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Simulations to Improve Circular Loop Antenna Characteristics at the Frequency of 1.42 GHz using Window Functions

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Abstract

This study is focused on simulations of the radiation pattern characteristics for a circular loop antenna that operates at a frequency of 1.42 GHz (λ = 21 cm). The circular loop antenna pattern is considered weak and depends on the antenna's circumference. Therefore, five values of antenna circumferences are chosen to achieve the best results for the antenna characteristics. These circumferences are taken to be smaller, equal, and larger than the operated wavelength. Then, the antenna characteristics are estimated. These characteristics are antenna directivity, effective area, efficiency, and solid angle, which are found to be 2.6, 0.009 (m2), 0.011, and 11.5 (radian), respectively. To improve these characteristics, four types of window functions are implemented by their multiplication with the Fourier transform of the circular loop antenna pattern. These window functions are rectangular window, Hanning Window, Hamming Window, and Kaiser Window. The promising results are obtained via the Hanning window since it gives acceptable values for antenna characteristics. These values are found to be (directivity = 100), (effective area = 0.35 m2), (efficiency = 0.6), and (solid angle = 0.1 radian). Overall, the encouragement results are obtained by a small circular loop antenna, especially at a circumference less than the operated wavelength.

Keywords: Radio astronomy antennas, circular loop antenna, antenna characteristics, neutral hydrogen emission line.

محاكاة لتحسين خصائص هوائي الحلقي الدائري عند التردد 1.42 غيغا هرتز بأستخدام دوال النافذة

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الخلاصة

ركزت هذه الدراسة على محاكاة خصائص نمط القدرة لهوائي حلقي دائري الذي يعمل بتردد 1.42 غيغا هرتز (الطول الموجي = 21 سم). يعد نمط القدرة للهوائي الحلقي الدائري نمط ضعيف، وهو يعتمد على محيط الهوائي. لذلك اختيرت خمسة قيم لمحيط الهوائي لتحقيق أفضل النتائج لخصائص الهوائي. قيم محيطات الهوائي اخذت لتكون اصفر، تساوي، وأكبر من الطول الموجي المخصص للرصد. ثم خمنت خصائص الهوائي. وهذه الخصائص هي الاتجاهية، المساحة الفعالة، الكفاءة، والزاوية الصلبة، ووجدت قيمها لتكون 2.6، 0.009 م^2، 0.011، 11.5 نقية على التوالي. لتحسين هذه الخصائص، أربعة من دوال النوافذ طبقت بضربهم بتحويل فوريير لنمط الحلقة الدائري. هذه الدوال هي نافذة المستطيل، نافذة هانينك، نافذة هامنك، ونافذة كايسر. تم الحصول على نتائج مبشرة عن طريق نافذة هانينك لكونها تعطي قيم مقبولة لخصائص الهوائي. ووجدت هذه

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القيم لتكون (الاتجاهية = 100)، (المساحة الفعالة = 0.35 م^2)، (الكفاءة = 0.6)، و (الزاوية الصلبة = 0.1 نقية). بشكل عام، تم الحصول على نتائج مشجعة بوساطة هوائي حلقي صغير وخصوصاً عند محيط اقل من الطول الموجي المخصص للرصد.

1. Introduction

The antenna is a basic component of every radio telescope. It can receive a radio wave from a free space as well as a transmitted radio wave, according to the reciprocity theorem [1]. There are several types of antennas, but one of the simplest is a loop antenna. This type depends on the designer's preference; it might have different shapes, including circular, square, triangular, hexagonal, and rectangular. It operates in the astronomical frequency range of around 300 MHz–3 GHz. It is divided into two categories: large-loop antennas and small-loop antennas [2, 3]. The first category is large loop antennas, also known as full-wave loops or self-resonant loop antennas, which are self-resonant at the operating frequency because their circumference is almost equal to one or more complete wavelengths. This type is the most effective form of antenna when applied to both transmission and reception. At its first full-wave resonance, this type of loop antenna radiates a two-lobe radiation pattern that peaks perpendicular to the loop's plane in both directions. It is also the most efficient of all designs for antennas of a comparable size [4]. In the second category, small loop antennas, which have a circumference less than half of the operational wavelength, are also known as magnetic loops or tuned loops. There are two primary types of small-loop antennas: square loop antennas and circular loop antennas. Although their efficiency has decreased, they are mostly employed as receiving antennas; loops with a radius smaller than around 1/10 wavelength are rarely utilized for transmission because of their extreme unproductiveness. Small loop antennas are radiated in the same manner as a short horizontal dipole antenna [5, 6]. Many studies have evaluated the literature on the many types of radio telescope antennas and the factors that affect them, such as antenna temperature, noise, radiation pattern, beam width, effective area, and efficiency fundamentals. Research was conducted on the radiation characteristics of a small loop antenna despite its straightforward structural design; the antenna loop and the physical dimensions of the wire conductor were used to conduct a simple loop antenna design in order to study the radiation characteristics. The Genetic Algorithm (GA) approach was utilized to calculate the antenna's size by presenting several possibilities for selection. Every option's radiation efficiency was calculated, and the results were presented. Furthermore, antenna parameters were calculated and presented. The antenna constituted the basis for the obtained radiation pattern [7]. A digital radio array for low-frequency radio astronomy was used to identify air showers caused by high-energy cosmic rays and neutrinos. To measure cosmic rays, the radio array must be calibrated to the exact amplitude to record the whole electric field on the antenna. There were four antenna stations in the new experimental setup recording electric fields in 50 µs with a spectral resolution of 20 KHz. The setup used matched filtering, digital beamforming, and radio frequency interference (RFI) with neural networks to decrease systematic uncertainty [8]. Inside a rectangular area constraint of the antenna, the theoretically ideal tiny loop antenna form was calculated. The best parameters and approaches with cut-off corners were computed [9]. A low-cost of compact loop antenna that consisted of two connected rectangular counter-wiring loop antennas was created for radio direction finding. It was a tracking control device with a broad linear detection range [10]. A low-frequency radio receiver was used for amateurs and researchers. The receiver had an overall gain of 34 dB, a minimum input voltage of 100 µV, and an output voltage of 135 mV. High-Definition Software-Defined Radio (HDSDR) was used to monitor and test the system in a lab setting [11]. Three square-shaped antennas were studied to improve the bandwidth of circular polarization. The 3 dB axial ratio bandwidth may reach 38% with a 0.04 wavelength arm width, which is three times bigger than a wire-loop antenna [12]. Our goal in this study is to simulate the circular loop antenna at a frequency of 1.42 GHz. This frequency is generated from a natural hydrogen atom by a well-known mechanism. The mechanism is called the spin-flip transition, in which the direction of the proton's spin is opposite to the electron's spin. In the normal case, the electron and proton have a parallel spin [13]. The difference between the two cases gives a photon with a frequency of 1.42 GHz [14, 15]. In addition, this frequency is protected and has wide applications in radio astronomy. For example, mapping the hydrogen clouds in the universe also determines the flux density or brightness temperature of the observed radio source that emitted this line. Besides, this frequency is used to estimate the rotation curve of our galaxy [16, 17, 18]. Since the circular loop is easy to design with less cost, this antenna is chosen to be observed or operated at a frequency of 1.42 GHz [19, 20]. Hence, the window functions are used to improve the characteristics of the circular loop antenna. The fundamental equations that compute the antenna characteristics are given in Section Two. Section Three gives the simulated results and discussion of the circular loop antenna before and after an improvement. Finally, the important conclusions are given in Section Four.

2. Theoretical Considerations

A radiation pattern is the key to measure the performance of any antenna. It represents an antenna field of view or an antenna response to the incident radio wave. The simplest form of a circular loop antenna radiation pattern (U) can be given as [21]:

$$U(\theta) = J_1(krsin(\theta)) \tag{1}$$

Where θ is the elevation angle, J_1 is the first order of the Bessel function, k is the wave number, and r is the radius of the circular loop antenna. Certain antenna characteristics may be used to evaluate the performance of the antenna. The radiation pattern has a major influence on these characteristics. Four of the most significant antenna characteristics are examined in this section. Antenna directivity, or a directional gain (D), is the first. It is the realization of U compared to the realization of the isotropic radiation antenna U_o. D is written as [22]:

$$D = \frac{U}{U_o} \tag{2}$$

Another form of U_o, is computed in terms of the radiated power (P_{rad}). P_{rad} is obtained by an integration of the U overall and the solid angle 4π. Consequently, the U_o is given by [22]:

$$U_o = \frac{P_{rad}}{4\pi} = \int_0^{2\pi}\int_0^{\pi} Usin\theta d\theta d\phi \tag{3}$$

Therefore, Eq. (2) can be rewritten as the following [23]:

$$D = \frac{4\pi U}{P_{rad}} \tag{4}$$

The second parameter is the effective area (A_e), or a receiving antenna. A_e is given as [24]:

$$A_e = \frac{\lambda^2 D}{4\pi} \tag{5}$$

Antenna efficiency (η) is the third parameter. This coefficient offers a connection between the antenna gain (G) and the D [24]:

$$\eta = \frac{G}{D} \tag{6}$$

Where G is useful in describing the performance of the antenna. It can be estimated by the following formula [24]:

$$G = \frac{4\pi A_e}{\lambda^2} \quad (7)$$

G is generally given by a logarithmic scale (dB). The last parameter is the antenna solid angle (Ω_A), sometimes called the beam width. This parameter is responsible for determining the angular resolution. One form of Ω_A can be computed in terms of D, as given by [25]:

$$\Omega_A = \frac{4\pi}{D} \quad (8)$$

3. Results and Discussion

One-dimensional numerical simulations are carried out to investigate and improve the essential characteristics of the circular loop antenna radiation pattern. This pattern is simulated in an array of size (N = 360) pixels according to Eq. (1). The frequency at which this equation is produced is 1.42 GHz, or 0.21 m in wavelength. The generated pattern of a circular loop antenna depends on the circumference (C) of the antenna. C values are chosen to be smaller, equal, and larger than the operated wavelength. The antenna circumferences are assumed to be ($C=\lambda/3$ m, $C=\lambda/1.5$ m, $C=\lambda$ m, $C=1.5\lambda$ m, and $C=3\lambda$ m). This is done to demonstrate the convenient antenna size for observing the hydrogen line emission (1.42 GHz). The results are displayed in Fig. 1. It is clear that the radiation patterns of (a, b, and c) in Fig. 1 have a wide main lope and no side lobes. Whereas in Fig. 1 (d and e), the radiation pattern is separated into different lobes as C increases larger than λ. Fig. 1 is depicted by another view, as shown in Fig. 2, to provide further details regarding the radiation pattern. It is clear that the pattern of the circular loop antenna is very weak and less than equal to one. The best value of C, which gives the highest intensity of the radiation pattern, is found to be at $C=\lambda/1.5$, as shown in Fig. 2-b. This figure shows an intensity pattern greater than 0.5 that is flatter than others. The most important antenna characteristics, which are built on the radiation pattern, are studied. These characteristics are antenna directivity (D), effective area (A_e), efficiency (η), and solid angle (Ω_A).

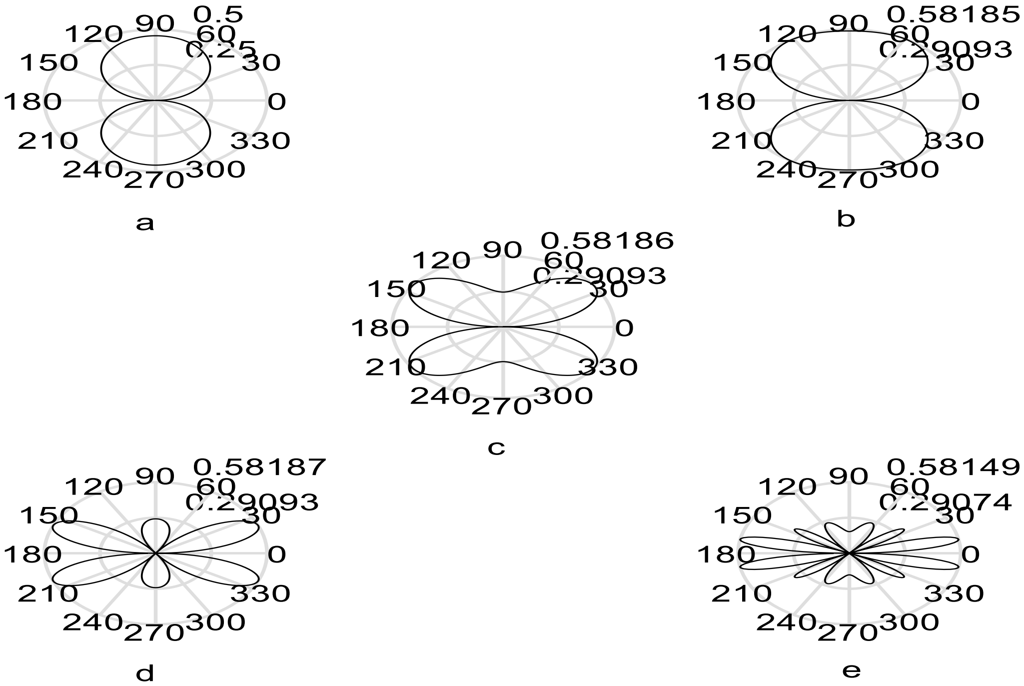

Figure 1: The polar radiation pattern (U) of the circular loop antenna at different values of circumference (C). a- $C=\lambda/3$, b- $C=\lambda/1.5$, c- $C=\lambda$, d- $C=1.5\lambda$, e- $C=3\lambda$.

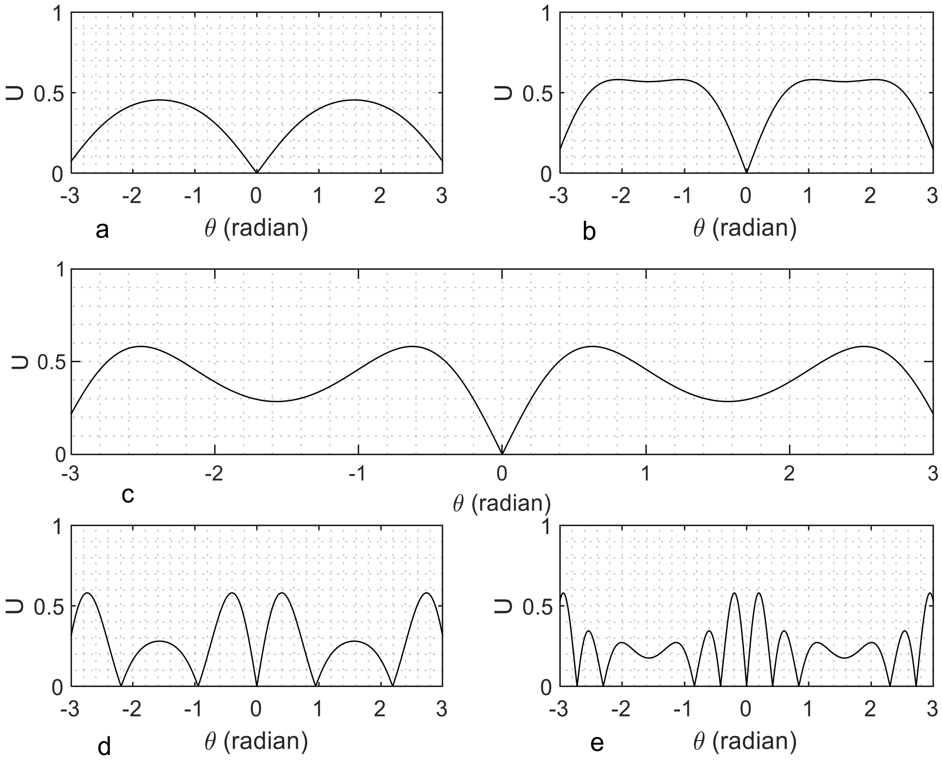

Figure 2: The radiation pattern (U) plot of the circular loop antenna at different values of circumference (C). a- $C=\lambda/3$, b- $C=\lambda/1.5$, c- $C=\lambda$, d- $C=1.5$, e- $C= 3\lambda$.

These antenna parameters are computed using Equations (2–8) as listed in the theoretical part. The results, displayed in Fig. 3., reveal the weakness of the computed characteristics (D, A_e, η, and Ω_A) for the circular loop antenna. Consequently, this study aims to improve the radiation pattern and increase the sensitivity of the loop antenna. This improvement can be implemented using window functions on the loop antenna radiation pattern. Window functions, sometimes, are called apodization or tapering functions. The most common types of window functions are Rectangular Window (RW), Hanning Window (HNW), Hamming Window (HMW), and Kaiser Window (KW). Mathematically, these types are given, respectively, by [26-30]:

$$RW = \begin{cases} 1, & n < N \\ 0, & otherwise \end{cases} \quad (9)$$

$$HNW = 0.5(1 - \cos\left(\frac{2\pi n}{N}\right)) \quad (10)$$

$$HMW = 0.5 - 0.46\cos\left(\frac{2\pi n}{N}\right) \quad (11)$$

$$KW = \frac{J_1(\sqrt{1-(\frac{2n}{N}-1)^2}}{J_1(\pi\alpha)} \quad (12)$$

Where, n is an integer ($0 \le n \le 360$), J_1 is the first kind of Bessel function, and α is the order of the Kaiser function, set to be 9.

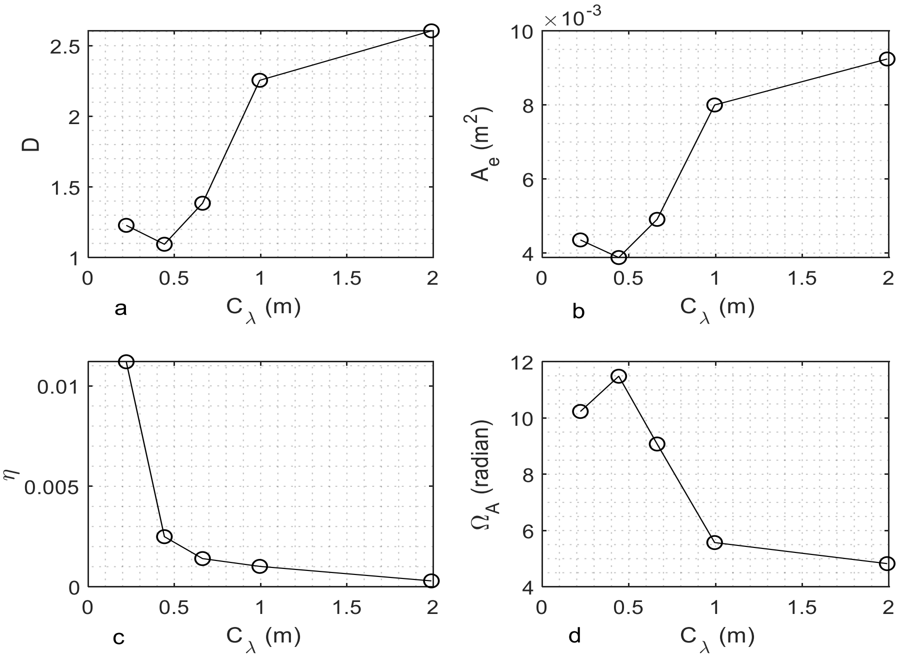

Figure 3: a- The directivity (*D*) as a function of the antenna circumference (*C*), b- The effective area (*Ae*) as a function of the antenna circumference (*C*), c- The efficiency (η) as a function of the antenna circumference (*C*), and d- The solid angle (Ω_A) as a function of the antenna circumference (*C*).

The results of Equations (9–12) are shown in Fig. 4. The window functions have zero values outside of a certain interval. These four window functions are applied via their multiplication with the Fourier transform of the radiation pattern. This is achieved to enhance or improve the characteristics of the circular loop antenna. The results are illustrated in Figs. 5, 6, 7, and 8, respectively. It should be noted here that the pattern in Fig. 5 (a, b, c, and d) has a clear main lobe with maximum gain with uniform side lobes, except (e) which has side lobes with a high gain. HNW is a vital window and leads to a main lobe approach to a Dirac delta function, and there are no side lobes, as shown in Fig. 6 (a, b, and c). This means any signal recorded, such as a system, will be itself without any attenuation. While (d and e) have several narrow side lobes with high gain, these side lobes could receive signals from different observed sources. Therefore, the final result will be confusing. Fig. 7 is only Fig. 2 magnified. HMW increases the gain of the main lobe radiation pattern to one, but it stays wide. Because signals from two nearby radio sources might be received. These results are practically unsuitable for radio astronomical observations. The results are achieved by KW, as are the results by HNW, but the main lobe is a little wide, and (d and e) have no side lobes. This is very clear from the comparison between Fig. 8 and Fig. 6**.** The antenna characteristics are computed after an implementation of the four window functions. Fig. 9 illustrates the results.

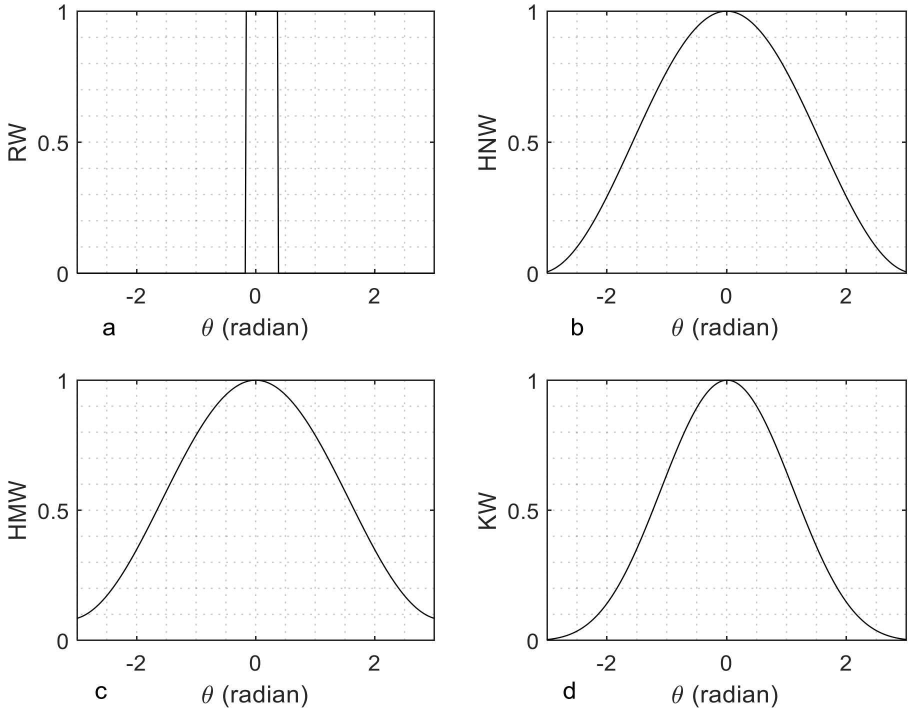

Figure 4: a- Rectangular Window (RW) as a function of (θ), b- Hanning Window (HNW) as a function of (θ), c- Hamming Window (HMW) as a function of (θ), and d- Kaiser Window (KW) as a function of (θ).

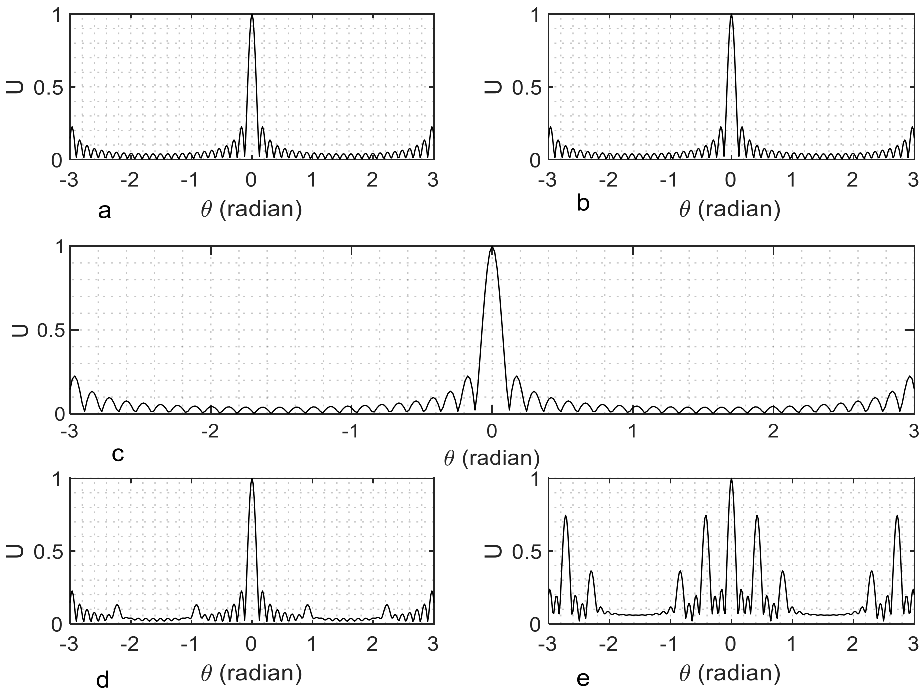

Figure 5: The radiation pattern (U) using the Rectangular Window (RW) as a function of (θ): a- $C=\lambda/3$, b- $C=\lambda/1.5$, c- $C=\lambda$, d- $C=1.5\lambda$, and e- $C=3\lambda$.

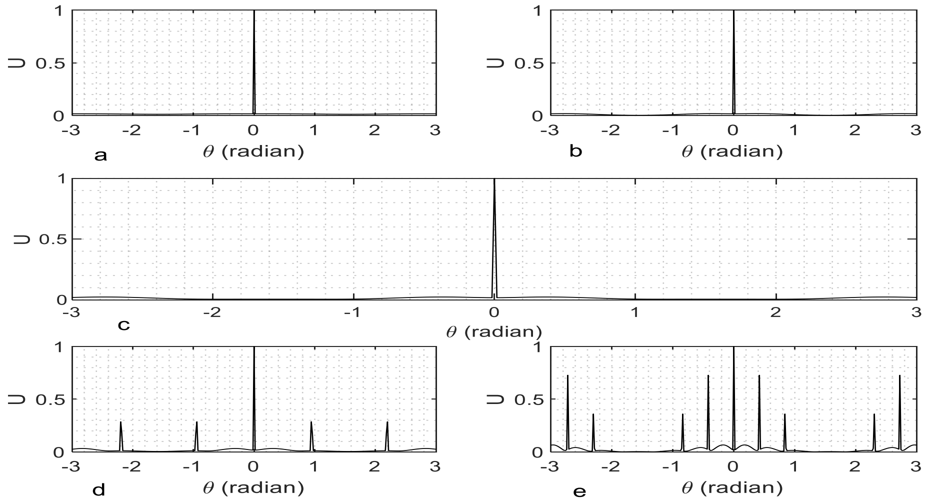

Figure 6: The radiation pattern (*U*) using the Hanning Window (HNW) as a function of (*θ*): a- *C*=*λ*/3, b- *C*=*λ*/1.5, c- *C*=*λ*, d- *C*=1.5*λ*, and e- *C*=3*λ*.

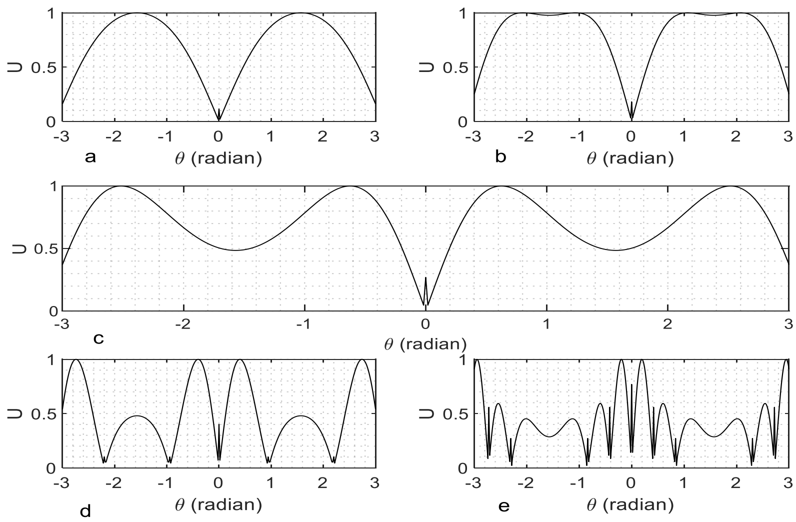

Figure 7: The radiation pattern (*U*) using the Hamming Window(HMW) as a function of (*θ*): a- *C*=*λ*/3, b- *C*=*λ*/1.5, c- *C*=*λ*, d- *C*=1.5*λ*, and e- *C*=3*λ*.

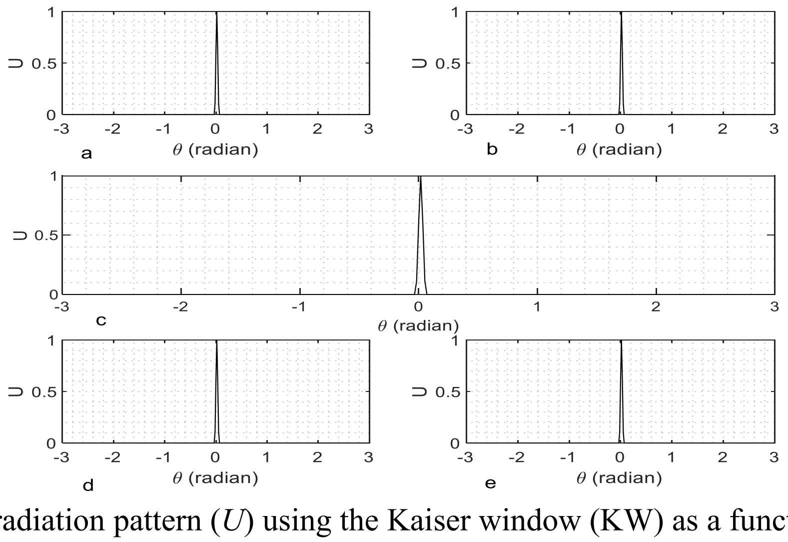

Figure 8: The radiation pattern (*U*) using the Kaiser window (KW) as a function of (*θ*): a- *C*=*λ*/3, b- *C*=*λ*/1.5, c- *C*=*λ*, d- *C*=1.5*λ*, and e- *C*=3*λ*.

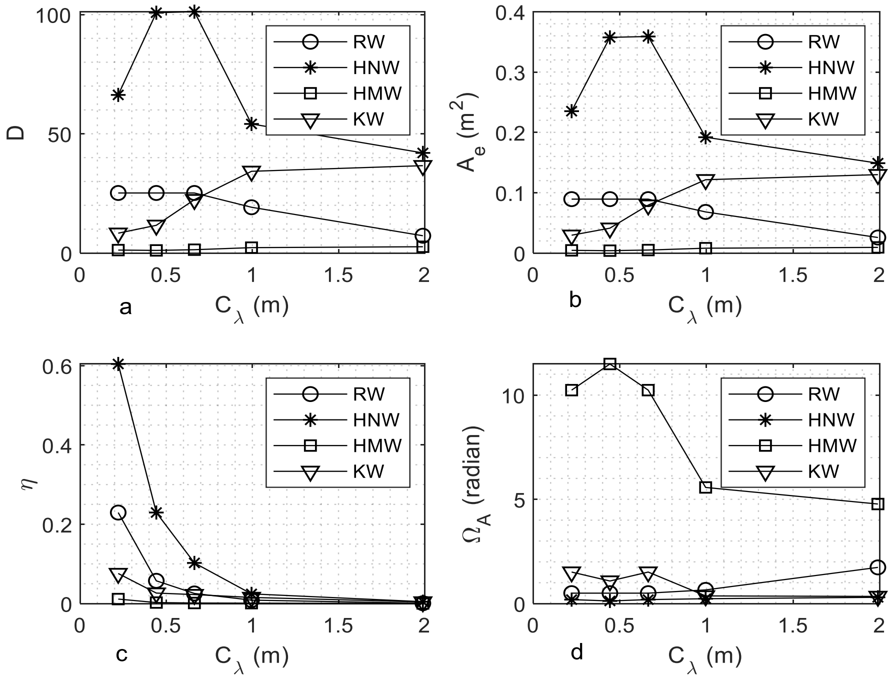

Figure 9: a- The directivity (*D*) as a function of the antenna circumference (*C*), b- The effective area (A_e) as a function of the antenna circumference (*C*).c- The efficiency (η) as a function of the antenna circumference (*C*), and d- The solid angle (Ω_A) as a function of the antenna circumference (*C*).

4. Conclusions

The radiation patterns of the circular loop antenna are simulated at a frequency of 1.42 GHz. This frequency belongs to the neutral hydrogen emission line and is considered very important due to its availability in the universe and wide applications in radio astronomy observations. Five values of the circular loop antenna circumference are taken to obtain acceptable results for antenna characteristics. These characteristics are antenna directivity (*D*), effective area (A_e), efficiency (η), and solid angle (Ω_A). The results showed that the maximum values of the antenna characteristics were found to be 2.6, 0.009 (m^2), 0.011, and 11.5 (radian), respectively. Although different values of the antenna circumference were used, the antenna characteristics were considered very weak (see Fig. 3). The Fourier transform of the circular loop antenna pattern was multiplied with the window functions to improve the antenna characteristics. Four types of window functions were implemented to obtain the desired antenna characteristics operating at a frequency of 1.42 GHz. These types were the rectangular window (RW), Hanning Window (HNW), Hamming Window (HMW), and Kaiser Window (KW). The results showed that the HMW gives higher values of antenna characteristics. These values are found to be (directivity D = 100 or 20 dB), (effective area A_e = 0.35 m^2), (efficiency η = 0.6), and (solid angle Ω_A = 0.1 radian), as shown in Fig. 9. Consequently, the small circular loop antenna, especially at the circumference ($C = \lambda/1.5$), is found to be the best antenna for observing the hydrogen emission line.

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