Turnstile antenna design and feeding study

AcubeSAT-COM-BH-028

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Contents

Changelog

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1 Introduction

AcubeSAT is going to use the UHF band when it comes to telemetry and telecommands (TT&C), which is commonly used in CubeSat missions for the same purpose. In launchers' interior we must have the predicted dimensions for our 3U CubeSat and at the same time our antenna (which I m going to present to you later in this report) because it occupies a lot of space. So, there is a need to deploy it because the existence of mechanical part protrusion is forbidden. Our deployment system will be approximately the same with UPSat's.

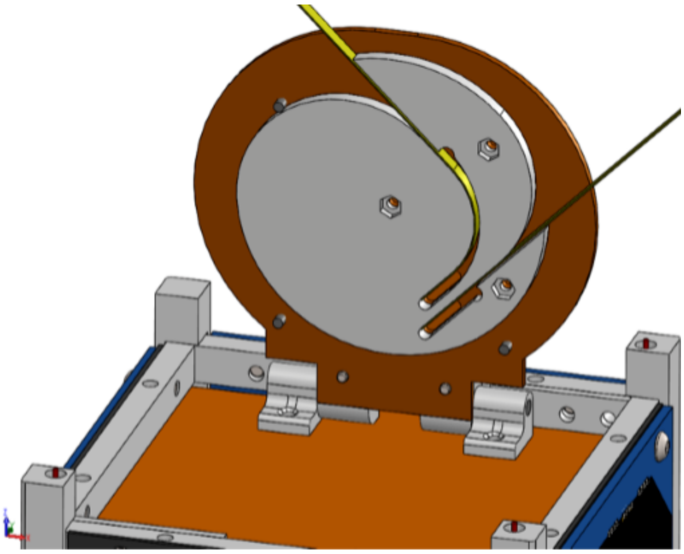

***Figure 1**: UPSat's deployment system*

We were interested in using an omnidirectional antenna which can provide circular polarization so that we do not have that much polarization losses (the enormous distance of our link imposes it). The deployment system above gives us the capability to use two monopole antennas. So, the idea is to examine if we could combine two monopoles in a way that will make them operate-radiate as a turnstile antenna. The turnstile antenna is a combination of two orthogonal dipoles fed with equal amplitudes and quadrature phase and this antenna is capable of producing circularly polarized field in the direction normal to the dipoles' plane (0^o and -90^o for Right Handed Circular polarization, called RHC). Let's say that the dipoles are along the x- and y- axes. The combination radiates Left Handed Circular polarization in the –z direction. The existence of a ground plane changes the sense of circular polarization of the wave radiated in the –z direction and adds to the direct radiated wave (+z direction).

2 Theory background

2.1 Boundary Conditions

Suppose that we have a locally plane boundary in space described by a point and a unit normal vector $\vec{n}$ that points from region 1 (ϵ_1,μ_1,σ_1) to region 2 (ϵ_2,μ_2,σ_2). We compute the tangential fields from the vector product of the fields and the normal vector. The fields can be discontinuous at the interface between the two regions if surface electric current J_s or charge densities exist on the surface. The boundary conditions are:

$$\vec{\mathbf{n}} \cdot (\vec{\mathbf{D}}_2 - \vec{\mathbf{D}}_1) = \rho_s \tag{1}$$

$$\vec{\mathbf{n}} \cdot (\vec{\mathbf{B}}_2 - \vec{\mathbf{B}}_1) = 0 \tag{2}$$

$$\vec{\mathbf{n}} \times (\vec{\mathbf{E}}_2 - \vec{\mathbf{E}}_1) = \vec{\mathbf{0}} \tag{3}$$

$$\vec{\mathbf{n}} \times (\vec{\mathbf{H}}_2 - \vec{\mathbf{H}}_1) = \vec{\mathbf{J}_s} \tag{4}$$

There is a very convenient surface. We use it to reduce analysis effort by using planes of symmetry and it is called Perfect Electric Conductor (PEC). A PEC surface causes the fields to vanish inside and to have electric currents induced on it:

$$D_n = \rho_s \tag{5}$$

$$B_n = 0 \tag{6}$$

$$E_t = 0 \tag{7}$$

$$\vec{\mathbf{n}} \times \vec{\mathbf{H}} = \vec{\mathbf{J}_s} \tag{8}$$

A PEC surface is also called an electric wall.

2.2 Image Theory

This method is about creating an equivalent problem in order to analyze the electromagnetic field of a current distribution which is near a PEC. The current distribution induces surface currents on it, which have effects on radiation. But these currents are such that the PEC condition is fulfilled ($E_t = 0$). It can be proved that $E_t = 0$ happens if we assume that there is an image current element into the PEC and its distance from the surface is equal to the actual current's distance from it. The final solution (for the area above the surface) will be the superposition of the radiation which is caused by the real current and its image.

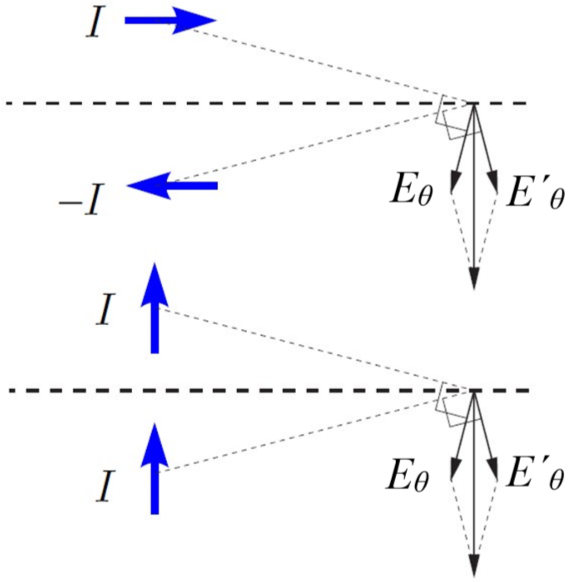

***Figure 2**: Image elements*

2.3 Monopole antenna

A monopole consists of a single conductor fed out of a ground plane from the center conductor of a coax. With its image, a monopole equates to a dipole. The fields vanish below the ground plane. By restricting the field to the upper hemisphere the gain is doubled (in comparison to a dipole's gain), since only half the input power of the dipole is needed to produce the same field strength. For the same current, the transmitted power is half. Therefore, the impedance of the monopole is half the impedance of the dipole. Last but not least, the directivity remains the same because for the same current, we have the same maximum power density (horizontal plane) and the same average power density because we have half transmitting power (half volume-upper hemisphere).

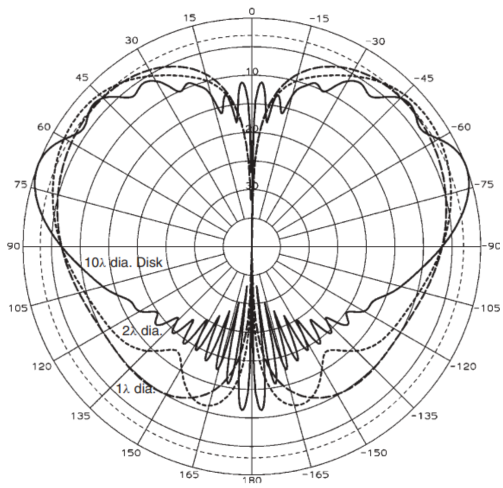

***Figure 3**: A $\frac{\lambda}{4}$ monopole located on 1λ-, 2λ-, and 10λ-diameter disk ground planes.*

Figure 3 shows the pattern of a monopole when placed on 1λ-, 2λ-, and 10λ-diameter circular ground planes. The back radiation can be reduced by placing the monopole over a ground plane with circular corrugations that forms a soft surface at the edge when the corrugations are slightly deeper than $\frac{\lambda}{4}$. When the corrugations are less than $\frac{\lambda}{4}$, the ground plane can support surface waves.

2.4 Sleeve monopoles

The sleeve monopole antenna consists of a coaxial cable which extends for some length above the ground plane (perpendicularly) and has the outer conductor and the dielectric filling removed when we are higher than that length. An important practical advantage of the sleeve antenna is that the coaxial line is contained within the structure, which can be used as a means of feeding the antenna. However, utilization of this type of feed requires the decoupling of the feed line exiting the antenna from the antenna itself. By placing a sleeve around a monopole we actually move the virtual feed point of the monopole higher.

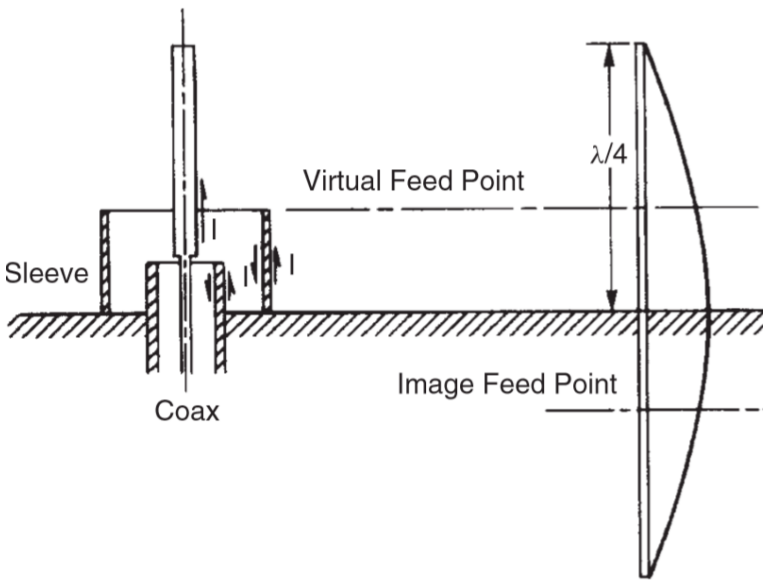

Figure 4*: Sleeve monopole and current distribution*

The sleeve shields radiation from the internal currents while the currents on the outside of the sleeve radiate. The radiation pattern is approximately the same with that of a classic monopole. The addition of a sleeve to a monopole can increase the bandwidth up to more than an octave because the current at the feed point is approximately constant over a wide band and fine-tune the input impedance.

Rispin and Chang in [2] introduced a simple thin-wire analysis for sleeve antennas as well as other wire antennas by constructing the standing wave current on the antenna surface. According to their research we get the following diagrams for input impedance:

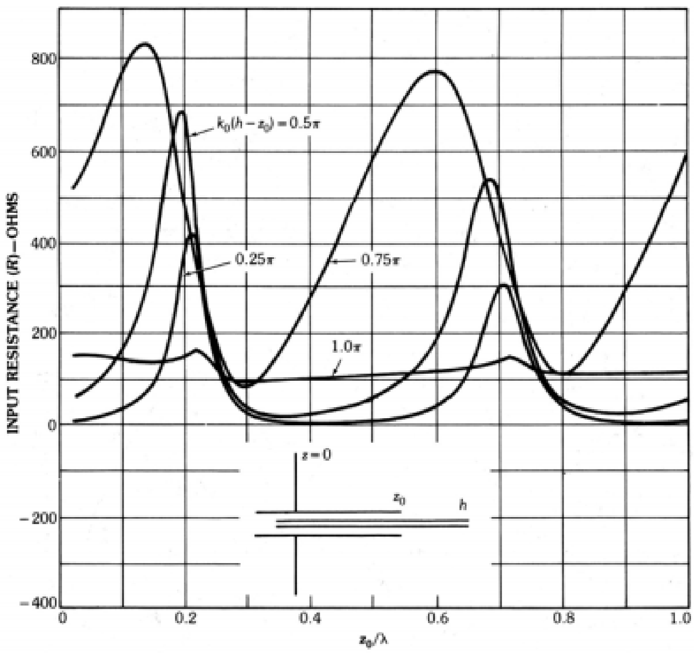

Figure 5*: Input resistance of a monopole sleeve antenna.*

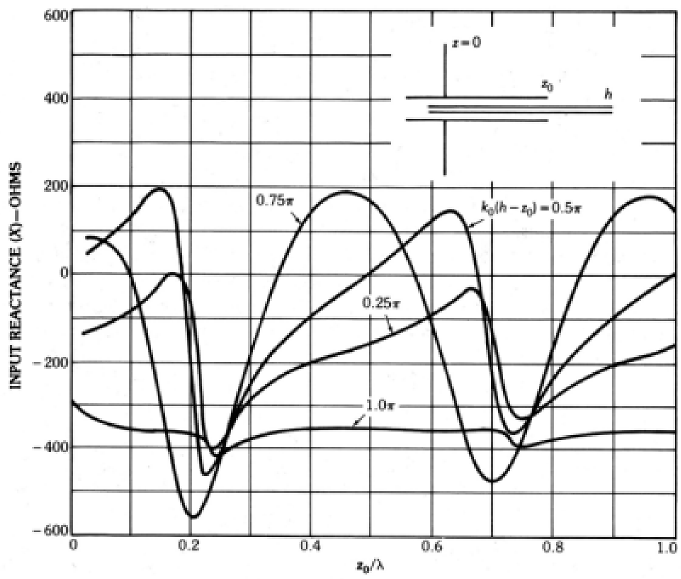

Figure 6*: Input reactance of a monopole sleeve antenna.*

2.5 Turnstile antenna

In addition to the theory presented in introduction, Figure 7 shows the basic geometry of a single turnstile antenna. It consists of a set of two half-wavelength dipoles aligned at right angles with respect to each other. The currents on the dipoles have equal magnitude and are in-phase quadrature. Consequently, the turnstile antenna is often referred to as a crossed dipole antenna.

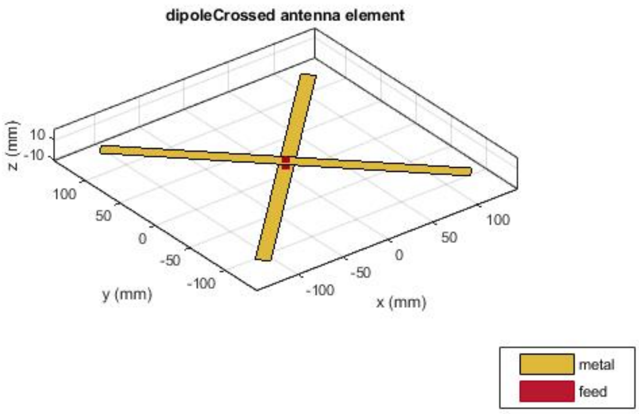

***Figure 7**: Turnstile antenna*

It has a near isotropic radiation pattern Figure 8, i.e., it is linearly polarized with a circularly symmetrical profile in the horizontal plane (x-y plane) and circularly polarized radiation in the $\pm$z directions. The front side radiates left-hand circular polarization (LHC), while the back side radiates right-hand circular polarization (RHC).

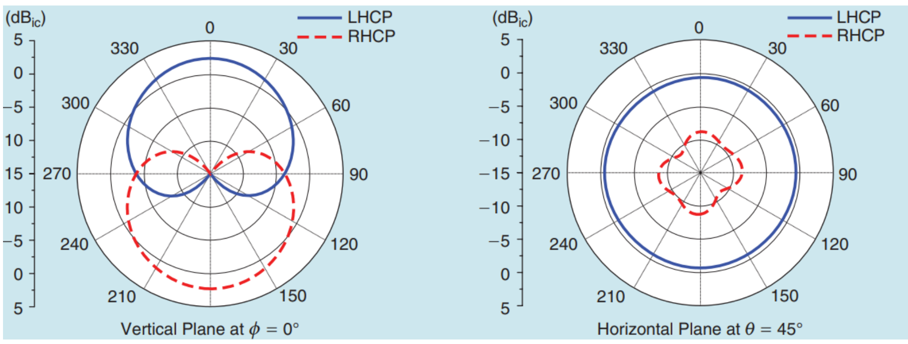

***Figure 8**: Radiation patterns*

Below I present turnstile's radiation pattern via MATLAB. In order to achieve circular polarization, the turnstile antenna has either an external quadrature hybrid as a 90 degree power divider/combiner or an internal built-in phase shifting network. In this example, the antenna is designed for 435 MHz. The spacing between the two crossed dipoles is of the order of $\frac{\lambda}{50}$. The turnstile antenna is created by using two identical dipoles oriented at right angles to each other.The default crossed dipole catalog element is rotated by 90 degrees to set it up in the x-y plane. The desired 90 degree phase shift is obtained by specifying the phase shift of the second dipole to 90 degree.

```
freq    = 435e6;
lambda  = 3e8/freq;
offset  = lambda/50;
spacing = lambda/2;
length  = lambda/2.1;
width   = lambda/50;
anglevar= 0:10:180;
```

```
freqrange = 200e6:2e6:400e6;
gndspacing = lambda/4;
d  = dipole('Length',length,'Width',width);
ant= dipoleCrossed('Element',d,'Tilt',90,'TiltAxis',[0 1 0]);
pattern(ant, freq);
```

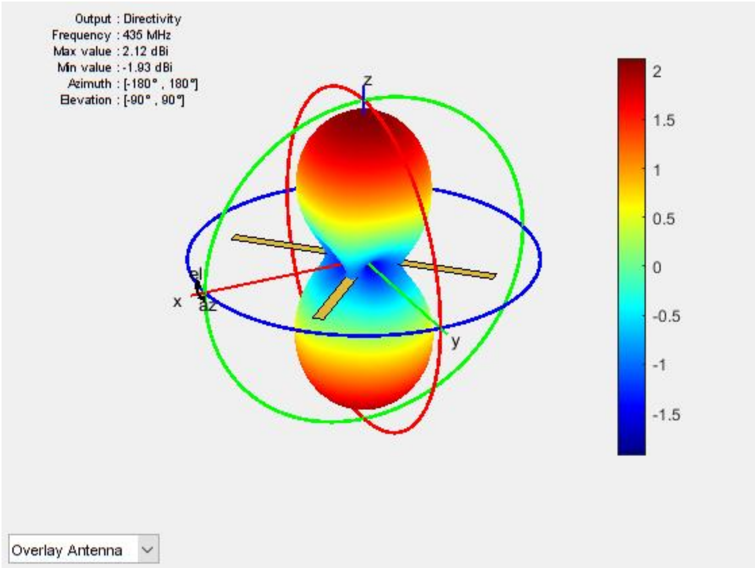

***Figure 9**: Radiation patterns*

3 Antenna design

In this section, I am going to present a possible solution for the turnstile's design problem.

3.1 Monopole design

Coaxial antennas extend along a straight line and can have multiple radii, so they can be placed in confined spaces like our deployment system. With this type of antenna we can avoid baluns (balanced to unbalanced adapter) because it is naturally adapted to a coaxial input connection. [3] presents different type of coaxial antennas which are modelled in a high frequency structure simulator (HFSS), constructed and measured. From the four different types the most interesting one is "antenna 3", which is a coaxial antenna with a $\frac{\lambda}{4}$ choke sleeve:

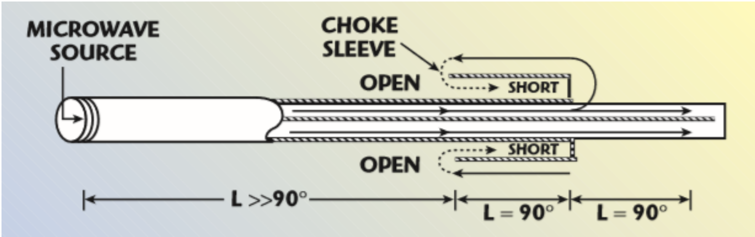

***Figure 10**: Diagram of antenna 3 with a $\lambda/4$ choke sleeve.*

In the figure above 90^o refers to the electrical length. By that we mean that the physical length is $\frac{\lambda}{4}$:

$$\beta \cdot l = \frac{\pi}{2} \Longleftrightarrow l = \frac{(\frac{\pi}{2})}{\beta} \Longleftrightarrow l = \frac{(\frac{\pi}{2})}{(\frac{2 \cdot \pi}{\lambda})} \Longleftrightarrow l = \frac{\lambda}{4}.$$

Due to the shorted end of the choke sleeve, an open circuit is presented to a signal that would go toward the source along the choke sleeve. As a result, the radiating source is restricted to the half-wavelength region between the open end of the choke sleeve and the extended inner conductor end of the coaxial line. From the end of the coaxial line, part of the wave radiates outward from the extended inner conductor, and another part radiates from the quarter-wavelength choke sleeve section that presents an open circuit on the end.

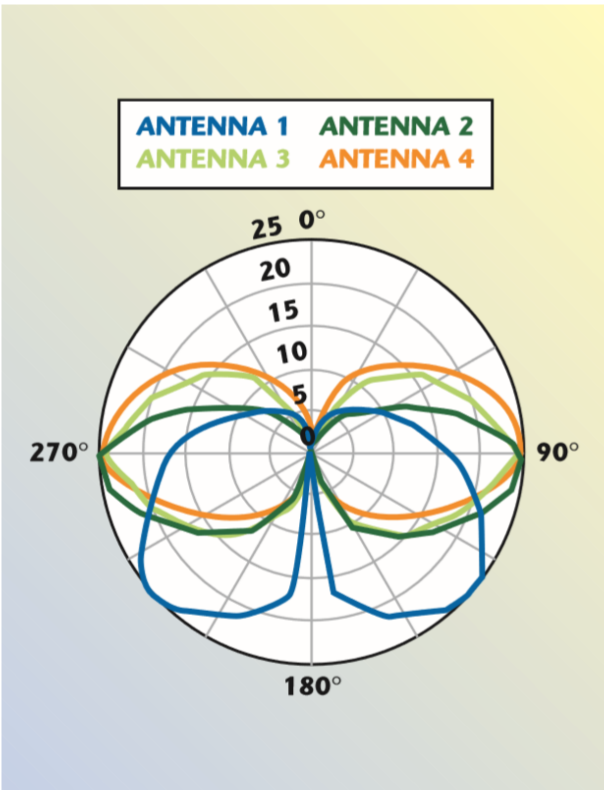

***Figure 11**: Measured far-field radiation pattern for all coaxial antennas.*

We care about the far-field because the distance between the CubeSat and our ground station is enormous. The simulation presented above (we only care about antenna 3) shows us the radiation pattern is tilted slightly upward, so that maximum directivity occurs at $\theta = 90^o$. This upward tilt is probably due to the necessarily larger radius of the choke sleeve fitted around the outer conductor.

Figure 12 shows the simulated input reactance and resistance of a two-wire $\frac{\lambda}{2}$ dipole, a quarter-wavelength spaced back-gap and a choke-sleeve antenna. Of the three, the choke-sleeve antenna (the one that we are interested in) appears to be most promising for additional optimization since the reactance remains near zero and the radiation resistance remains constant over a range of frequencies above and below where $2L = \lambda$. This implies that this antenna could be impedance matched to a 50 Ω source over a broad range of frequencies.

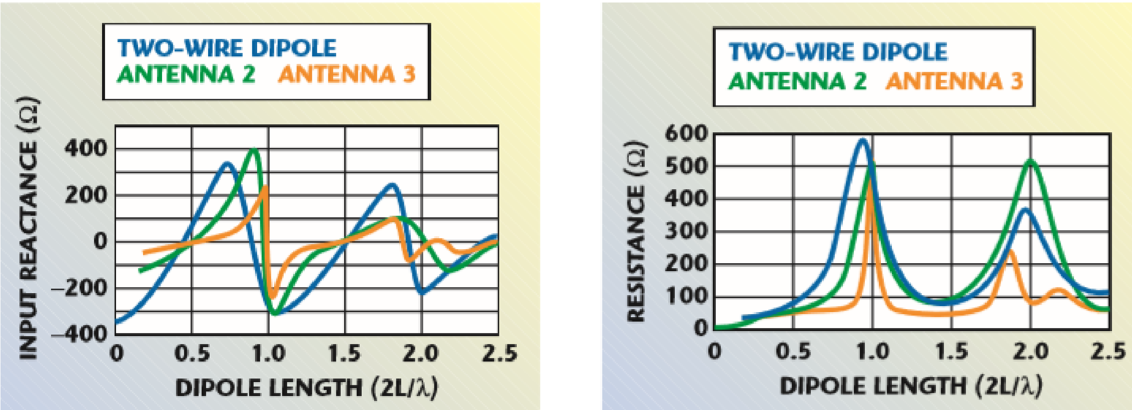

Figure 12: *Simulated input impedance of a two-wire dipole antenna and antennas 2 and 3.*

A problem with that solution is the "great" wavelength at the UHF band which we are going to use (435-438 MHz). For example if we have $\lambda = 688mm$ ($f = \frac{c}{\lambda} \approx 435.75MHz$), then $\frac{\lambda}{4} = 17.2cm$ which is large for our $10cmx10cm$ area. That might lead us to redesign the spool (white part in Figure 1) of the deployment system or maybe we could model it with shorter choke sleeve and see if this scenario is suitable to our case.

3.2 Turnstile design

Now that we have shown the type of monopole presented above behaves like a $\frac{\lambda}{2}$ dipole we can proceed to the turnstile's design. The idea is that we combine two monopoles of that kind in a way that they function as a turnstile antenna together. Turnstile antenna is a combination of two **orthogonal** dipoles fed with equal amplitudes and **quadrature** phase. So, a proper combination of the monopoles might be suitable for us. The monopoles act like two dipoles, so being perpendicular to each other equals a crossed dipole structure (turnstile).

The next step is to feed them with quadrature phase. Obviously, we will feed each monopole with different cables. The problem of quadrature phase feeding can be easily solved if one of the cables is larger than the other by $\frac{\lambda}{4}$ (physical length). In this way the signal will have a phase difference of $\frac{\pi}{2}$ (electrical length). Of course this might be difficult because a 17.2 cm length difference is too much, especially if we take into consideration the monopoles' structure. Another idea is to use a quadrature hybrid equal-amplitude power divider to feed the two monopoles, which is much easier.

For a dipole length of $\frac{2L}{\lambda} = 0.5$ input's reactance is near zero and resistance seems to be close to 50 Ω. It seems that both monopoles can be impedance matched to 50 Ω. In order to do that we have to know the exact input impedance of each monopole. Then, each antenna's matching is a problem that can be solved by using a variable capacitor or inductor and some extra transmission line length.

References

[1] THOMAS A. MILLIGAN, "MODERN ANTENNA DESIGN" Second Edition, A JOHN WILEY & SONS, INC., PUBLICATION

[2] LW Rispin, DC Chang, "Wire and Loop Antennas"

[3] BRIAN DROZD AND WILLIAM T. JOINES, "COMPARISON OF COAXIAL DIPOLE ANTENNAS FOR APPLICATIONS IN THE NEAR-FIELD AND FAR-FIELD REGIONS", Duke University Durham, NC