Analysis of Ground Network Impact on VHF Antenna Performance (Postprint)

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Abstract

Based on antennas for VHF-band radio astronomy interferometer arrays, this study investigates the influence of ground screens and different environments on antenna radiation characteristics, including parameters such as gain, radiation pattern, and resonant points. The results show that under conditions without a ground screen, the antenna gains on dry soil and sandy ground are 3.06 dB and 1.44 dB, respectively, with significant sidelobes and backlobes present; on two types of wet ground, the gains are 4.33 dB and 4.25 dB, respectively. After adding a ground screen, the antenna gains on dry soil and sandy ground are 4.87 dB and 4.97 dB, respectively, and on wet soil and sandy ground are 4.39 dB and 4.40 dB, respectively. Furthermore, the radiation pattern exhibits no significant backlobes or sidelobes, the resonant points remain stable at 27.0 MHz and 69.5 MHz, and within the frequency band between them, the standing wave ratio satisfies the galactic noise limit constraints. Finally, it is concluded that when a ground screen is installed on dry soil and sandy ground, VHF antenna performance is optimal with the lowest noise, which is crucial for the selection of foundational construction environments for large-scale VHF antenna arrays.

Full Text

Preamble

Analysis of Ground Screen Influence on VHF Antenna Performance

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Abstract: Based on antennas for VHF-band radio astronomical interferometric arrays, this study investigates the influence of ground screens and different environments on antenna radiation characteristics, including gain, radiation pattern, and resonance points. Results show that without a ground screen, antenna gains on dry soil and sand are 3.06 dB and 1.44 dB respectively, with obvious side and back lobes present. On two types of wet ground, gains are 4.33 dB and 4.25 dB respectively. After adding a ground screen, gains on dry soil and sand increase to 4.87 dB and 4.97 dB, while those on wet soil and sand become 4.39 dB and 4.40 dB. The radiation patterns show no significant back or side lobes, with resonance points stabilizing at 27.0 MHz and 69.5 MHz. Within this frequency band, the standing wave ratio satisfies galaxy noise-limiting conditions. The conclusion is that VHF antenna performance is optimal with lowest noise when ground screens are installed on dry soil and sand, which is crucial for environmental selection in large-scale VHF antenna array construction.

Keywords: ground screen; dipole antenna; radiation coefficient; gain

Classification: P162

In radio astronomy, the low-frequency spectrum refers to frequencies below 100 MHz, representing a new and important research window and observational band. Currently under construction are low-frequency radio projects such as LOFAR (Low-Frequency Array for Radio Astronomy) (10-240 MHz), LWA (Long Wavelength Array) (10–88 MHz), and MWA (The Murchison Widefield Array) (80–300 MHz). Research areas include cosmology and reionization-era galaxy surveys, detection of ultra-high-energy particles, galaxies and interstellar medium, solar eruptions and coronal mass ejections. It is foreseeable that low-frequency radio observations will bring new perspectives and discoveries to major scientific topics of today [1].

VHF-band radio telescope systems consist of large phased arrays built from numerous single antennas, requiring unified basic element antenna structures and performance parameters. Constructing standardized ground screens can reduce ground effects on antenna performance and achieve uniformity. Measurements of low-frequency dipole antenna patterns and gains are constrained by far-field conditions:

Here the meaning of each letter in equation (1) is missing. In the formula, L is the dipole antenna length, is the operating wavelength, and R is the distance between the test antenna and receiving antenna. With L taken as 2 m and the operating band as 30 MHz–70 MHz, the minimum operating wavelength is 4.3 m, yielding a calculated distance greater than 8 m. To eliminate ground reflection effects, the antenna must be elevated:

where d is the receiving antenna aperture, taken as 1 m, and R has been calculated as 8 m from equation (1). From equation (2) [2], the antenna must be elevated at least 16 m. The test site requires absorbing materials and strict measurement conditions. Currently, Yunnan Observatories lacks such facilities for antenna measurement. Therefore, this paper uses HFSS simulation software to conduct preliminary exploration and simulation of antenna radiation characteristics under different ground and ground screen conditions, and to calculate and optimize ground screen design parameters, providing a basis for future VHF-band radio interferometric array construction.

1 Structure and Operating Principle of V-type Dipole Antenna

The inverted V-type dipole antenna currently used for experimental arrays at Yunnan Observatories, Chinese Academy of Sciences, operates in the 30 MHz–70 MHz band. The antenna consists of two pairs of orthogonal blade-type dipole antennas with arm lengths of 2 m and widths of 0.33 m. The main body is rectangular, with an isosceles trapezoid at the top feed point. The antenna structure is shown in Figure 1 [Figure 1: see original paper]. The dipole arms receive radio signals and convert them into electrical signals, which are led through standard 50Ω coaxial cable to the first-stage filter and amplifier. After secondary filtering, a 180° phase-shift combiner performs balanced-unbalanced conversion of signals from the two arms into a single unbalanced signal, which is then secondarily amplified and collected by an analog-to-digital converter [3].

2.1 Preliminary Ground Screen Design

Real ground is not an ideal conductor. After electromagnetic wave reflection from the ground, both amplitude and phase change, inevitably affecting antenna gain and directivity. Moreover, ground conditions vary across different observation stations, and environmental changes cause significant variations in ground permittivity and conductivity , which alter antenna radiation characteristics.

If the antenna' s radiation field in free space is E ( ), then the radiation field of a vertically polarized antenna elevated on a screen-ground system is [4]:

where W( ) is the screen-ground system factor, which is strongly related to ground permittivity , conductivity , antenna polarization direction, incidence angle , mesh spacing d, and ground screen size s [4]. The ground screen is initially determined to be a square mesh metal grid with side length a. To facilitate analysis and calculation, the ranges of a and d are first determined.

In the screen-ground system, the ground screen impedance and ground normal impedance are in parallel, giving total impedance:

where Z is the ground normal impedance and Z is the ground screen impedance. When Z = Z, Z Z , meaning the ground screen plays the dominant role in the ground-screen system, thereby effectively improving ground conditions and enhancing antenna performance. It is known that [4]:

From equation (5), smaller d yields smaller Z but at higher cost. Based on commercially available metal meshes, appropriate d satisfying Z = Z can be found.

Second, mesh spacing must satisfy d = g, where g is the wavelength in ground. When d g, electromagnetic waves penetrate the ground screen into the earth, rendering it ineffective. The wavelength in ground can be obtained from equation (6) [4]:

Taking dry soil as an example, the ground wavelength calculated from the antenna' s upper operating frequency limit of 70 MHz is 2.17 m, a condition easily satisfied. Therefore, d is set to 0.01 m in simulations.

The ground screen side length a directly affects reflection of radio signals and significantly influences antenna directivity. According to empirical formulas, the relationship between antenna main lobe elevation angle and ground screen length is:

where is the angle between the antenna main lobe direction and ground, and a is the electrical length extension of the ground screen. The antenna main lobe points vertically toward the sky, so is 90°, yielding a calculated ground screen side length a of 0.78 .

2.2 Antenna and Ground Model Parameter Settings

The HFSS model of the antenna, ground, and ground screen is shown in Figure 2 [Figure 2: see original paper], comprising the V-type dipole antenna, insulating support rod, ground screen, and ground. The antenna feed point must be more than 0.25 above ground, taken here as 1.8 m, with ground dielectric layer thickness of 0.2 m.

In regions far from directly beneath the antenna dipole, the electromagnetic wave incidence angle is very small. On finite-conductivity ground, the ground reflection coefficient approximates -1 when the incidence angle is extremely small [5], meaning ground loss remains consistently high in reflection regions with very small incidence angles. Therefore, ground screens far from directly beneath the dipole do not significantly improve antenna gain [6]. Based on this conclusion, to reduce cost, the ground screen side length a is taken as 4 m.

In electromagnetic field numerical analysis, metal wire mesh models are commonly used to simulate electromagnetic effects of actual conductor surfaces [7]. Under conditions where a = l and l = 0.25 [7], metal plates can effectively simulate the electromagnetic effects of square-mesh metal grids. Therefore, for modeling convenience, metal plates are used in software to simulate the ground screen. Considering corrosion resistance, antenna and ground screen materials are set as aluminum and stainless steel, with the support rod made of insulating bakelite. For the ground, parameters such as permittivity, permeability, conductivity, and density can be set according to different conditions. Simulations were conducted for four different ground types both without and with ground screens.

2.3 Ground Electrical Parameter Settings

Generally, different grounds have different permittivity and conductivity , but the permeability of most media is close to the vacuum permeability [9], so = is generally assumed. In ground simulations, four ground types with different electrical parameters were set: dry soil, dry sand, wet soil, and wet sand. Based on existing research results [10], the electrical parameters for the four ground types are shown in Table 1 .

3 Simulation and Analysis

The antenna operating band is 30 MHz-70 MHz with a center frequency of 50 MHz. The entire antenna system is enclosed by an air box with its boundary set as a radiation boundary condition. The feed structure is shown in Figure 3 [Figure 3: see original paper], using standard 50Ω coaxial line to feed the antenna. Each pair of dipole arms is connected to the coaxial line’ s inner and outer conductors via thin metal wires, with lumped port excitation applied at the coaxial port’ s annular region. Port resistance is set to 50Ω and reactance to 0Ω.

3.1.1 Antenna Directivity Without Ground Screen

Without a ground screen, gains on wet soil and wet sand are 4.33 dB and 4.25 dB respectively, while gains on the other two ground types are lower, as shown in Table 2 . The antenna’ s 3D gain pattern and E-plane pattern are shown in Figures 4 [Figure 4: see original paper] and 5 [Figure 5: see original paper]. On the two dry ground types, the main, side, and back lobe gains are shown in Table 3 , where main lobe gain is small while side and back lobe gains are relatively large. On the two wet ground types, antenna directivity is significantly better with main lobe gains of 4.5 dB and no back lobes. The influence of different ground types on antenna radiation characteristics results from differing conductivity—wet ground conductivity is far superior to dry ground, providing higher electromagnetic wave reflection efficiency, thus producing higher antenna gains on wet ground.

3.1.2 Antenna Directivity With Ground Screen

After setting the ground screen in the model, the calculated antenna maximum gains and main lobe gains are shown in Table 4 . Among the maximum gains, the highest is 4.97 dB and the lowest is 4.39 dB, indicating that maximum gains are very similar across the four ground types. Regarding directivity, as shown in Figures 6 [Figure 6: see original paper] and 7 [Figure 7: see original paper], the 3D gain patterns and E-plane patterns are quite similar across the four ground types. In summary, after adding a ground screen, the influence of different ground types on antenna radiation characteristics becomes similar, effectively improving antenna directivity by reducing side and back lobes while also increasing antenna gain.

3.2.1 Antenna Resonance Characteristics Without Ground Screen

Without a ground screen, reflection coefficients at resonance points differ significantly, as shown in Table 4. On dry soil and dry sand, the antenna S11 curves exhibit dual resonance points, but reflection coefficients at these points differ, particularly at the second resonance point, as shown in Figure 8 [Figure 8: see original paper]. On the two wet ground types, significant changes occur compared to dry ground. As shown in Figure 9 [Figure 9: see original paper], the antenna S11 curves are very similar, with close reflection coefficients and resonance frequencies.

where S11 is the return loss, Γ is the voltage reflection coefficient, Zin is the antenna input impedance, and Z0 is the antenna characteristic impedance. From equations (8) and (9), changes in antenna reflection coefficient alter the antenna input impedance, degrading antenna-feedline matching and reducing antenna radiation efficiency, which in practice leads to unstable antenna performance.

3.2.2 Antenna Resonance Characteristics With Ground Screen

As shown in Figure 10 [Figure 10: see original paper], after setting the ground screen, the reflection coefficient curves for the antenna on four different ground types are very similar, with close reflection coefficient values and resonance frequencies. This indicates that antenna resonance points, reflection coefficients, and input impedance do not change with ground variations.

Based on the above simulation and analysis results, for VHF-band V-type dipole antennas without ground screens, changes in ground electrical parameters significantly affect antenna gain, directivity, and resonance frequency. Wet ground provides higher gain and better directivity compared to dry ground. After adding a ground screen, antenna radiation characteristics stabilize, reducing the impact of ground electrical parameter variations while effectively improving antenna gain and directivity, resulting in more stable antenna performance. This provides important guidance for environmental selection in future low-frequency radio array construction.

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Note: Figure translations are in progress. See original paper for figures.