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.

1.0 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), Internet of Things (IOT), optical sensors, radio frequency and microwave sensors, x-ray sensors, gamma ray sensors, infrared and ultraviolet sensors.

2.0 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 (Double Neutron Star mergers), and 1-5 GHz (synchrotron radiation from post-merger events).

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 (Low Frequency Array) systems while larger radio telescopes such as the JVLA (Jansky Very Large Array) detect pulsar emissions from approximately 1 GHz to 8.4 GHz.

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.

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).

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.

3.0 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.

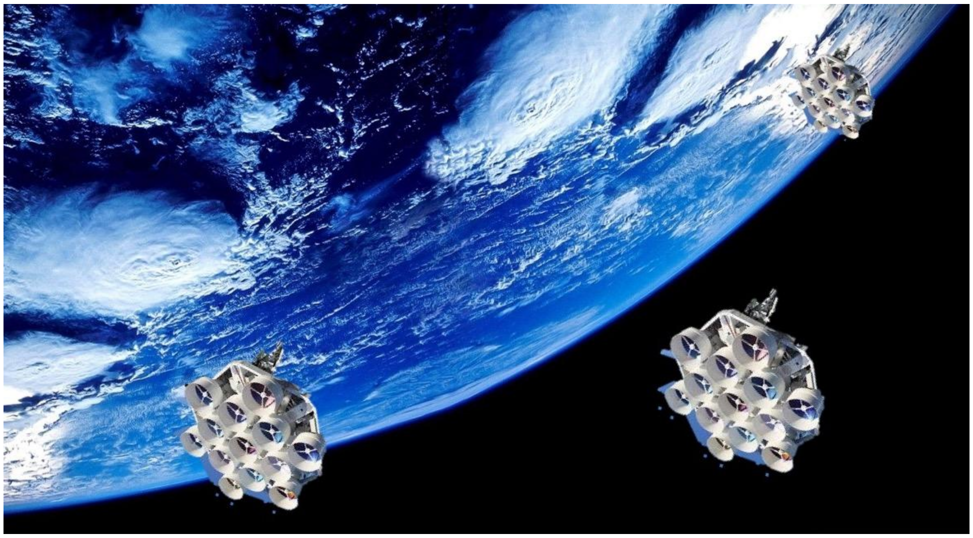

Figure 1: A Three Element VLBI CubeSat Constellation (Courtesy ASTRON & Joint Institute for VLBI)

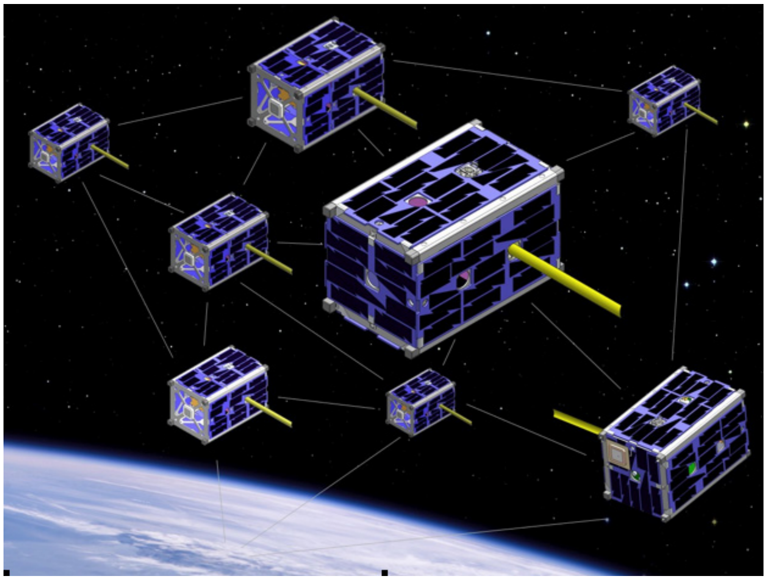

Figure 2: A CubeSat Swarm (Courtesy NASA)

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.

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. For a deep space application such as around one of the three 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.

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 for 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(sys), the overall antenna performance is defined as the System Equivalent Flux Density (SEFD)

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

(1 Jy = 10 exp-26 Watts per meter squared per Hertz of bandwidth)

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

$$\Delta S\ (i,j) = 1/\eta \times \text{sqrt}\ [(\text{SEFD}\ (i) \times \text{SEFD}\ (j))/2 \times \Delta v \times \tau(\text{acc})] \qquad \text{Eq. (2)}$$

Here $\tau(\text{acc})$ is the accumulation time, η is the system or array efficiency, and Δv is the collecting bandwidth of each antenna. A two element interferometer is shown below in Figure 3(e) with its fringe spacing. The 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) unique baselines with each baseline adding improved sensitivity as well as a wider operating frequency range.

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 in 1975 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 antenna arrays also results in multiband/broadband arrays. 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 3 shows several fractal antenna and array structures. Figure 3(a) is a Cantor slot patch. This fractal antenna operates from frequency f to frequency 32f all within one structure. The structure shown in Figure 3(b) is called a Sierpinski dipole. Figure 3(c) is a Cantor linear fractal array and Figure 3(d) 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 3(d) shows the various baselines that can be formed by combinations of the distances d (d1-d4) among the array elements. Figure 3(f) shows the improvement in field pattern quality by expanding the array from two antennas (top) to four antennas (bottom). The field pattern or fringe for two antennas is shown in Figure 3(e) and the top of Figure 3(f). Adding a third antenna produces a main response peak, which is termed a synthesized beam, but also results in large sidelobes. Adding a fourth antenna suppresses the sidelobes, resulting in a much cleaner beam shape as shown at the bottom of Figure 3(f).

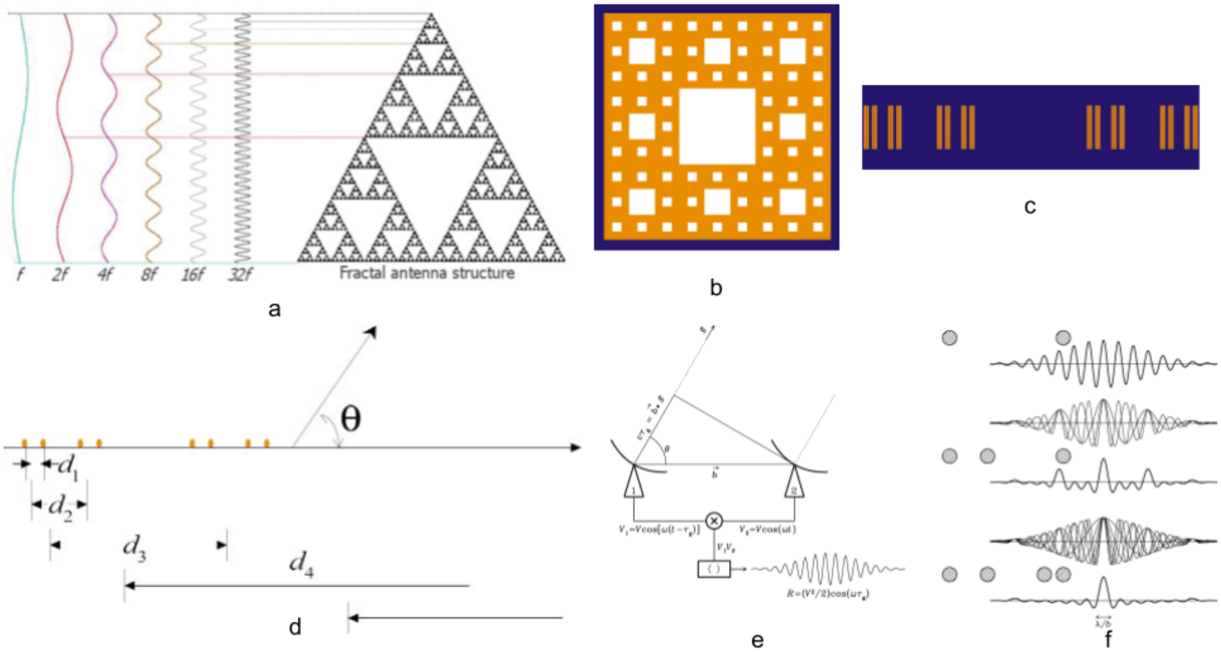

Figure 3: Fractal Antenna and Array Structures
(Courtesy Yang, et al; Ponnapalli, et al)

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 (SDR) 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 4. The software functions are indicated as shown.

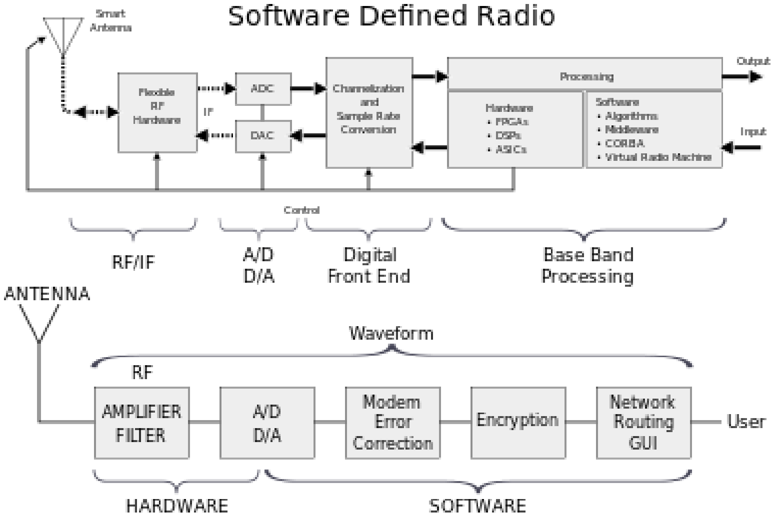

Figure 4: Software Defined Radio

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 application and target. Figure 5 shows a tunable bandpass filter and a switching network. Figure 5(a) is the basic filter element. Figure 5(b) is the top view of the basic switch element and Figure 5(c) is the cross section of the switch structure. The switch structure is fabricated utilizing 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. Figure 5(d) is a single pole four throw switch (sp4t) network implemented with the MEMS switches outlined above. Figure 5(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.

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 6. 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.

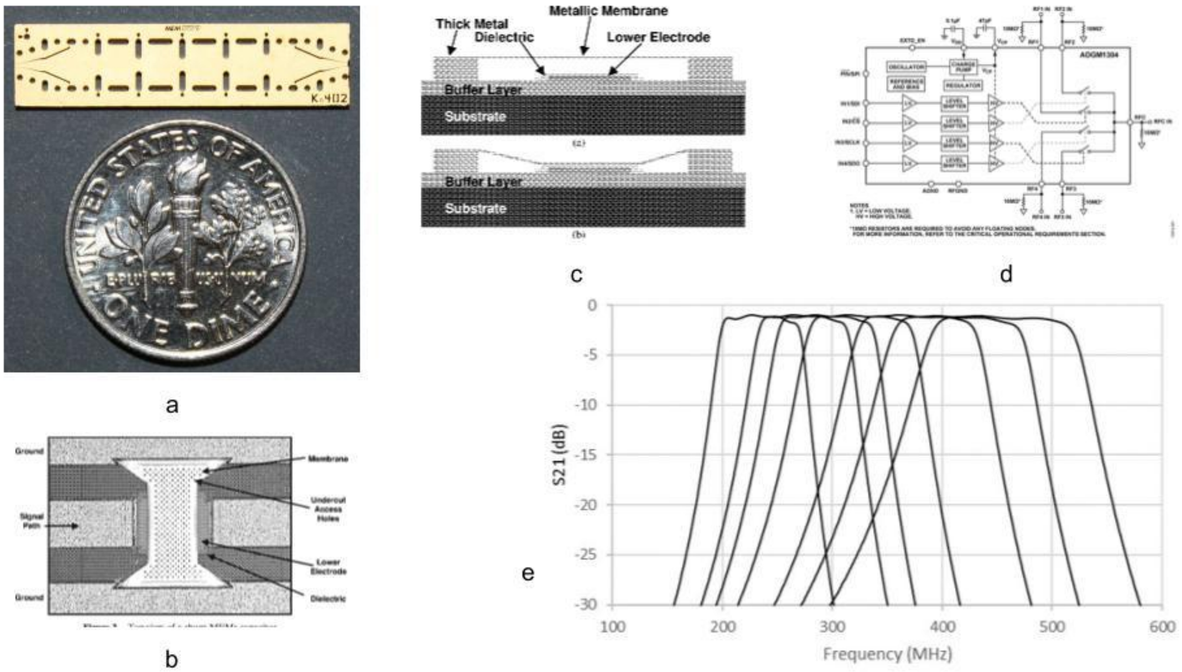

Figure 5: Tunable Bandpass Filter and Switching Network (Courtesy Memtronics, Inc.; Microwave Journal, 2020)

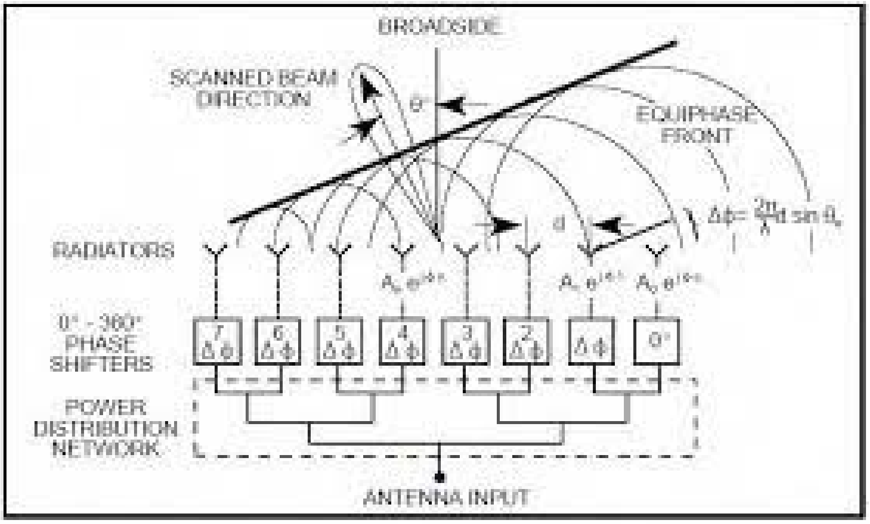

Figure 6: CubeSat Antenna Beam Steering Utilizing MEMS Technology (Courtesy Elbanna, H., et al.)

4.0 Results

Figure 7 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 7 is only a notional concept and not meant to represent an actual proposed system. Figure 7(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 7(b) is the Cantor linear fractal array as discussed above showing the beam steered to an angle $\boldsymbol{\Theta}$, and Figure 7(c) illustrates what a network of CubeSats in this type of array might look like on station.

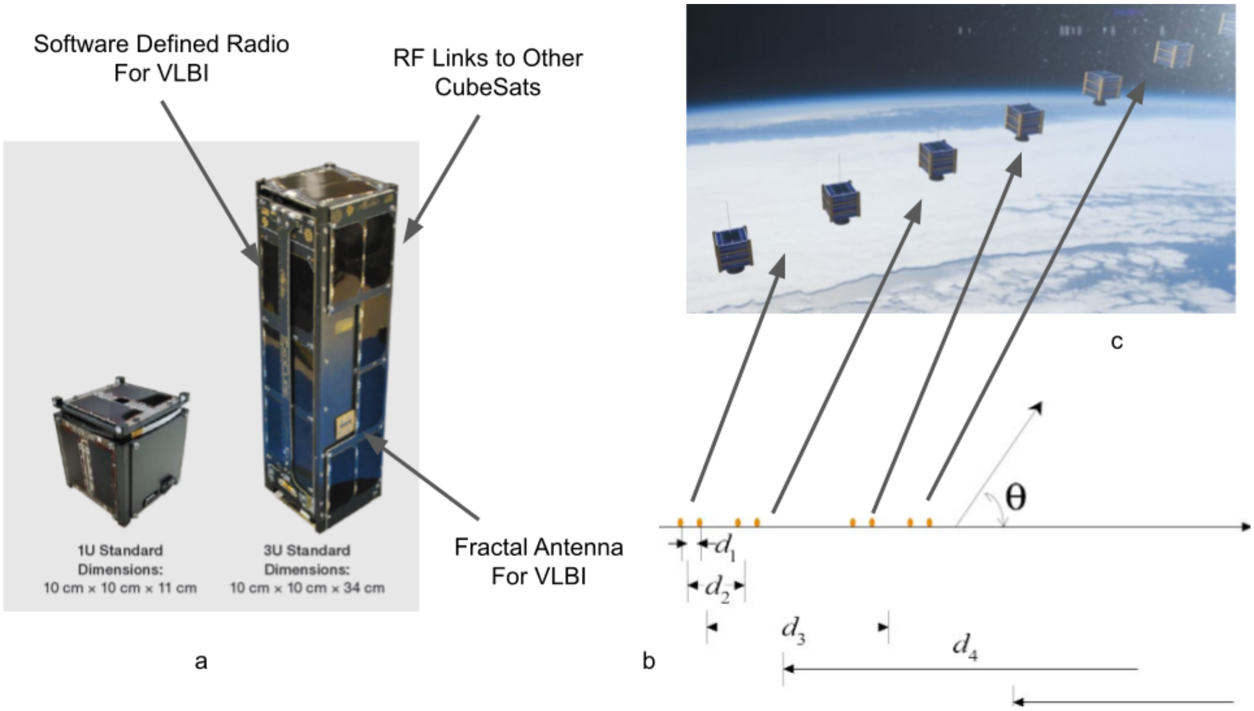

Figure 7: Notional Concept for CubeSat Array for VLBI (Courtesy NASA)

6.0 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 tunable filters, switches, and phase shifters for agile frequency selection and antenna beam steering.

References

Elbanna, H., et al., 2018, Electronically Scanned Phased Array Antenna Design and Implementation, 2018 IEEE International RF and Microwave Conference.

Goldsmith, C.L., et al., 1999, RF MEMS Variable Capacitors for Tunable Filters, Special Issue on RF Applications of MEMS technology, International Journal of RF and Microwave Computer-Aided Engineering.

Hinzel, D., 1998/1999, UltraComm Wideband Multi-Channel Multi-Mode Advanced Digital Receiver, Raytheon RF Symposium.

Hinzel, D., 1998/1999, Microelectromechanical System (MEMS) Tunable Bandpass Preselect Filters for an Advanced Digital Receiver, Raytheon RF Symposium.

Hinzel, D., 1998, Tunable RF Filters, 1998 DARPA ETO MEMS Principal Investigator Meeting, Research Triangle Park, North Carolina.

Hinzel, D., 1998, Microelectromechanical Systems (MEMS) Tunable Bandpass Preselect Filters for an Advanced Digital Receiver, 1998 IEEE Microwave Theory and Techniques Society Lecture Series, University of Maryland, College Park, Maryland.

Hinzel, D., 1999, Microelectromechanical Systems (MEMS) Tunable Bandpass Preselect Filters for Advanced Digital Receivers and Transmitters, The 2nd International Conference on Integrated Micro/Nanotechnology for Space Applications, Jet Propulsion Lab, Pasadena, California.

Hinzel, D., 1999, Microelectromechanical Systems (MEMS) Tunable Bandpass Preselect Filters for an Advanced Digital Receiver, 1999 MEMS Workshop, The American Center for Physics, College Park, Maryland.

Hinzel, D., 2000, RF MEMS Bandpass Filters for Military Applications, Naval Research Laboratory RF MEMS Workshop.

Hinzel, D., et al., 2003, Method of Integrating MEMS Devices with Low-Resistivity Silicon Substrates, Patent # 6559530.

Hinzel, D., 2018, Unmanned Aerial Systems for Variable Star Astronomical Observations, The Journal of the American Association of Variable Star Observers, JAAVSO Volume 46, 2018.

Hotokezaka, K., et al., 2016, Radio Counterparts of Compact Binary Mergers Detectable In Gravitational Waves. A Simulation for an Optimized Survey arXiv:1605.09395v2 [astro-ph.HE] 4 Sep 2016

Mandelbrot, B. B., 1983, The Fractal Geometry of Nature, Freeman.

Ponnapalli, V. A. Sankar., Jayasree, P. V. Y., Fractal Array Antennas and Applications; http://dx.doi.org/10.5772/intechopen.74729.

Rioja, M., Radio Astronomy-VLBI Technique, International Centre for Radio Astronomy Research.

Walker, D., et al, 2022, The Ultraviolet Follow-on Observatory (UFO), Proceedings of the AAVSO 111th Annual Meeting.

Wikipedia: Software Defined Radios

Yang, X. et al., Fractal Antenna Elements and Arrays, Applied Microwave and Wireless.