Astronomical Antenna for a Space Based Low Frequency Radio Telescope

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ABSTRACT

The Orbiting Low Frequency Antennas for Radio Astronomy (OLFAR) project is investigating an orbiting low frequency radio telescope. Due to strong ionospheric interference and Radio Frequency Interference (RFI) found at frequencies below 30 MHz, such an instrument is not feasible on Earth, hence the proposed solution of a swarm of autonomous nano-satellites sent to a remote location in space. On each satellite, the astronomical antenna consists of three orthogonal dipoles designed to work within the constraints of a nano-satellite. Due to mechanical constraints, the dipoles are not optimally integrated into the nano-satellites from an antenna point of view. Therefore, the effect of the finite non uniform ground plane, the non symmetrical antenna deployment, and the non infinitesimal dipole gap on the antenna properties need to be investigated. Unfortunately, the operational band of 0.3 MHz to 30 MHz and the dimensions of the astronomical antenna of just under 5.0 m prohibit tests within the controlled environment of an anechoic chamber; ergo, a scale model is required. This work describes the design, simulation and measurement of such a scale model.

INTRODUCTION

Low frequency telescopes [1, 2, 3] can achieve excellent results down to approximately 20 MHz, but for observations in lower frequencies these telescopes face severe ionospheric distortions and complete reflection of radio waves as wavelengths become longer. Even in orbit around the Earth, man made interference and radio emissions from the Earth’s aurora make radio astronomy impractical. To achieve excellent results in frequencies lower than 30 MHz, a telescope must be sent far from the Earth and preferable to a location that provides shielding from the Earth, such as behind the Moon.

Only two missions dedicated to low frequency observations have ever been launched; the Radio Astronomy Explorer (RAE) A in 1968 [4] and the RAE B in 1973 [5]. The RAE B mission is of particular interest because it was launched into lunar orbit, whereby it performed measurements shielded from Radio Frequency Interference (RFI) from the Earth by the Moon. However, a spacecraft with only a single antenna, even one capable of extending to 457 m like in RAE A, is unable to provide the necessary spatial resolution required by radio astronomy at low frequencies.

Advances in technology have resulted in the reduction in size, mass and cost of spacecraft, allowing for the development of distributed space missions capable of creating large instruments through the use of aperture synthesis. The Orbiting Low Frequency Antennas for Radio Astronomy (OLFAR) project [6] will bring this concept into the field of low frequency astronomy, a domain that has been largely ignored due to technical challenges involved. The scientific drivers include the exploration of the early cosmos during the dark ages, the discovery of planetary and solar bursts in other solar systems, and the tomographic mapping of the interstellar medium [7].

The OLFAR telescope will consist of a swarm of around 50 identical nano satellites sent to a location that allows for unperturbed low frequency measurements. The satellites will be identical and autonomous, and together the swarm will be spread over a virtual sphere with a diameter of 100 km functioning as a single instrument [8]. The nano satellites will be custom built to carry out the scientific mission. Using novel communication links [9], the signal processing will be distributed among the swarm [10],
resulting in an instrument that can tolerate the failure of a number of its nodes [11].

Conventional radio telescopes on Earth only require two orthogonal detectors to record the incoming astronomical signals, as the Field of View (FoV) of the telescope is focused by a reflector and the orientation of the telescope is controlled by a rotor mechanism. Therefore, the direction of incidence of the incoming astronomical signals is normal to the detector, with all of the information contain in the plane orthogonal to the detector. However, OLFAR requires three orthogonal detectors, as the direction of incidence of the incoming astronomical signals is not known a priori. As a result, the astronomical antenna consists of three pairs of orthogonal monopoles.

Ideally, a satellite would have a cuboid shape with each of the monopoles deployed orthogonally to the satellite from the centre of each side; each pair of monopoles would have nearly identical properties and would result in the purest component signals. In our scenario, the satellites are based on CubeSat platforms with an elongation of one of the dimensions. Also, to simplify the mechanical design, the monopoles are deployed in groups of three at either end of the satellite also resulting in a geometrical offset in the deployment between antipodal monopoles. All of this deteriorates the monopole properties and reduces the purity of the component signals.

While preliminary simulations have been carried out on the antenna system [12], due to the unusual configuration, the accuracy of these simulations must be verified through Radio Frequency (RF) testing. Tests in both the controlled environment of an anechoic chamber as well as an outdoor site are planned for verifying the simulations. Due to the prohibitive size of the anechoic chamber required to measure the Far Field (FF) properties of a 10 m dipole, where the Fraunhofer distance is approximately 20 m, a scaled down model of the astronomical antenna was built. As a result, the operational band of the scale model is equivalently shifted up in frequency.

This paper describes the design, simulation and measurement of the scale model of the astronomical antenna for a space based low frequency radio telescope. The expected results include the coupling factors between the orthogonal monopoles, and the non ideal FF properties due to the finite non uniform ground plane, the non symmetrical antenna deployment, and the non infinitesimal dipole gap. Firstly, an overview of the OLFAR project is given. Secondly, the design of the antenna model built for the measurements is described. Next, the simulations are presented and the measurement setup is described.

**ASTRONOMICAL ANTENNA**

The multi-octave operational band of 0.3 MHz to 30 MHz requires an astronomical antenna in the order of metres to hundreds of metres to efficiently detect astronomical sources. These cannot be mounted on the exterior of the satellite in the form of patch antennas or aperture antennas, due to the dimensions of the satellites being in the order of decimetres. The only available option is to deploy wire antennas from the exterior of the satellite. Due to mechanical restrictions, such as the mass and volume that can be housed within the satellite, the antennas are restricted to lengths in the order of metres.

Short dipoles, dipoles that are much shorter than a wavelength, have the desired antenna pattern shapes of 3 dB beam widths of 90°. However, they are inefficient due to their low radiation resistance. Increasing the length to the order of a wavelength improves the efficiency in increasing the radiation resistance, while maintaining decent antenna pattern shapes with 3 dB beam widths in the order of 75°. Above one wavelength, the antenna patterns start to lose their shape through becoming dominated by side lobes, thereby restricting the dipole lengths to approximately one wavelength.

In our scenario, this restricts the dipoles to 10 m, this being a full wavelength at 30 MHz. However, this is the theoretical limit for an infinitesimally thin dipole, while for a real antenna, depending on the wire radius, side lobes will start to appear at frequencies below 30 MHz. Therefore, the dipoles are chosen to be 9.6 m to shift the theoretical full wavelength resonance to 31 MHz in an attempt to avoid side lobes in the operational band. Due to the varying port impedance over the operational band, the antennas are used as active antennas. An active antenna does not remove energy from the field being measured, but instead acts as an electric field probe.

For optimal performance, the corresponding monopole pairs for each dipole should be deployed opposite each other, sharing two planes, with the minimal feed gap size possible separating them. Also, the three dipole pairs should be orthogonal to each other, sharing the same geometric centre. However, due to mechanical constraints this is not possible. The cramped confines within the satellite
prohibit an electric connection for one of the dipole pairs. Instead, this pair must be electronically coupled, resulting in a pair of pseudo antipodal monopoles mounted on finite ground planes. Also, each dipole pair has a different geometric centre. The resulting astronomical antenna is composed of six monopole antennas deployed in three orthogonal directions, as depicted in Figure 1. Antennas are internally housed during launch, to be deployed when the orbit has been reached. To minimise the volume taken up by the payload within the satellite, the antennas are deployed in groups of three at either end of the satellite. Antipodal pairs C-D and E-F are electrically coupled and pseudo antipodal pair A-B is electronically coupled to form dipole pairs.

The exterior of the satellites is also used to mount the twin deployed solar panel arrays [13], the surface mounted patch antennas for inter satellite communication and Earth downlink, the surface mounted propulsion system, and the surface mounted astronomical source sensors. The satellites themselves are based on the CubeSat platform in the three unit (3U) configuration. Each satellite is an aluminium rectangular structure measuring approximately 10 × 10 × 30 cm housing the electronics.

Each monopole is composed of a copper wire enclosed by an RF transparent structure with a Triangular Rollable And Collapsible (TRAC) [14] cross section (as depicted in Figure 2) to keep the antennas rigid. The diameter of the copper element is set to 0.24 mm, which is twice the skin depth of copper at the lowest frequency of the operational band of 300 kHz. This diameter ensures that the antenna loss resistance will be at a minimum whilst keeping the antenna as thin and as light as possible. Dimensions of the satellite and astronomical antennas are listed in Table 1.

**SCALE MODEL**

In previous work [12], simulations where carried out for an initial antenna configuration. Since then, the placement of the monopoles has changed with the development of the deployment mechanism [15] and so the simulations need to be adapted. Coupled to this, the twin deployed solar panel arrays need to be incorporated into the simulation to determine their influence on the antenna properties. Finally, the deviations of the realised antennas from the theoretically perfect case necessitates thorough measurement results to validate the simulated results.

The optimal test setup is to perform FF measurements in an anechoic chamber. However, the low operational band, the large physical size and the large radius of the Near Field (NF) regions exclude this option. Therefore, either the astronomical antenna is measured at an outdoor FF range or a scale model is measured in an anechoic chamber. In this work, the scale model is the chosen option, due to the controlled environment provided by an anechoic chamber and the reduced manufacturing costs.

In designing a scale model, the controlling parameter is the frequency multiplier $n$ determined from $f' = nf$, which subsequently reduces the physical dimensions and increases the conductivity according to $l' = l/n$ and $s' = ns$, respectively [16]. The multiplier shifts the operational band to a frequency range that is compatible with the anechoic chamber. Also, reduction of the physical dimensions allows the scale model and the radius of the FF region to fit within the dimensions of the chamber. It should be noted however that the smaller the multiplier, the more
representative the model.

The lower limit of the anechoic chamber at the European Space Research and Technology Centre (ESTEC) site in Noordwijk, the Netherlands is approximately 400 MHz. The frequency multiplier of 1333 required to shift the whole operational band is prohibitively large, as it would result in dipoles with lengths of millimetres and satellite with dimensions of micrometres. Therefore, a frequency multiplier of 27 is chosen, in order to be able to measure down to the half wave resonance of the dipoles.

While the twin deployed solar panel arrays are scaled by 27, this is a prohibitively large scaling factor for the physical dimensions of the satellite body, as well as the geometric offsets of the pseudo antipodal dipole pair. Instead, a scaling factor of 12.5 was chosen as a compromise between manufacturability and representativeness. The conductivity and wire diameter should be scaled equivalently, however, obtaining the necessary material is unrealistic so a standard gauge copper wire is used. Dimensions of the scale model seen in figure 3 are listed in table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite Body</td>
<td>$8 \times 8 \times 24$ mm</td>
</tr>
<tr>
<td>Monopole Length</td>
<td>178 mm</td>
</tr>
<tr>
<td>Monopole Wire Diameter</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>Monopole Offset</td>
<td>$1.54 \times 1.29$ mm</td>
</tr>
<tr>
<td>Solar Panel</td>
<td>$17 \times 12.6 \times 1.56$ mm</td>
</tr>
<tr>
<td>Solar Panel Yoke Length</td>
<td>1.63 mm</td>
</tr>
</tbody>
</table>

**Table 2: Scale Model Dimensions**

![Figure 3: Scale Model](image)

**RESULT**

The electrical port parameters of each monopole are measured to derive multiple properties of the astronomical antenna. In measuring the passive port impedances, the feed lines can be designed and the resonant frequencies of the monopoles can be determined. In exciting the monopole under test, its radiation efficiency can be measured. In exciting another monopole, the mutual coupling between these two monopoles can be measured.

The resonant frequencies of the monopoles are determined by measuring the reactance of the monopoles. From the simulations, the monopoles have three resonant frequencies in the band of interest, as depicted in Figure 4. The first, around 420 MHz, is equal to the half wave resonance. The second, around 745 MHz, and the third, around 880 MHz, are either side of the full wave resonance.

![Figure 4: Reactance](image)

**Figure 4: Reactance**

The radiation efficiency of the monopoles is determined by comparing the resistance of the realised monopoles with their ideal versions, thereby removing the loss resistance from the radiation resistance. From the simulations, the monopoles have low radiation efficiencies in the low end of the operational band, with near perfect radiation efficiencies above the half wave resonance, as depicted in Figure 5.

![Figure 5: Radiation Efficiency](image)

**Figure 5: Radiation Efficiency**

From the simulated results of Figure 5, it is evident that a long as possible monopole length is desired, as this would result in a higher radiation efficiency, and in turn higher gain, in the lower half of the operational band. However, from the simulated results of Figure 4, it is evident that this would shift the antenna pattern at longer wavelengths within the operational band, with the desire to not exceed a wavelength to avoid side lobe domination.
The antenna pattern above the third resonance of 880 MHz is simulated, as depicted in Figure 6. The antenna pattern for each monopole consists of multiple lobes of various gain, as depicted in Figure 6a. The desired antenna pattern of a single beam cannot be recovered by forming dipole pairs, as depicted in Figure 6b. However, the desired single beam is still present at frequencies around 1 GHz, thereby limiting the dipole lengths to about one wavelength.

The antenna pattern around the second resonance of 745 MHz is simulated, however there are no obvious aberrations in the antenna pattern of any of the monopoles. Also, based on the simulations with the twin deployed solar panel arrays added to the model, the presence of these solar panels has no obvious effect on the antenna patterns until around the third resonance of 880 MHz, which is outside of the operational band, and therefore of no concern.

The antenna pattern at the first resonance at 420 MHz is simulated, as depicted in Figure 8. The antenna pattern for each monopole consists of four lobes of similar gain, as depicted in Figure 8a. While the desired antenna pattern of a single beam is recovered by forming antipodal dipole pairs C–D and E–F, the antenna pattern for pseudo antipodal dipole pair A–B is unexpected, as depicted in Figure 8b.
The half wave resonance at 420 MHz can be shifted outside of the operational band by halving the monopole lengths. However, this would result in a decrease in the radiation efficiency in the lower half of the operational band. Alternatively, this part of the band can be completely ignored, thereby reducing the operational band, or specialised calibration techniques can be derived for this part of the band, thereby reducing the sensitivity.

CONCLUSION
A novel astronomical antenna configuration has been designed for a space based low frequency radio telescope. The science requirements, in the need to be able to detect signals from all directions, necessitates the use of three orthogonal dipoles. However, the mechanical requirements, in the need to be able to fit the whole system within a nano-satellite, necessitates the use of a non-ideal configuration. A representative scale model of the astronomical antennas was designed and built in order to successfully test the antennas.

Due to the finite ground plane the monopoles do not have antenna patterns that match the theoretical values for monopoles on infinite ground planes. However, in forming dipoles of antipodal pairs, the expected patterns are recovered for two of the three pairs. Due to the non-symmetrical antenna deployment and the extended dipole gap, the antenna pattern of the third pair is not recovered.

The effect of the twin deployed solar panel arrays is minimal within the operational band. This simplifies the system design, in not having to dock the solar panels during observations. Due to the varying port impedance over the operational band, the monopoles are connected as active antennas. This simplifies the feed and front end design considerably, in not having to design a wide band noise amplifier.

REFERENCES


