
**Courtesy NASA**

Sun–Earth L2 is a good spot for space-based observatories. Because an object around L2 will maintain the same relative position with respect to the Sun and Earth, shielding and calibration are much simpler. L2 (like L1 and L3) is normally unstable, but this can be mitigated with a minimal amount of station keeping. The L2 Lagrange Point is approximately 1,500,000 km or 930,000 miles from earth. As such, this gives a worst case (furthest distance) for communications link analysis between earth and the CubeSat. L2 will be the basis for CubeSat orbital analysis in this study.

### **Ground Station Segment**

The ground station segment of the CubeSat network will be based upon the architecture of the [Swedish Space Corporation \(SSC\)](#). While there are numerous other options, including designing the ground station as part of the CubeSat effort, the use of currently existing ground infrastructure is proposed for this effort. This reduces cost and complexity for the CubeSat architecture.

SSC operates a global ground network of antennas in the 13-m class, primarily used by earth-bound satellites in S/X-band as well as the occasional near deep space mission. This would allow the possibility of using an existing commercial ground network like the SSC network for direct-from-earth operations of Cubesats or very small spacecraft in near deep space such as the moon, Lagrange Points, or Near-Earth Asteroids. In the analysis of this scenario, the RF link power between the Cubesat and ground is one key critical consideration, where limitations of the spacecraft apply both for the on-board power generation and the size of on-board antennas that can be mounted on a CubeSat or small spacecraft. The paper discusses assumptions and technical developments related to the on-board parameters, and the requirements that deep space operation would have to meet for the on-board radio system in terms of bit rate, modulation, and support for ranging and coherent lock, especially when being used in conjunction with “small” apertures in deep space terminology. Based on these assumptions, the operational range and potential performance for usage of commercial 13-m antenna networks and associated equipment are presented. The downlink bitrates from these spacecraft will be significantly less than what is expected today from traditional large deep space spacecraft. Figure A3 illustrates the uplink and downlink architecture of the SSC ground station/satellite configuration.

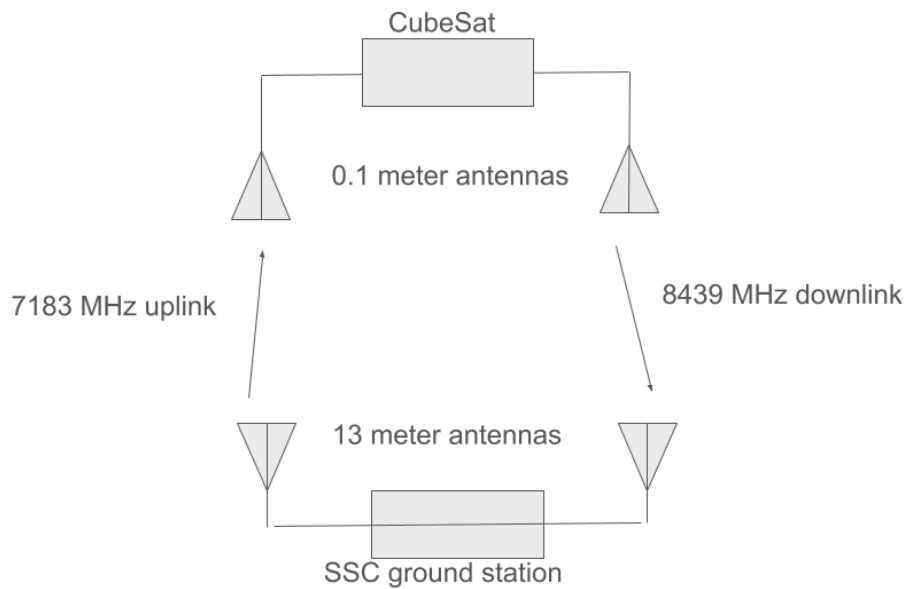


**Figure A3: SSC Ground Station/CubeSat Link Architecture**

The deep space communication system is usually a power limited link, due to the large distances. With the very low bit rates that are possible, the bandwidth that the signal occupies is usually not a limiting factor. There are a large number of options for modulation and coding for deep space communications. The most common modulation mode for deep space missions is residual carrier modulated with square wave subcarrier for the downlink and a sine wave modulation for the uplink. Residual carrier with subcarrier modulation mode is useful for several purposes:

- Supports ranging signals such as PN code ranging
- Supports simultaneous ranging and telemetry/command and control
- Provides sufficient energy in core carrier for locking the receiver PLL loop on the signal
- Can provide GPS data received at the ground station to the spacecraft for timing/synchronization

With the low bitrates in this type of communication, the higher harmonics of the square wave does not give excessive bandwidth and thus avoids filtering which would reduce the energy in the signal. The alternative, suppressed carrier does not support simultaneous ranging. For deep space command and telemetry subcarriers use BPSK modulation. Figure A4 shows the signal structure of command/control and telemetry utilized within the SSC system and network.

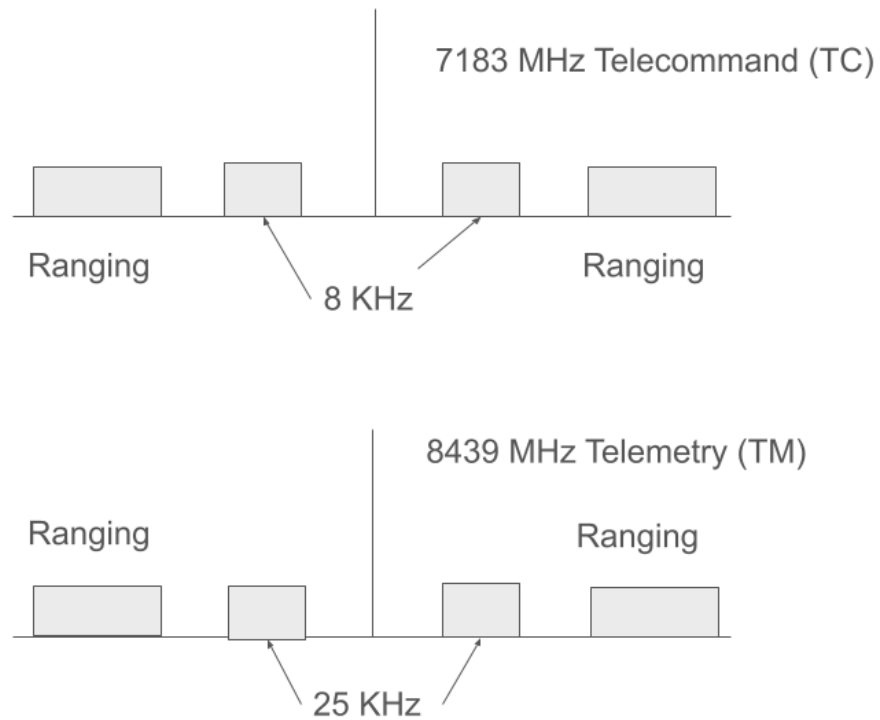


**Figure A4: SSC Ground Station/CubeSat Signal Structure**

Figures A5 and A6 show the link margin calculations for the SSC/CubeSat uplink and downlink, respectively. The L2 distance of 1,500,000 is assumed as well as the ground station antenna size (13 meters) and a typical antenna efficiency of 50%. The CubeSat parameters (antenna size, noise temperature, bandwidth, etc.) are reasonable estimates at this time. There appears to be good net link margin signal-to-noise ratios for both uplink and downlink.

## The SETI League, Inc.

## Uplink Analysis

User specifies variables shown in **Bold**

### Transmitter:

|                                    |                    |             |                          |
|------------------------------------|--------------------|-------------|--------------------------|
| Frequency =                        | <b>7183 MHz;</b>   | $\lambda$ = | <b>4.2 cm</b>            |
| Transmit Power =                   | <b>1.0E+02 W =</b> | 20.0 dBW =  | 50.0 dBm                 |
| Eff. antenna diam. =               | <b>13 meters =</b> | 43 ft       |                          |
| Illum. Efficiency =                | <b>50 %</b>        |             |                          |
| Computed Antenna Gain =            |                    | 4.8E+05     | Ap = 56.8 dBi            |
| Antenna Half Power Beamwidth =     |                    | 3.3E-03     | radian = 1.9E-01 degrees |
| Effective Isotropic Radiated Pwr = |                    | 4.8E+07     | W = 106.8 dBm            |

### Path:

|                                  |                            |                    |                |
|----------------------------------|----------------------------|--------------------|----------------|
| L2 Range =                       | <b>0.0000001 parsecs =</b> | 3.26E-07           | LY = 1.5E+09 m |
| Free Space Isotropic Path Loss = |                            |                    | 233.3 dB       |
| Incident Isotropic Power =       |                            | EIRP - path loss = | -126.5 dBm     |

### Receiver:

|                                      |                     |                 |                            |
|--------------------------------------|---------------------|-----------------|----------------------------|
| Eff. antenna diam. =                 | <b>0.1 meters =</b> | 0.32808333 ft   |                            |
| Illum. Efficiency =                  | <b>50 %</b>         |                 |                            |
| Computed Antenna Gain =              |                     | 2.8E+01         | Ap = 14.5 dBi              |
| Antenna Half Power Beamwidth =       |                     | 4.3E-01         | radian = 2.462E+01 degrees |
| Drift Scan time (zero declination) = |                     | 9.8E+01         | min = 5909.7 sec           |
| Recovered Power =                    |                     | P inc + G ant = | -112.0 dBm                 |
| System Noise Temperature =           | <b>1000</b>         | K =             | 5.4 dB/To                  |
| Detector Noise Bandwidth =           | <b>8000</b>         | Hz =            | 39.0 dB/Hz                 |
| Receiver Noise Threshold =           | kTB =               | 1.104E-16       | J/S = -129.6 dBm           |
| Integration Time =                   |                     | <b>10</b>       | sec = 24.5 dB/cy           |

SIGNAL TO NOISE RATIO

42.1 dB

Figure A5: SSC/CubeSat Uplink Analysis

| The SETI League, Inc.                |                            | Downlink Analysis  |                 |
|--------------------------------------|----------------------------|--------------------|-----------------|
| User specifies variables shown in    |                            | Bold               |                 |
| <u>Transmitter:</u>                  |                            |                    |                 |
| Frequency =                          | <b>8439</b> MHz;           | $\lambda$ =        | 3.6 cm          |
| Transmit Power =                     | <b>1.0E+00</b> W =         | 0.00 dBW =         | 30.0 dBm        |
| Eff. antenna diam. =                 | <b>0.1</b> meters =        | 0.328 ft           |                 |
| Illum. Efficiency =                  | <b>50</b> %                |                    |                 |
| Computed Antenna Gain =              | 3.9E+01                    | Ap =               | 15.9 dBi        |
| Antenna Half Power Beamwidth =       | 3.7E-01                    | radian =           | 2.1E+01 degrees |
| Effective Isotropic Radiated Pwr =   | 3.9E+01                    | W =                | 45.9 dBm        |
| <u>Path:</u>                         |                            |                    |                 |
| L2 Range =                           | <b>0.0000001</b> parsecs = | 3.26E-07 LY =      | 1.5E+09 m       |
| Free Space Isotropic Path Loss =     |                            |                    | 234.7 dB        |
| Incident Isotropic Power =           |                            | EIRP - path loss = | -188.8 dBm      |
| <u>Receiver:</u>                     |                            |                    |                 |
| Eff. antenna diam. =                 | <b>13</b> meters =         | 42.6508333 ft      |                 |
| Illum. Efficiency =                  | <b>50</b> %                |                    |                 |
| Computed Antenna Gain =              | 6.6E+05                    | Ap =               | 58.2 dBi        |
| Antenna Half Power Beamwidth =       | 2.8E-03                    | radian =           | 1.6E-01 degrees |
| Drift Scan time (zero declination) = | 6.4E-01                    | min =              | 38.7 sec        |
| Recovered Power =                    |                            | P inc + G ant =    | -130.6 dBm      |
| System Noise Temperature =           | <b>100</b>                 | K =                | -4.6 dB/To      |
| Detector Noise Bandwidth =           | <b>25000</b>               | Hz =               | 44.0 dB/Hz      |
| Receiver Noise Threshold =           | kTB =                      | 3.45E-17 J/S =     | -134.6 dBm      |
| Integration Time =                   | <b>10</b>                  | sec =              | 27.0 dB/cy      |
| SIGNAL TO NOISE RATIO                |                            |                    | 31.0 dB         |

Figure A6: SSC/CubeSat Downlink Analysis

## Concept of Operations

Launch: the CubeSat swarm/array is launched by a NASA booster ([NASA's CubeSat Launch Initiative](#)) and placed into an operational orbit (low/medium/high/geostationary earth orbit in GPS-like orthogonal orbital planes or a Lagrange Point (L2 for this example)). The Earth-Sun L2 Lagrange Point is 1,500,000 km or 930,000 miles from earth. It is outside the moon's orbit and backs toward the sun looking into deep space. The CubeSat array communicates with the SSC ground station as outlined above.

Spacecraft L2 operation: once the CubeSat is at L2 the SSC ground station deploys the array in the proper position, attitude, and configuration to form the interferometer structure. Once the interferometer is configured, the ground station manages day-to-day operations. This includes uplink command/control/timing, downlink monitoring of spacecraft/array health and status (thermal, position, attitude, electrical power, spacecraft RF communications and RF sensor signal calibration, and propulsion management).

Cubesat/array/interferometer management: after initial configuration and during active astronomical observation and measurement operations, the interferometer array and/or individual CubeSat elements will be commanded to a specific array geometry, receiver frequency, beam scanning scenario, etc. to observe selected astrophysical targets of interest. Upon detection of astrophysical signals (e.g., pulsar rotation periods), the pertinent data will be downlinked to the ground station for follow up analysis. Upon completion of the current target observation, the interferometer array/CubeSat elements will be reconfigured to observe the next target of interest.

## Detailed Analysis and Design

CubeSat interferometer array configuration: Figure A7 shows the configuration of the interferometer array in operation at the L2 Lagrange Point. Since L2 is in deep space and, as such, needs to have a complete spherical view around the array (since there is no way of knowing where potential astrophysical events will occur), the proposed array architecture will consist of three mutually orthogonal arms, each consisting of four CubeSat elements. Additionally, each CubeSat element in the larger interferometer array will have a 360 degree field of view around the array (three 120 degree fields of view). This is conceptually illustrated in Figure A8. Therefore, as depicted in Figures A7 and A8, the CubeSat interferometer array should enjoy a full spherical field of view around the array.

The interferometer array consists of four CubeSats in each orthogonal arm of the array. Operationally, either four or three CubeSat elements can be utilized to achieve a specific receiver sensitivity. As shown in Figures A9 and A10, the four element operation is an order of magnitude more sensitive than a three element operation ( $0.0000000000001382$  Jy for  $N=3$  antennas and  $0.0000000000000977$  Jy for  $N=4$  antennas). One Jy or Jansky =  $10 \times 10^{-26}$  Watts per meter squared per Hertz of bandwidth. In both cases, all of the other parameters are identical. The length of each arm of the array, hence the array aperture (effective signal collection size of the array) is 24000 km. This is a typical distance for a space-based interferometer array.

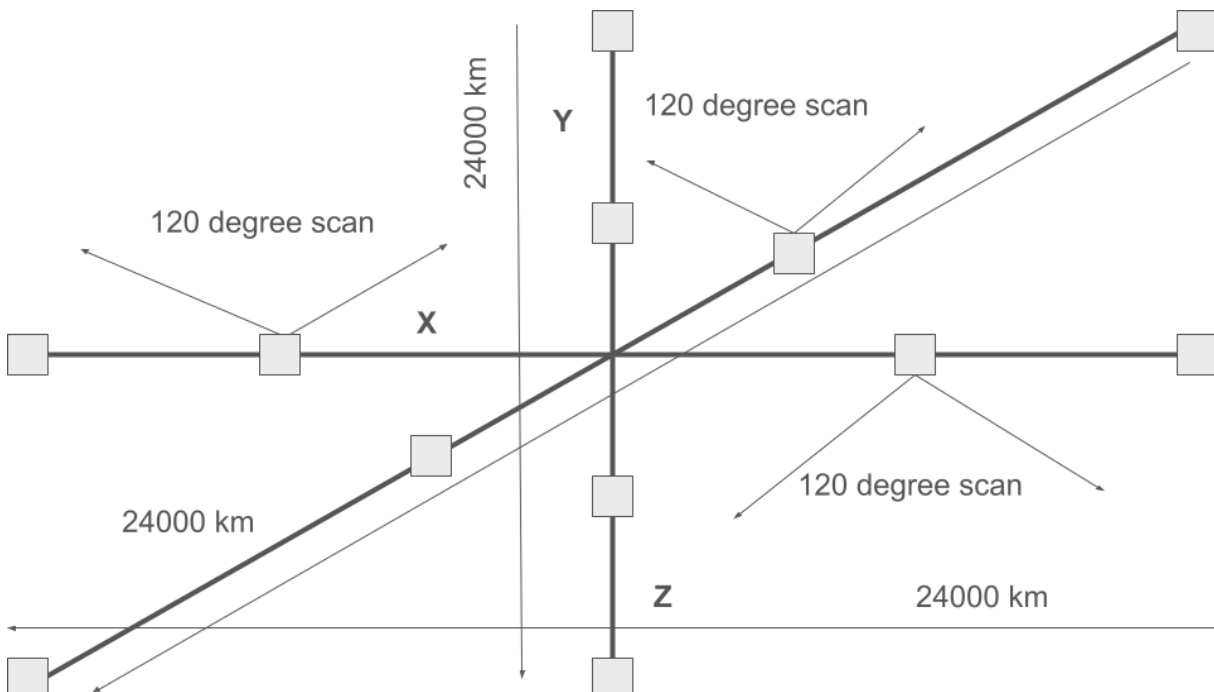


Figure A7: CubeSat Interferometer Array Configuration

## Antenna 120 Degree Offset

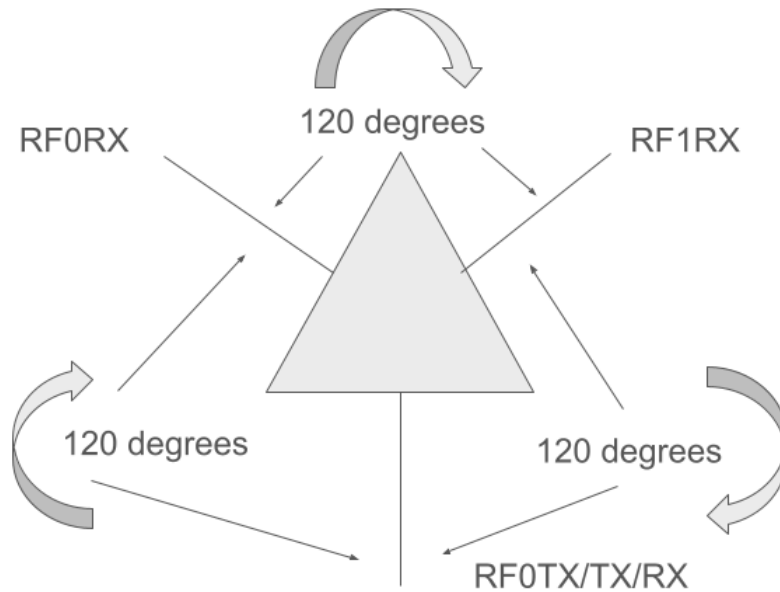


Figure A8: CubeSat 360 Degree Field of View

| The SETI League, Inc.                     |                          | Radio Telescope |                                          |
|-------------------------------------------|--------------------------|-----------------|------------------------------------------|
| User specifies variables shown in         |                          | <b>Bold</b>     | <b>Sensitivity Analysis</b>              |
| Frequency =                               | <b>1420</b> MHz;         | $\lambda =$     | 21.1 cm                                  |
| Eff. antenna diameter =                   | <b>24000000</b> meters = |                 | 78740000.0 ft                            |
| Illumin. Efficiency =                     | <b>50</b> %              |                 |                                          |
| Computed Antenna Gain                     | =                        | 6.4E+16         | Ap = 168.0 dBi                           |
| Antenna Half Power Beamwidth              | =                        | 9.06E-09        | radian = 0.0 degrees                     |
| Drift Scan time (zero declination)        | =                        | 0.00            | min = 0.0 sec                            |
| Effective Capture Area                    | =                        | 226194671058465 | m <sup>2</sup>                           |
| System Noise Temperature                  | =                        | <b>150</b>      | K = -2.9 dB/To                           |
| Detector Noise Bandwidth                  | =                        | <b>1200000</b>  | Hz = 60.8 dB/Hz                          |
| Receiver Noise Threshold = kTB            | =                        | 2.484E-15       | W = -116.0 dBm                           |
| Incident Isotropic Power Threshold (SEFD) | =                        | 3.90054E-32     | W = -284.1 dBm                           |
| Sensitivity                               | =                        | 1.09817E-29     | W/m <sup>2</sup>                         |
| #Antennas                                 | =                        | <b>3</b>        | N                                        |
| Integration Time Constant                 | =                        | <b>60</b>       | sec = 72000000 samples                   |
| Integration Power Gain                    | =                        | 8485.3          | Ap = 39.3 dB                             |
| Incident Isotropic Power Threshold        | =                        | 4.59684E-36     | W = -323.4 dBm                           |
| Sensitivity w/ integration                | =                        | 1.3E-33         | W/m <sup>2</sup> = 0.0000000000001382 Jy |
| Observed Signal to Noise Ratio            | =                        | <b>10.0</b>     | Ap = 10.0 dB                             |
| Incident Flux Density                     | =                        | 1.2942E-32      | W/m <sup>2</sup> = 0.000000000001 Jy     |

Figure A9: Array Sensitivity with N=3 Antennas/Cubesats

| The SETI League, Inc.                     |                          | Radio Telescope |                                         |
|-------------------------------------------|--------------------------|-----------------|-----------------------------------------|
| User specifies variables shown in         |                          | Bold            | Sensitivity Analysis                    |
| Frequency =                               | <b>1420</b> MHz;         | $\lambda =$     | 21.1 cm                                 |
| Eff. antenna diameter =                   | <b>24000000</b> meters = |                 | 78740000.0 ft                           |
| Illumin. Efficiency =                     | <b>50</b> %              |                 |                                         |
| Computed Antenna Gain                     | =                        | 6.4E+16         | Ap = 168.0 dBi                          |
| Antenna Half Power Beamwidth              | =                        | 9.06E-09        | radian = 0.0 degrees                    |
| Drift Scan time (zero declination)        | =                        | 0.00            | min = 0.0 sec                           |
| Effective Capture Area                    | =                        | 226194671058465 | m <sup>2</sup>                          |
| System Noise Temperature                  | =                        | <b>150</b>      | K = -2.9 dB/To                          |
| Detector Noise Bandwidth                  | =                        | <b>1200000</b>  | Hz = 60.8 dB/Hz                         |
| Receiver Noise Threshold = kTB            | =                        | 2.484E-15       | W = -116.0 dBm                          |
| Incident Isotropic Power Threshold (SEFD) | =                        | 3.90054E-32     | W = -284.1 dBm                          |
| Sensitivity                               | =                        | 1.09817E-29     | W/m <sup>2</sup>                        |
| #Antennas                                 | =                        | <b>4</b>        | N                                       |
| Integration Time Constant                 | =                        | <b>60</b>       | sec = 72000000 samples                  |
| Integration Power Gain                    | =                        | 8485.3          | Ap = 39.3 dB                            |
| Incident Isotropic Power Threshold        | =                        | 4.59684E-36     | W = -323.4 dBm                          |
| Sensitivity w/ integration                | =                        | 1.3E-33         | W/m <sup>2</sup> = 0.000000000000977 Jy |
| Observed Signal to Noise Ratio            | =                        | <b>10.0</b>     | Ap = 10.0 dB                            |
| Incident Flux Density                     | =                        | 1.2942E-32      | W/m <sup>2</sup> = 0.000000000001 Jy    |

**Figure A10: Array Sensitivity with N=4 Antennas/Cubesats**

Cubesat Architecture: The interferometer array consists of four CubeSats in each orthogonal arm of the array. Operationally, either four or three CubeSat elements can be utilized to achieve a specific receiver sensitivity. This is depicted in Figure A7. The CubeSat RF systems are the ground station/CubeSat uplink/downlink, and the interferometer receiver array. The uplink/downlink architecture is shown in Figure A11. The frequencies are fixed at the uplink and downlink frequencies as shown along with estimated power/signal levels based upon the uplink/downlink requirements.

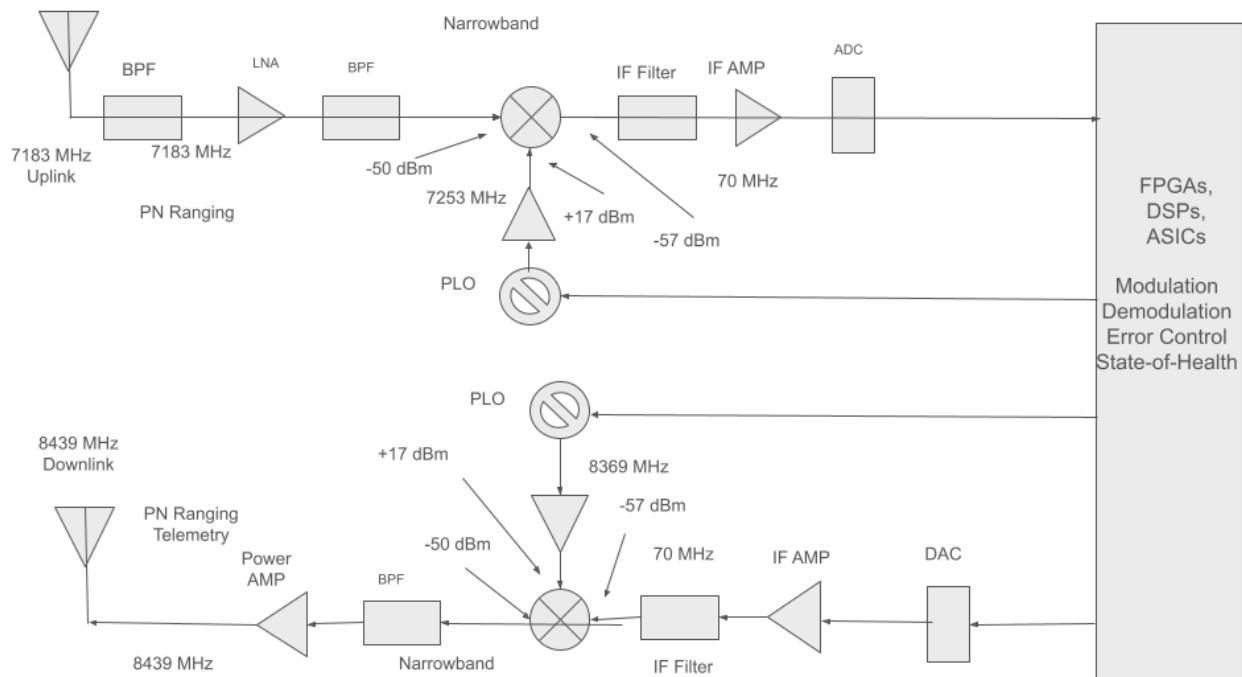


**Figure A11: CubeSat Uplink/Downlink Configuration**

Figure A12 shows the overall architecture of the four element interferometer. The core of each of the four elements is the [Ettus USRP N310](#) software defined receiver, operating in the 10 MHz to 6 GHz frequency range. Figure A13 is the detailed design of the N310 motherboard and Figure A14 is the detailed design of the N310 RF/digital subsystem. Figure A15 shows the components external to the N310 required to convert from the 10 MHz-10 GHz operational frequencies to the frequencies needed by the N310.

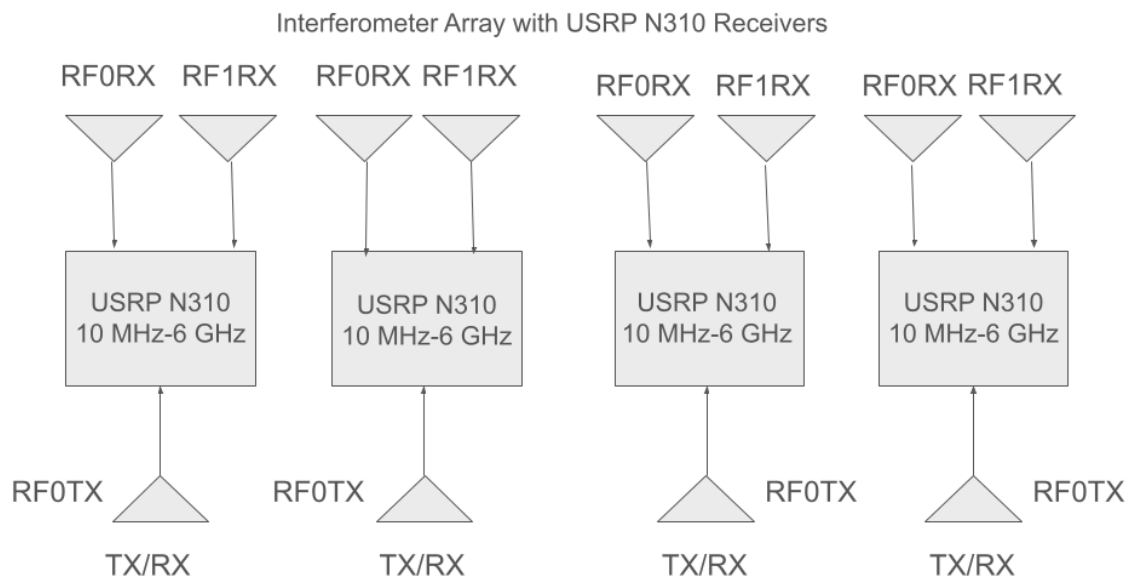


**Figure A12: Architecture of Four Element Interferometer**

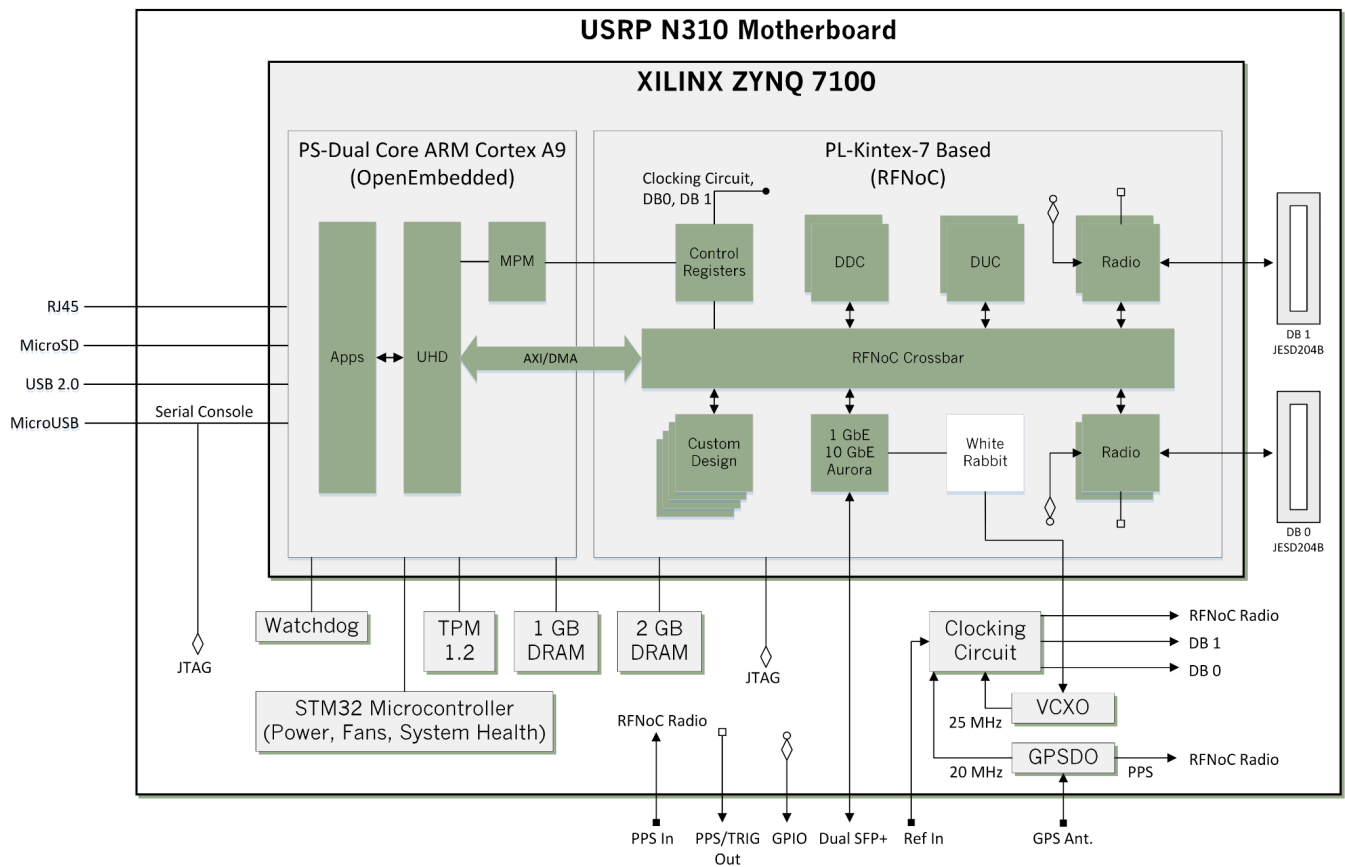


**Figure A13: USRP N310 Motherboard**

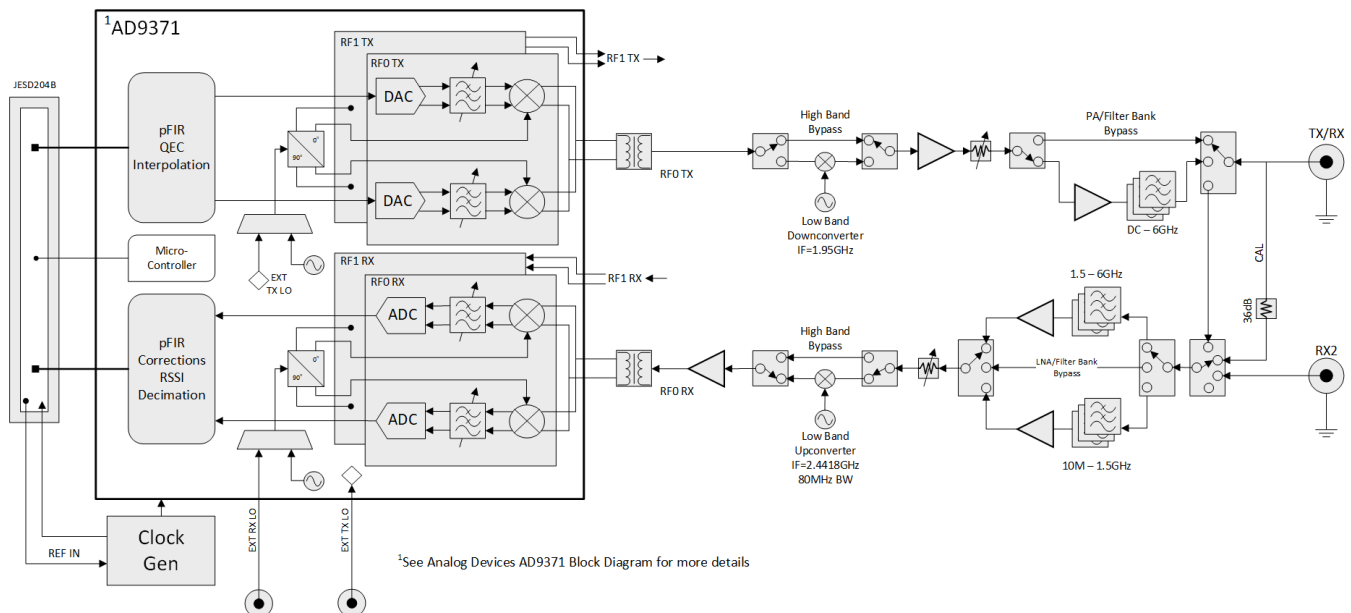


**Figure A14: USRP N310 RF/Digital Design**

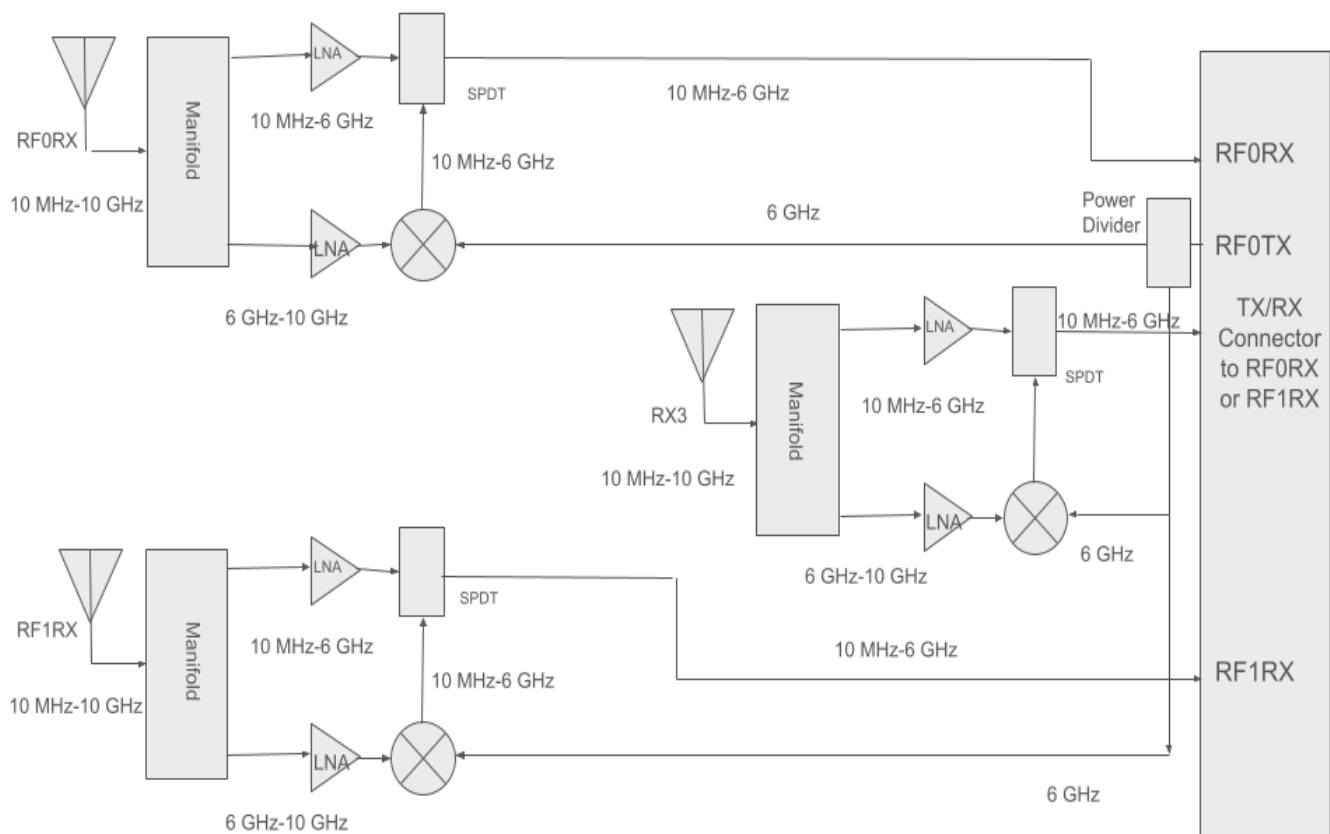


**Figure A15: CubeSat Signal Architecture**

**Frequency Plan and Spurious Products:** Based upon the frequencies shown in Figures A12-A15, a spurious product analysis yields the products below.

RF = 10 GHz; LO = 6 GHz: LO feedthrough at 6 GHz = -35 dBm/2LO-1RF spur at -46 dBm

RF = 6 GHz; LO = 6 GHz: LO feedthrough at 6 GHz = -35 dBm/2LO-1RF spur at -46 dBm

These are the only spurious products. Their frequencies and signal levels are not a problem for the operation of the CubeSat system architecture.

**CubeSat Antennas:** The CubeSat antennas include the uplink and downlink antennas and the interferometer antennas. The uplink frequency is 7183 MHz and the downlink frequency is 8439 MHz. These are the frequencies utilized by the Swedish Space Corporation as discussed above. These frequencies can be handled by miniature antennas incorporating fractal principles. Below is an example. The papers that discuss these are shown in the references, with select figures herein to illustrate the results.

#### **Miniaturized UWB Monopole Microstrip Antenna**

This antenna is a fractal monopole antenna combining two fractal geometries to achieve wider bandwidth. Additionally, it has an omnidirectional radiation pattern, good gain, and high efficiency. This is shown in Figures A16-A18.

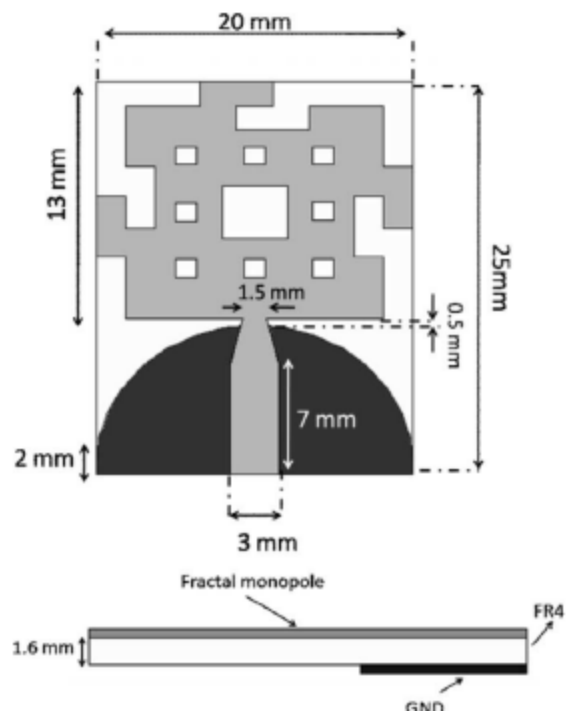


Figure A16: Structure of Uplink/Downlink Fractal Antennas  
(Courtesy Oraizi, H. and Hedayati, S.)

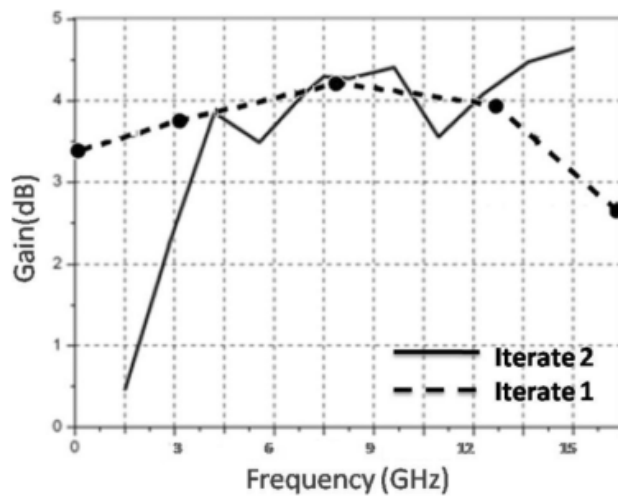


Figure A17: Gain vs. Frequency of Uplink/Downlink Fractal Antenna  
(Courtesy Oraizi, H. and Hedayati, S.)

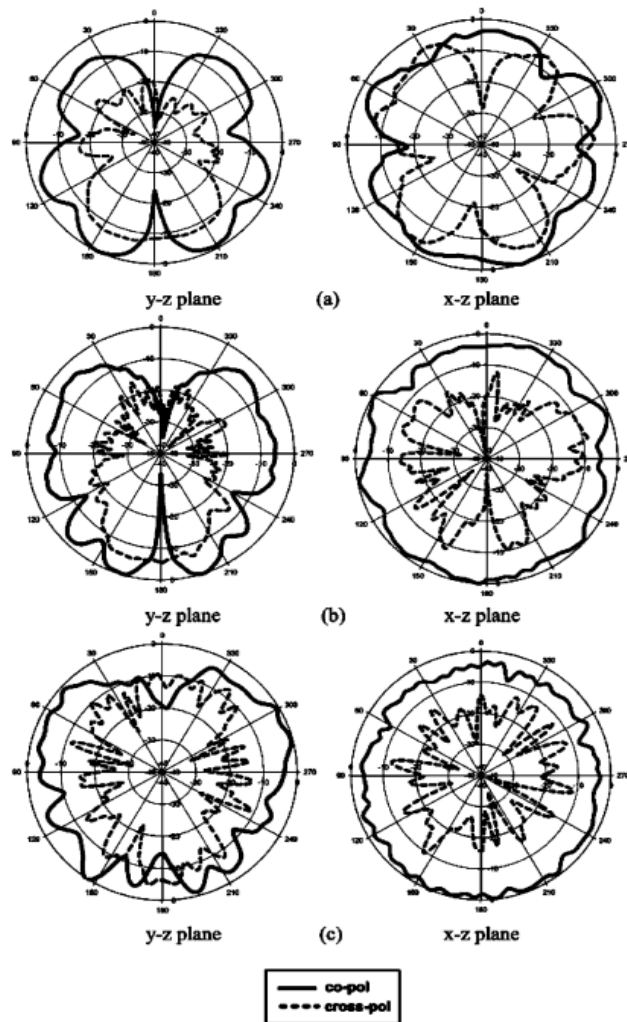


**Figure A18: Measured Radiation Patterns of Uplink/Downlink Fractal Antenna at (a) 3 GHz, (b) 8 GHz, and (c) 12 GHz (Courtesy Oraizi, H. and Hedayati, S.)**

The interferometer antennas cover four frequency bands: High Band, 2.0 GHz - 10.6 GHz; Mid Band 1, 550 MHz - 2.0 GHz; Mid Band 2, 130 MHz - 550 MHz; and Low Band, 10 MHz - 130 MHz. Examples of each are outlined below.

High Band: 2.0 GHz-10.6 GHz

#### **Wideband Monopole Fractal Antenna**

This antenna also has wide bandwidth, good gain, high efficiency, and an omnidirectional radiation pattern. Additionally, its gain is extremely flat and uniform across a wide bandwidth. It could also be used in the uplink/downlink antenna discussed above. The omnidirectional radiation pattern is critical to spherical coverage for the interferometer array as discussed above. Otherwise, this volume would need to be covered by a beam scanning system that would severely complicate the interferometer array architecture. This is shown in Figures A19-A21.

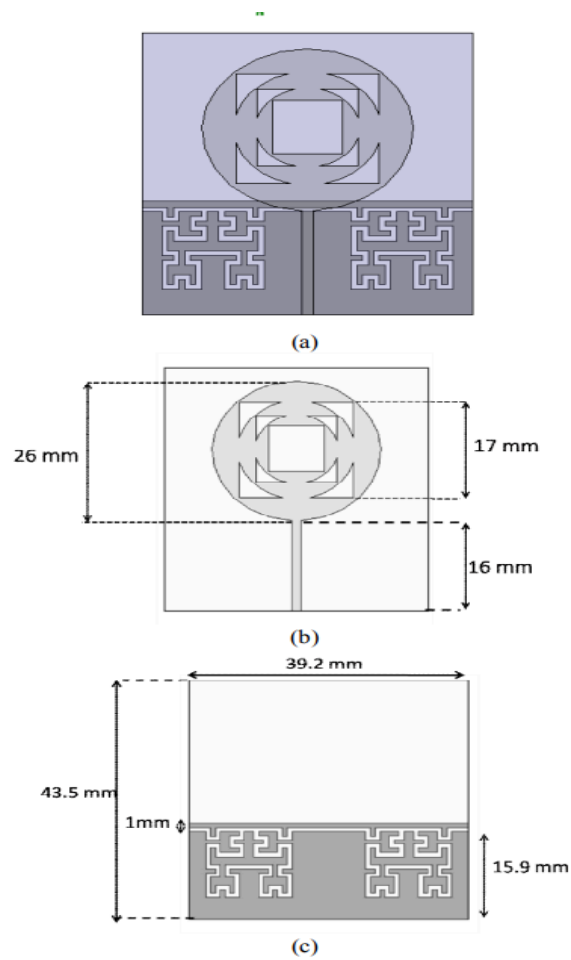


**Figure A19: Fractal Antenna Configuration**  
(Courtesy Oraizi, H. and Hedayati, S.)

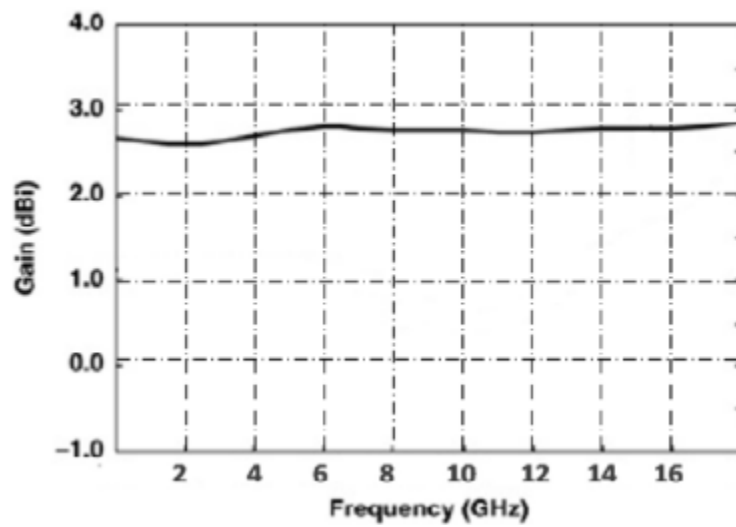


**Figure A20: Gain vs. Frequency of Fractal Antenna Configuration**  
(Courtesy Oraizi, H. and Hedayati, S.)

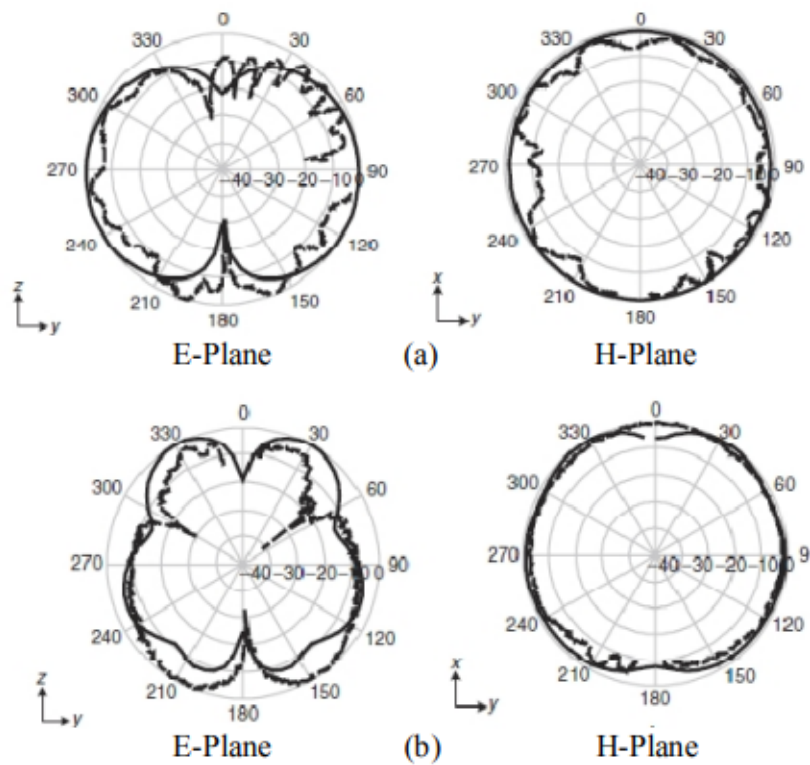


**Figure A21: Radiation Pattern of Fractal Antenna Configuration**  
(Courtesy Oraizi, H. and Hedayati, S.)

#### **Miniaturized UWB Log-Periodic Square Fractal Antenna**

This fractal antenna also has the very favorable gain, efficiency, bandwidth, and radiation pattern required for the CubeSat interferometer array. It incorporates 15 square patches. This is shown in Figures A22-A26.

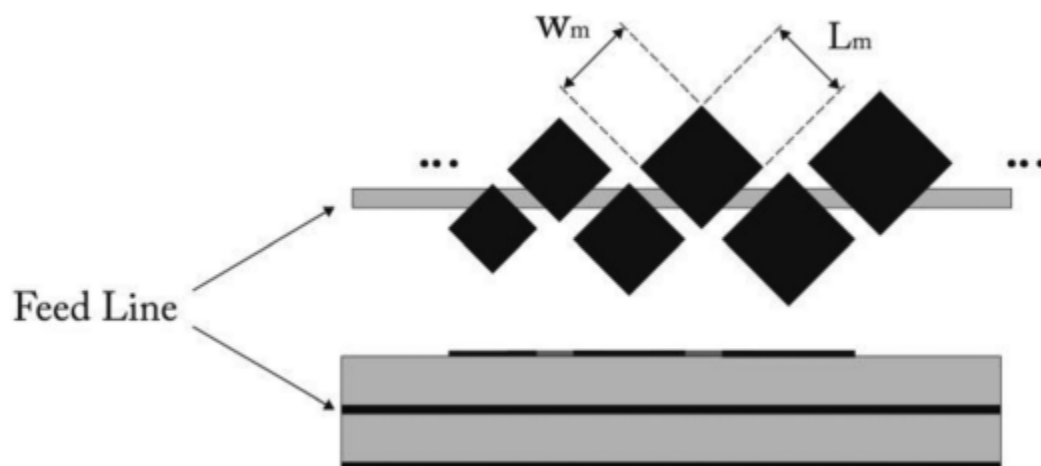


**Figure A22: Log-Periodic Fractal Antenna Design**  
(Courtesy Amini, A., et al.)

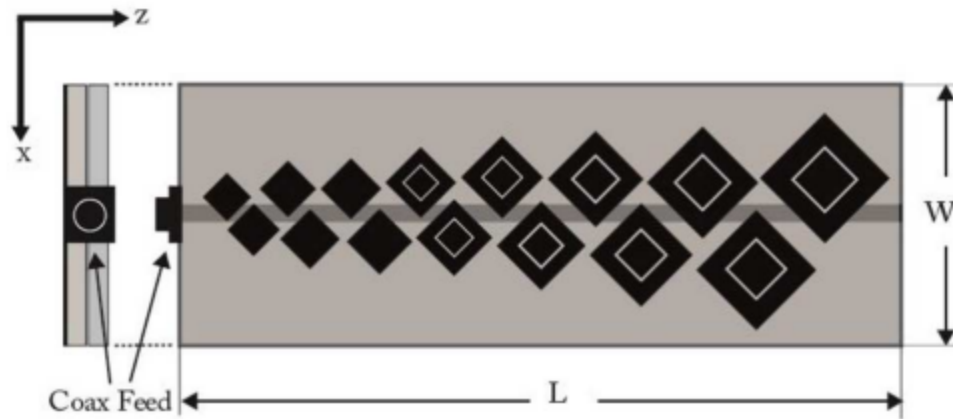


Figure A23: Log-Periodic Fractal Antenna Configuration  
(Courtesy Amini, A., et al.)



Figure A24: Fabricated Log-Periodic Fractal Antenna Configuration  
(Courtesy Amini, A., et al.)

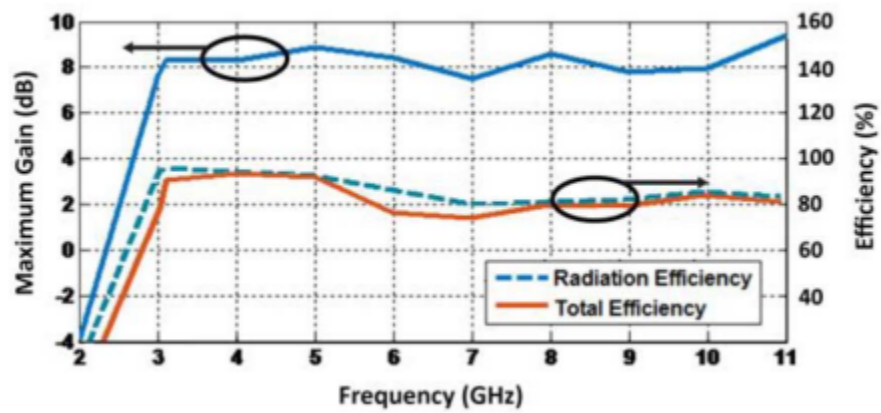


Figure A25: Gain vs. Frequency of Log-Periodic Fractal Antenna  
(Courtesy Amini, A., et al.)

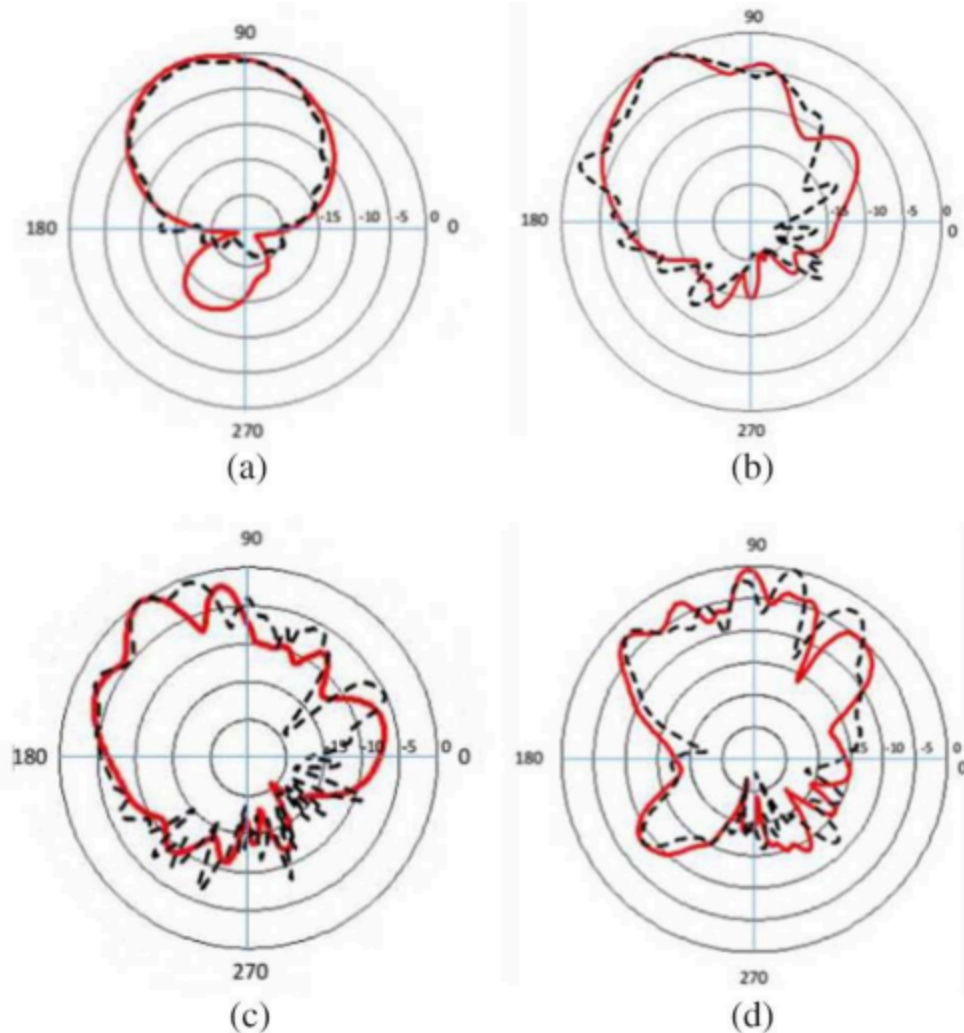


**Figure A26: Radiation Patterns of Log-Periodic Fractal Antenna**  
**(a) 3.1 GHz, (b) 5 GHz, (c) 7 GHz, (d) 10.6 GHz**  
**(Courtesy Amini, A., et al.)**

Midband 1: 550 MHz-2.0 GHz

This frequency band utilizes the same design technique as for High Band. This incorporates 16 square patches between 550 MHz and 2.0 GHz.

Midband 2: 130 MHz-550 MHz

#### **UHF/VHF Tightly Coupled Dipole Array**

This antenna incorporates a deployable, two-layer Tightly Coupled Dipole Array (TCDA) for CubeSat constellation based upon Synthetic Aperture Array (SAR) concepts. The entire antenna array can be folded across two sides of a 6U CubeSat chassis for minimal space usage. The antenna details are shown in Figures A27-A29.

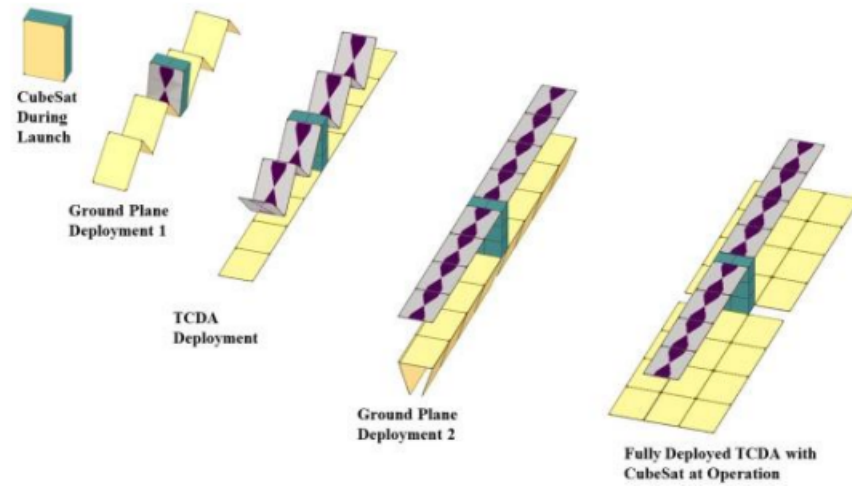


Figure A27: Antenna Array Deployment  
(Courtesy Hossain, M. et al.)

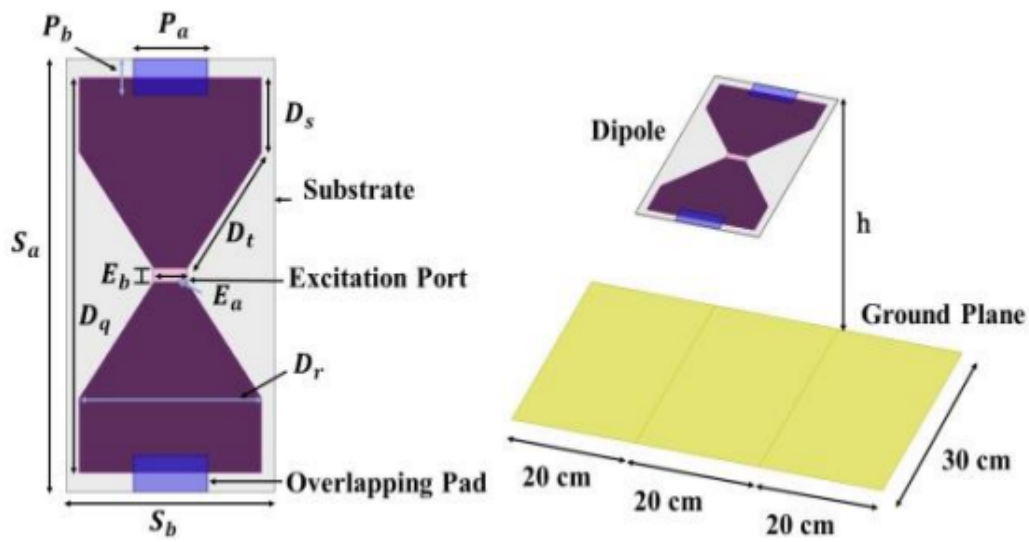
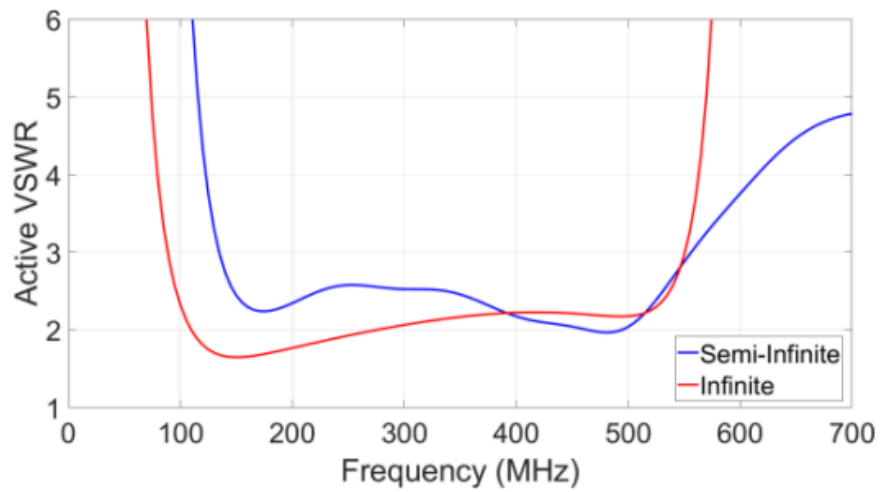
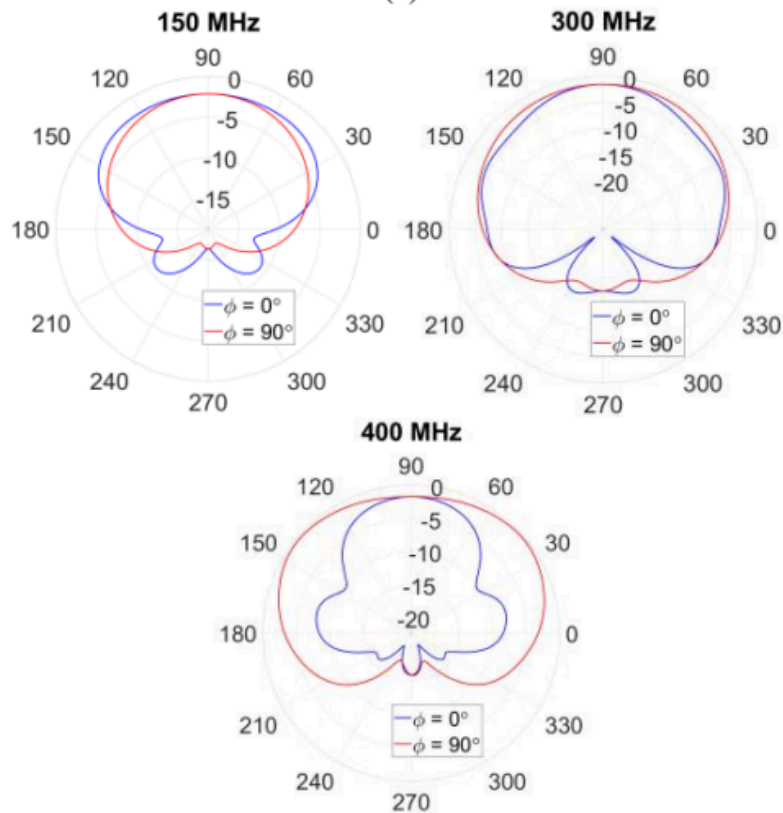


Figure A28: Geometry of the Array Unit Cell  
(Courtesy Hossain, M. et al.)



(a)



(b)

**Figure A29: (a) Array VSWR; (b) Radiation Patterns (150 MHz, 300 MHz, 400 MHz)**  
(Courtesy Hossain, M. et al.)

Low Band: 10 MHz-130 MHz

The Low Band frequency range is challenging for CubeSat implementation. This is due to the fact that the CubeSat is fundamentally a very small vehicle, while antennas in the 10 MHz - 130 MHz frequency range tend to be quite large. This can be seen in the paper “Design of a Broadband HF Antenna for Multimode Naval Communications—Part II: Extension to VHF/UHF Ranges” listed below in the References section. As such, this is

an excellent topic for further study and development. The use of metamaterials may offer excellent approaches to reducing the size and weight of antennas operating in this band.

## **APPENDIX**

### **Advanced Technologies for CubeSat Applications for RF Counterpart Interferometer Systems**

The Ettus USRP N310 has been selected for a baseline design, but there are multiple approaches to this system. The CubeSat design can use all COTS (Commercial Off The Shelf) technology, advanced developmental technology, or some combination of both technologies. For any advanced technology applications, the CubeSat project can be used as a technology development platform. Several of these potential technology developments are discussed below. These are: RF metamaterials and components, metamaterial antennas, and multi frequency fractal antennas. In addition to electromagnetic applications, metamaterials can be used for photonic/optical, structural, and thermal applications for CubeSats.

#### **RF [Metamaterials](#) for Cubesat Applications**

A metamaterial is any material engineered to have a property that is rarely observed in naturally occurring materials. They are made from assemblies of multiple elements fashioned from composite materials such as metals and plastics. These materials are usually arranged in repeating patterns, at scales that are smaller than the wavelengths of the phenomena they influence. Metamaterials derive their properties not from the properties of the base materials, but from their newly designed structures. Their precise shape, geometry, size, orientation and arrangement gives them their smart properties capable of manipulating electromagnetic waves by blocking, absorbing, enhancing, or bending waves, to achieve benefits that go beyond what is possible with conventional materials. Appropriately designed metamaterials can affect waves of electromagnetic radiation in a manner not observed in bulk materials. Those that exhibit a negative index of refraction for particular wavelengths have been the focus of a large amount of research. These materials are known as negative -index metamaterials.

#### **Introduction and Background**

Metamaterials or artificial electromagnetic materials are those that do not have any occurrence in nature. They are synthesized artificially through man-made processes. Metamaterials are materials that gain their properties and characteristics from internal structure rather than from their composition as would be found in nature. The internal structure usually consists of periodic arrays of metals, atoms, crystal structures, etc. Electromagnetic metamaterials are usually composed of periodic sub-wavelength units which can produce electric, magnetic, and electromagnetic responses under the excitation of external incident waves or other stimulation. Electromagnetic metamaterials can be made of metallic conductors, dielectrics, magnetic substances, semiconductors, and superconductor materials. Due to the small electrical size of metamaterial resonators, they are very attractive for the design of multiple RF and microwave circuits and structures, particularly compact planar structures such as microstrip filters. Metamaterial filters have advantages over conventional microwave filters as they result in improved performance as well as compact sizes. This is particularly significant for lower frequency structures that can be made smaller with metamaterials than with conventional materials as determined by the resonant wavelength, i.e. quarter wavelength at a particular frequency.

The electromagnetic characteristics of normal electronic materials is primarily determined by the permittivity, the permeability, and the conductivity. The permittivity (electric) and permeability (magnetic) properties in normal materials are both positive. In contrast, metamaterials exhibit both negative permittivity and negative permeability and are referred to as left handed material. In left handed material, the vectors correspond in direction to the thumb and two fingers of the left hand rather than the right hand as in the normal right hand rule routinely used in electromagnetics. In other words, the phase velocity can be made anti-parallel to the direction of the Poynting vector, which is contrary to wave propagation in naturally occurring materials.

Due to the fact that both permittivity and permeability are negative, these materials show a negative index of refraction and as a result, there is a reversal of Snell's Law and the Doppler Effect. Since the characteristic wavelengths of the periodic structures are far smaller than the working wavelengths, various applications can be realized in smaller form factors than with traditional materials. This is particularly significant for lower frequency structures that can be made smaller with metamaterials than with conventional materials as determined by the resonant wavelength, i.e. quarter wavelength at a particular frequency. These special materials can be utilized in the development of antennas, filters, amplifiers and other electromagnetic devices.

## 1. Structures and Devices

### Resonators

Resonators are crucial to RF/microwave applications of all kinds. Traditionally, resonators have been classified as dielectric, cavity, lumped-element, and transmission line topologies. Resonant-type metamaterial transmission lines can be used for RF filter applications to obtain a propagating medium with controllable characteristics. The transmission lines can combine the sub-wavelength resonators with elements such as series capacitances or shunt inductors. The two major types of metamaterial resonators are split-ring resonators (SRR) and complementary split-ring resonators (CSRR). Both SRRs also can be realized in double-slit topology (DS-SRR and DS-CSSR). These are shown in Figure App 1. The metal regions are the dark gray areas. The equivalent circuit topologies for the SRR and CSRR are shown in Figures App 2 and App 3, respectively.



**Figure App 1: Split Ring Resonators (SRR, CSRR, DS-CSRR, DS-SRR)**  
(Courtesy Jindal, S. and Sharma, J.)

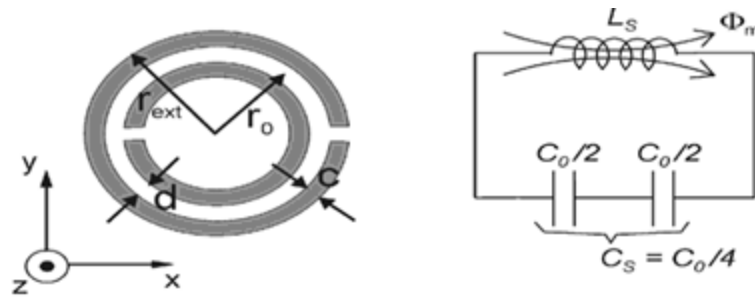


**Figure App 2: Equivalent Circuit Topologies for the SRR**  
(Courtesy Jindal, S. and Sharma, J.)

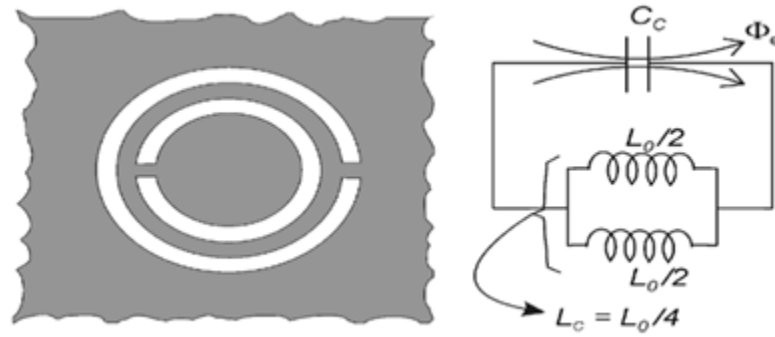


**Figure App 3: Equivalent Circuit Topologies for the CSRR**  
(Courtesy Jindal, S. and Sharma, J.)

### Transmission Lines

Transmission lines can also be implemented with planar metamaterials. The equivalent circuit model of a conventional right-handed transmission line is shown in Figure App 4. It consists of series inductors and shunt capacitors, of which the dimensions are much less than the wavelength of the operating frequency. It is well known that many important characteristics, such as characteristic impedance, phase velocity, dispersions and so on, can be obtained from the circuit model. The equivalent circuit model of a left-handed transmission line is shown in Figure App 5, which is a dual of Figure App 4. All series inductors in the right-handed transmission line model are replaced by capacitors in the left-handed transmission line model, and all shunt capacitors are substituted by inductors. It is an ideal model, which does not exist in nature.



**Figure App 4 : Right-handed Transmission Line** (Courtesy Jindal, S. and Sharma, J.)



**Figure App 5 : Left-handed Transmission Line** (Courtesy Jindal, S. and Sharma, J.)

A composite right/left-handed transmission line model, as shown in Figure App 6, is more suitable than the left-handed transmission line circuit model, since the parasite series inductance and shunt capacitance

cannot be avoided in nature. It consists of series resonators LR and CL and shunt resonators CR and LL, where the subscript “L” and “R” denote left-handed and right handed, respectively. This transmission line circuit model is a combination of left-handed and right-handed transmission line. At low frequency, CL and LL are dominant, the transmission line shows left-handed characteristics; at high frequency, LR and CR are dominant, the transmission line shows right-handed characteristics.



**Figure App 6. Equivalent Circuit Model of Composite Right/Left-Handed Transmission Line**  
(Courtesy Jindal, S. and Sharma, J.)

### Impedance Matching

Metamaterial impedance matching networks are another critical component of RF/microwave circuits and systems. The metamaterial impedance matching network is a passive two port network that generates  $S_{11}$  (input scattering parameter) notches around the  $\lambda/2$  open stubs resonators. These notches can be identified as resonant frequencies that minimize the  $S_{11}$  parameter. The number of notches in the structure response is related to the number of coupled stubs. Two identical  $\lambda/2$  open stubs capacitively coupled generate two split resonant frequencies around the original  $\lambda/2$  resonance. In general  $N$  stubs will generate  $N-1$  notches; however, the quality factor of the new resonant frequencies decreases with  $N$ . The distance between the split frequencies depends on the coupling coefficient between the resonators which is controlled by the distance between adjacent stubs. Therefore, this coupling distance in an optimization process can situate a deep notch at the desired frequency. The metamaterial impedance matching network takes advantage of these notches behavior to match the input impedance of multiple frequencies simultaneously.

### Filters

In recent years, several filter applications at microwave frequency have been developed by means of metamaterials based on subwavelength resonators such as the split-ring resonators. Because of the small electrical size of the unit cells, the metamaterial-based resonator offers a great solution to the design of miniaturized microwave resonators. This has been used not only to design miniaturized filters but also to obtain microwave devices with enhanced bandwidth. Metamaterial resonators have usually been used mainly for notch band and narrow bandpass filters. However, this technology can also be used for miniaturization of wideband transceiver components.

In order to obtain a wideband bandpass filter, two techniques are combined to obtain a good wideband characteristic. The first technique is the use of a coupled metamaterial resonator, namely the narrowband split ring resonator. The other is the use of the defected ground structure (DGS), which is adopted to tighten the coupling of the narrowband split ring resonator in order to improve the bandpass filter's performance. This process modifies the characteristics of the transmission line such as the line capacitance and inductance. Therefore, the DGS is usually used to improve the passband and stopband characteristics. Figure App 7 shows the two coupled narrowband split ring resonator scheme of the filter structure. Figure App 8 shows the simulated S-parameters ( $S_{11}$  and  $S_{21}$ ) of the wideband bandpass filter with and without the DGS.

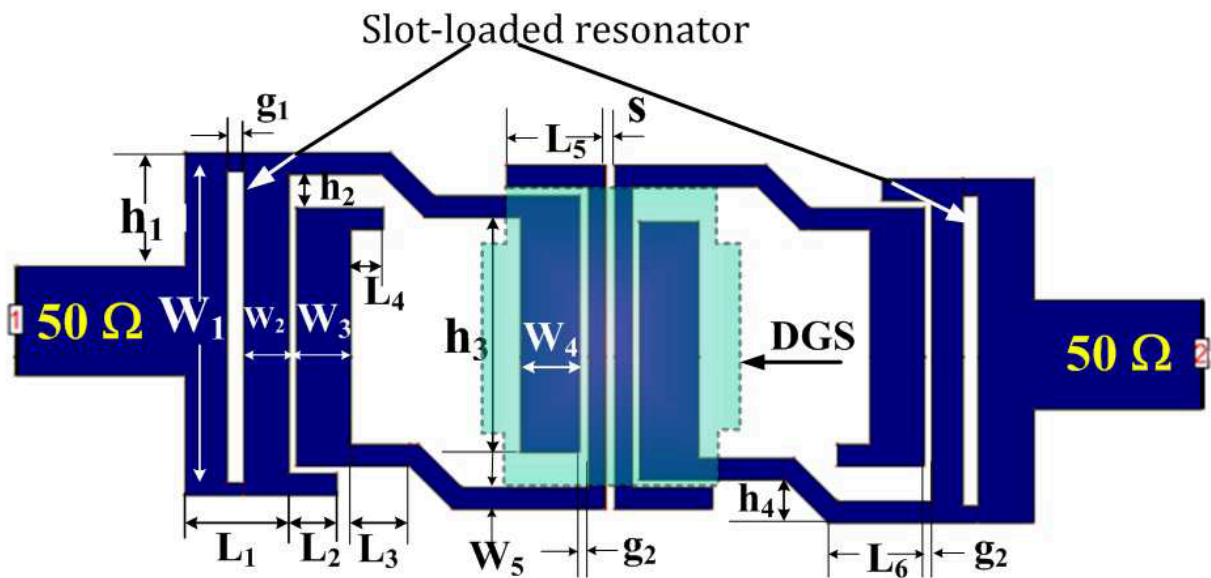


Figure App 7: Two Coupled Narrowband Split Ring Resonator Scheme of the Filter Structure  
(Courtesy Chaimool, S., and Akkaraekthalin, P.)

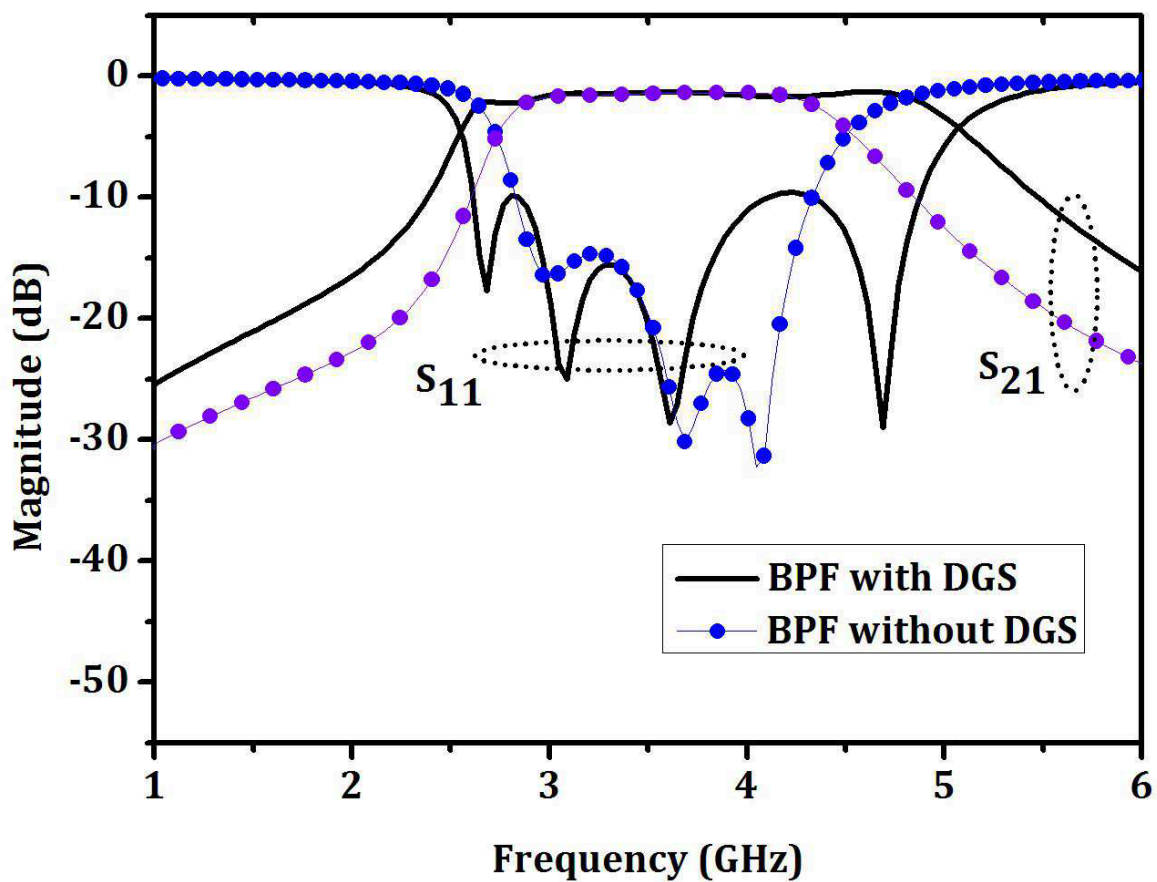


Figure App 8: Simulated S-parameters ( $S_{11}$  and  $S_{21}$ ) of the Wideband Bandpass Filter With and Without the DGS  
(Courtesy Chaimool, S., and Akkaraekthalin, P.)

## 2. Fractal and Metamaterial Antennas

Fractal antennas have unique characteristics associated with the various geometries and mathematical properties of fractals. Fractals were first defined by Benoit Mandelbrot (1975) and published in his book (Mandelbrot, 1983) as a way of classifying structures whose dimensions were not whole numbers, but rather fractional dimensions (fractals). Application of fractal geometry to various antenna elements yields smaller antenna size, resonant frequencies that are wideband and multiband, and are optimized for antenna gain. Applying fractals to entire network antenna arrays also results in multiband/broadband performance. Therefore, fractal geometries are highly advantageous to both individual antenna elements and entire antenna arrays.

The key feature of fractal systems is self-similarity, that is, different parts of the antenna or antenna array are similar to each other at different physical scales (scale invariance). This makes it possible to design antennas and arrays capable of wideband and multi-band frequency response at a fraction of the size of conventional antennas. Fractal antennas operate from frequency  $f$  to frequency  $Nf$  all within one structure. The array factor is a function of the positions of the individual antennas in the array and the relative weighting of each antenna. Various baselines that can be formed by combinations of the distances  $d$  among the linear array elements.

A fractal element antenna is a radiative element shaped using fractal geometry. Fractal antenna types include dipoles, monopoles, patches, conformal, biconical, disccone, spiral, helical, and others as well as compact variants of each only possible through fractal technology. The inherent qualities of fractals enable the production of high performance antennas that are typically 50%-75% smaller than traditional ones. Typical advantages are increased bandwidth, multiband operation, and improved gain in addition to smaller size. Antenna performance is obtained through the geometry of the conductor rather than the addition of separate components or elements. In addition, fractal antennas afford unique improvements to antenna arrays including increased bandwidth thereby allowing multiband capabilities, decreased size load, and enabling smart antenna technology. Fractal parts produce fractal loading which makes the antenna smaller for a given frequency, typically 2-4 times smaller. Multiband behavior is manifest at non-harmonic frequencies while some bands are broadened, and can be made frequency independent without a log periodic geometry.

Metamaterial antennas are a class of antennas which use metamaterials to increase performance of miniaturized (electrically small) antenna systems. Their purpose, as with any electromagnetic antenna, is to launch energy into free space. However, this class of antenna incorporates metamaterials, which are materials engineered with novel, often microscopic, structures to produce unusual physical properties. Antenna design incorporating metamaterials can step-up the antenna's radiated power. Conventional antennas that are very small compared to the wavelength reflect most of the signal back to the source. A metamaterial antenna behaves as if it were much larger than its actual size, because its novel structure stores and re-radiates energy. Established lithography techniques can be used to print metamaterial elements on a PC board.

Antenna designs incorporating metamaterials can step-up the radiated power of an antenna. The newest metamaterial antennas radiate as much as 95 percent of an input radio signal. Standard antennas need to be at least half the size of the signal wavelength to operate efficiently. At 300 MHz, for instance, an antenna would need to be half a meter long. In contrast, experimental metamaterial antennas are as small as one-fiftieth of a wavelength, and could have further decreases in size. Metamaterials are a basis for further miniaturization of microwave antennas, with efficient power and acceptable bandwidth. Antennas employing metamaterials offer

the possibility of overcoming restrictive efficiency-bandwidth limitations for conventionally constructed, miniature antennas. Metamaterials permit smaller antenna elements that cover a wider frequency range, thus making better use of available space for space-constrained cases. In these instances, miniature antennas with high gain are significantly relevant because the radiating elements are combined into large antenna arrays. Furthermore, metamaterial's negative refractive index focuses electromagnetic radiation by a flat lens versus being dispersed.

## References

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