Efficient Transmission Antenna Designs for Long-Range Sounding Rockets

Mei Qi Tang

McGill University

Abstract

Due to unreliable communications, notably inefficient antennas, the McGill Rocket Team has been unable to recover their 30 000 feet altitude sounding rockets for the past three Spaceport America Cup competitions. With the goal of helping the team recover future rockets, three efficient antenna designs were evaluated with respect to their radiation pattern, beamwidth, and peak gain. These performance parameters were analyzed in the context of high-altitude sounding rocket flight environment and dynamics. Each with great potential for enabling reliable long-range communications, the solutions reviewed in this paper are the dipole antenna, the microstrip patch array, and the beamforming phased dipole array. Despite the first two solutions' simplicity and low cost, the third solution exhibits exceptional efficiency due to its adaptive electronic beamsteering capability. More precisely, the beamforming phased array antenna can redirect its radiation beam to track the ground-station, which is the most optimal solution for long-range sounding rocket communications.

Keywords: long-range radio communications, sounding rocket antennas, dipole, microstrip patch, beamforming phased array

Word count: 151

Introduction

Founded five years ago in 2014, the McGill Rocket Team (MRT) participates annually at the Spaceport America Cup (SAC), as part of the Intercollegiate Rocket Engineering Competition (IREC). The competition takes place in the New Mexico desert, with over 120 teams attempting to launch sounding rockets in a few possible categories, aiming at an altitude of either 10 000 ft or 30 000 ft. Since sounding rockets are designed to perform sub-orbital scientific experiments, an important characteristic is the recoverability of both the rocket and the payload. Unfortunately, the MRT has yet to successfully recover, after their 30 000 ft flights, by maintaining a reliable communication link between the rocket transmitter and the ground-station receiver.

Even though there are many potential causes for losing communication, the choice of inefficient transmission antennas is concluded to be a main contributor. To maximize the recoverability of the MRT’s 30 000 ft rocket for SAC 2020, potential antenna solutions, such as the single-element dipole, the 3-element microstrip patch array, and the 2-element beamforming phased dipole array, will be analyzed. Despite its greater complexity and costs, the beamforming phased array is the most efficient design for long-range sounding rockets. The efficiency of these antenna designs is evaluated with respect to their performance parameters, such as radiation pattern, beamwidth, and peak gain.

Background

For the previous SAC 2019 rocket, the MRT employed two omnidirectional patch antennas mounted next to each other on the inside of the airframe. The team hypothesizes that the two antennas interfered with each other since they were not designed to be next to other radiating sources. Hence, last year’s design did not achieve optimal radiation efficiency due to interference. However, it is important to understand the design requirements about long-range communications before exploring any designs for the upcoming SAC 2020.

Assuming a fixed choice of radios, the link budget needs to be calculated to set performance requirements on the antennas. The link budget quantifies a communication link's performance by adding all the gains and subtracting all the losses present in a system. Other than gains and losses, there are parameters such as the Link Margin (LM) and the Free Space Path Loss (FSPL), representing a safety margin allocated to the system and the signal's attenuation through free space, respectively (Chelstowski, Dobrzyniewicz, Kant, & Michalski, 2018). Calculating based on SAC 2019's telemetry system where the transmitter radio had 30 dBm transmit power, the receiver radio had -100 dBm sensitivity, the ground-station receiver antenna had 10 dBi gain, the FSPL was 115 dB for 915MHz radio waves travelling 15 km (Pasternack Entreprises), and the allocated link margin was 20 dB, the transmission antenna's gain needs to be at least -3 dBi for a reliable communication link (Equation 1):

$$-100\ dBm = 30\ dBm + G_T - 115\ dBm + 10\ dBi - 20\ dBm - 2\ dB \qquad (1)$$

$$G_T = -3\ dBi$$

This gain requirement will be used later in the peak gain comparison.

The first potentially efficient solution is to use a single dipole antenna, vertically mounted, in the center of the rocket. A dipole is composed of two radiating elements that are joined together by a single feed line in the center, as illustrated in Figure 1 below. Dipoles are the most commonly used omnidirectional antennas for lower frequencies bands such as the megahertz frequencies that we operate in (Varma & Anjaneyulu, 2020).

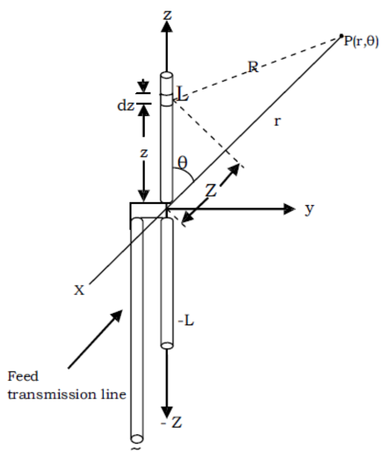

Figure 1. General geometry of a dipole antenna

(Varma & Anjaneyulu, 2020)

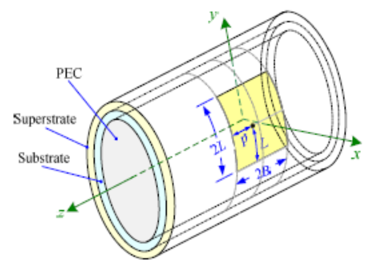

Figure 2. General geometry of a microstrip antenna

(Filho, Tinoco-S, Nascimento, & da S Lacava, 2013)

The second solution is to design an array composed of three identical microstrip patch antenna elements shown by above Figure 2 (Filho, Tinoco-S, Nascimento, & da S Lacava, 2013). The microstrip patch antenna is a more modern invention where its design facilitates the integration with Printed Circuit Boards (PCB) (Chen, 2005). This antenna consists of two thin metallic surfaces on both sides of a dielectric substrate of certain thickness. The antenna can be fed by a microstrip feed line on one of its edges. An antenna array involves the usage of more two or more identical antenna elements to superpose each antenna's individual radiation contribution. Each antenna will radiate waves in either constructive or destructive ways to create a new radiation behavior. Therefore, the solution is to design a three-element microstrip patch circular array, which consists of three patch antennas circularly equidistant from each other, fed by a same signal source equally split three ways. (Ribeiro Filho, Tinoco-S, Nascimento, & Da Lacava, 2017).

The third solution is to design a beamforming phased dipole array antenna. Enhancing the first solution a step forward, this solution creates a 2-element array with two identical dipole antennas while combining it with beamforming technology. A beamformer circuit will be inducing phase delays to the signal waveform for one of the antenna elements, electrically steering the radiation beam to a desired direction, which is also called beamsteering. The steering angle is denoted by ϕ in Figure 3. The beamformer circuitry also includes a Radio Frequency (RF) switch for turning the beamsteering functionality on and off (Liberti & Rappaport, 1999) according to the rocket's real-time point in flight.

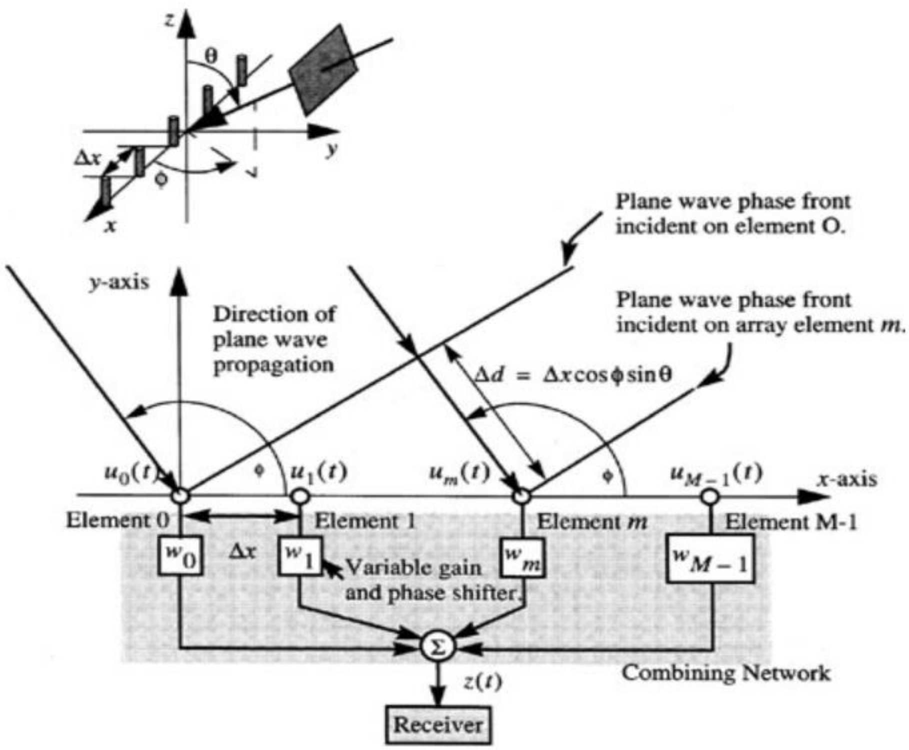

Figure 3. Architectural model of a linear equally spaced array oriented along the x-axis, receiving a plane wave from direction (θ, ϕ).

(Liberti & Rappaport, 1999)

The efficiency of the transmission antennas will be analyzed over three performance parameters, notably their radiation pattern, beamwidth, and peak gain. First, the radiation pattern is 3-dimensional polar plot that defines the variation of power, in decibels (dB), radiated by an antenna as a function of the angle (°). The radiation pattern plot allows the interpretation of an antenna's directivity. Second, the beamwidth, also referred as the half-power beamwidth, is the angle between the two half-power (-3 dB) points of a main radiation lobe. The beamwidth can be measured from a horizontal or vertical 2-dimensional radiation pattern polar plot. Lastly, an antenna's gain, also referred as its power gain, describes an antenna's ability to convert input power into radiating radio waves for a specific direction. The peak gain is hence the overall maximum gain value of an antenna. It is an important component of the link budget equation when determining whether a communication link is reliable.

Analysis

Radiation Pattern

First, the radiation pattern is analyzed for each of the potential antenna designs to evaluate the efficiency of the link coverage. The dipole antenna exhibits the most commonly seen "donut shaped" or toroidal radiation pattern, illustrated in Figure 4 (Balanis, 2016).

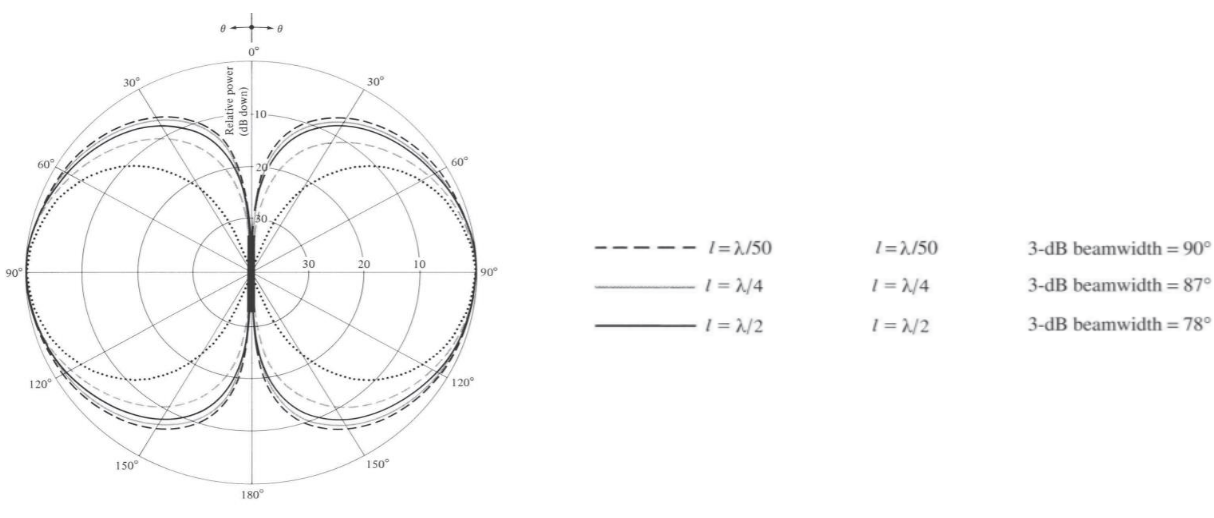

Figure 4. Vertical plane radiation pattern of a dipole antenna for $l = {}^{\lambda}/_{2}, {}^{\lambda}/_{4}, {}^{\lambda}/_{50}$

(Balanis, 2016)

If the dipole is vertically positioned, the radiation pattern would then be omnidirectional on the horizontal plane, with maximum radiation, but have minimal radiation directly overhead of the antenna, along its vertical axis. The dipole's toroidal radiation pattern shows that strongest transmission happens at the beginning and the end of flight, but the signal weakens significantly during apogee or at the highest altitude point of flight.

The 3-element microstrip patch array along the rocket's circumference is depicted, in Figures 5 (green curve) and 6, to have a triangular radiation pattern on the horizontal plane, with maximum radiation gains happening in front of each patch element (Filho et al., 2013). Looking at the vertical plane, the radiation pattern is however somewhat omnidirectional, which indicates a wide overall coverage. This low-directivity radiation pattern indicates that the signal received will have little power variations regardless of the rocket's point in flight, unlike the dipole antenna.

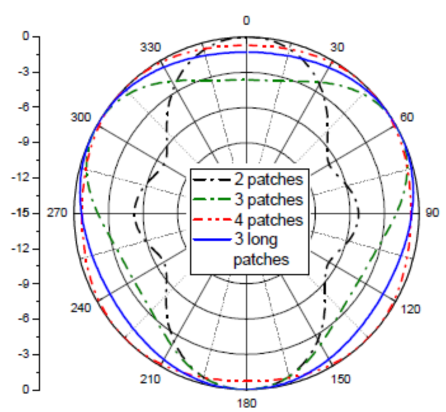

Figure 5. Horizontal plane radiation pattern of 3-element microstrip patch array (Filho et al., 2013)

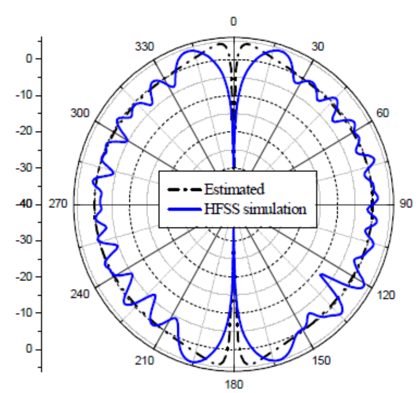

Figure 6. Vertical plane radiation pattern of 3-element microstrip patch array (Filho et al., 2013)

Lastly, the 2-element beamforming phased dipole array antenna, when the beamsteering functionality is switched off, behaves like a simple 2-element dipole array, where the radiation pattern is toroidal like that of a dipole, except with narrower beams, demonstrating more directivity. Figures 7 and 8 show an example of the beam narrowing from a 64-element beamforming array (Jaros & Beran, 2019). When the beamforming network switches on the phase shifting electronics, the beam steers to a pre-programmed desired angle (Jagadesh & Rani, 2016). The ability to adapt the radiation pattern's directivity depending on the point in flight avoids the issue of having weak radiation when the rocket is at apogee, as in the case of a dipole antenna. After comparing the radiation pattern of all three designs, the beamforming antenna is demonstrated to be of greater efficiency since the radiating beam can redirect itself towards the ground-station. This adaptive capability will ensure a strong communication link throughout the full duration of flight.

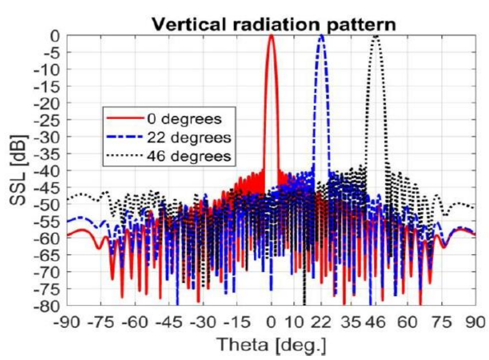

Figure 7. 2-dimensional vertical plane radiation pattern of single array element

(Jaros & Beran, 2019)

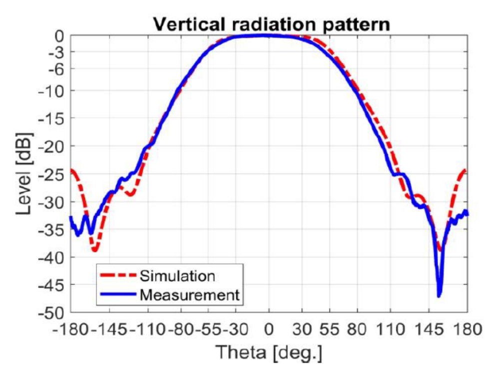

Figure 8. 2-dimensional vertical plane radiation pattern of 64-element array with beamsteering

(Jaros & Beran, 2019)

Beamwidth

Second, the beamwidth is analyzed to evaluate the radiation efficiency with respect to directivity. From the same Figure 4 shown previously, a dipole antenna typically exhibits a vertical beamwidth of 78° and a horizontal beamwidth of 360° due to its omnidirectionality (Balanis, 2016). On the other hand, if we measure from the same Figures 5 and 6 shown previously, the 3-element microstrip patch array show a vertical beamwidth of about 167° and a horizontal beamwidth of 86°. The patch array's greater vertical beam coverage, in comparison to the dipole, solves the issue of weak transmission when the rocket is at apogee, which suggests greater efficiency.

Furthermore in contrast with the dipole, the beamforming array antenna's vertical beamwidth is 32°, as shown in Figure 9 (Chang, 2015), which is less than half of the dipole's. This signifies that the signal weakens more than twice as early on. However, since the beamformer can switch on its beamsteering mode before the signal begins to weaken, this would not be an issue. The beaming angle, instead, follows the ground-station's direction as the rocket flies vertically. In conclusion, the microstrip patch array is a good choice as a non-adaptive solution due to its wider overall beam coverage. However, the beamforming dipole array is nevertheless the more efficient option since it adaptively steers its beam to maintain a strong signal throughout flight despite its narrower beamwidth.

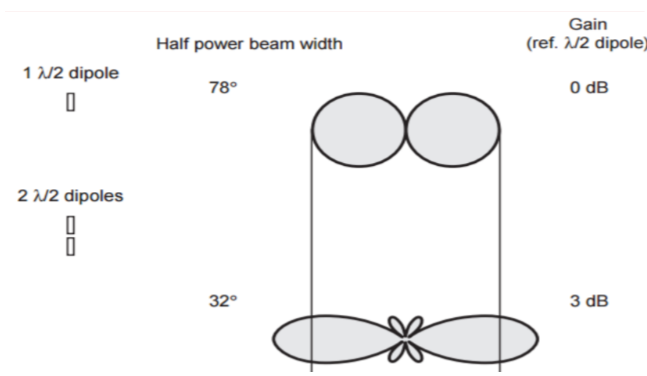

Figure 9. Comparison of single element dipole array with 2-element beamforming dipole array

(Chang, 2015)

Peak Gain

Lastly, the peak gain is analyzed to get an idea of the maximum possible gain value the communication link can experience, evaluating the link budget with the most optimal situation. The dipole's peak gain is typically 0°, the microstrip patch array is 4 dB, measured from Figures 7 and 8, and the beamforming dipole array is around 3dB from Figure 9 shown previously. All these gain values are greater than the previously calculated minimum gain requirement of -3 dB with Equation 1, which concludes that all these designs meet the minimum efficiency requirement. The most optimal link budget will be achieved with the microstrip patch array, with the lowest receivable signal power at -93 dB, providing an extra 7 dB in the link budget. The beamforming array provides only 1 dB less than the microstrip patch array, adding 6 dB, which suggests that both would be a good design choice.

Conclusion

In conclusion, the 2-element beamforming phased dipole array is demonstrated to be the most optimal design in ensuring a reliable communication link for 30 000 ft sounding rocket flights. Compared to the single-element dipole or the 3-element microstrip patch array, the beamforming antenna is the most adaptive, hence efficient, solution for a moving target with unpredictable directionality like a rocket. In fact, its radiation pattern provides an omnidirectional coverage, its narrower beamwidth is not an issue due to its steerable beam, and its peak gain provides an extra 6 dB to the overall link budget. However, the beamforming antenna will need to be custom designed, manufactured, and thoroughly tested before flight. Implementing this solution for this year's SAC might be a challenge. Therefore, the dipole or the microstrip patch array would still temporarily be efficient solutions if limited by time or budget.

References

Balanis, C. A. (2016). Antenna Theory - Analysis and Design (4th Edition). In: John Wiley & Sons.

Chang, P.-C. (2015). LTE introduction part1. Retrieved from https://www.slideshare.net/peichechang/lte-introduction-part1?qid=d91c6365-08f3-4bb7-8507-e0edcef4ff8c&v=&b=&from_search=1

Chelstowski, T., Dobrzyniewicz, K., Kant, P., & Michalski, J. J. (2018). *Long range radio location system employing autonomous tracking for sounding rocket.* Paper presented at the 2018 22nd International Microwave and Radar Conference (MIKON), 14-17 May 2018, Piscataway, NJ, USA.

Chen, W.-K. (2005). Antenna Elements. In *The Electrical Engineering Handbook* (pp. 569-578). Retrieved from https://doi.org/10.1016/B978-012170960-0/50043-8

Filho, P. C. R., Tinoco-S, A. F., Nascimento, D. C., & da S Lacava, J. C. (2013). *Flush-mounted telemetry antenna design for a sounding rocket competition.* Paper presented at the 2013 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, 7-13 July 2013, Piscataway, NJ, USA.

Jagadesh, T., & Rani, B. S. (2016). *Actualization of a phased array antenna utilizing digital beamforming.* Paper presented at the 2016 International Conference on Control, Instrumentation, Communication and Computational Technologies (ICCICCT), 16-17 Dec. 2016, Piscataway, NJ, USA.

Jaros, O., & Beran, L. (2019). *Design of an Electronically Steered Antenna Array in the X band.* Paper presented at the 2019 Conference on Microwave Techniques (COMITE), 16-18 April 2019, Piscataway, NJ, USA.

Liberti, J. C., & Rappaport, T. S. (1999). *Smart antennas for wireless communications : IS-95 and third generation CDMA applications*. Upper Saddle River, NJ: Prentice Hall PTR.

Pasternack Entreprises. Free Space Path Loss Calculator. Retrieved from https://www.pasternack.com/t-calculator-fspl.aspx

Ribeiro Filho, P. C., Tinoco-S, A. F., Nascimento, D. C., & Da Lacava, J. C. S. (2017). A Telemetry Antenna Design for a Sounding Rocket Competition. *IEEE Antennas and Propagation Magazine, 59*(3), 100-140. doi:10.1109/MAP.2017.2686096

Varma, T. A. N. S. N., & Anjaneyulu, G. (2020). *Design of Uniform Linear Practical Antenna Arrays for Ultralow*. Paper presented at the Optical and Wireless Technologies. OWT 2018, 10-11 Feb. 2018, Singapore, Singapore.