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Direction of Arrival Estimation of Meteors Echoes using Array Radio Antennas

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Abstract
Array antennas have an interesting role in the radio astronomy field. The array antennas allow astronomers to obtain high-resolution signals with high sensitivity to weak signals. This paper estimates the meteors' positions entering the Earth's atmosphere and develops a simulation for array antenna radar to analyze the meteor's echoes. The GNU radio software was used to process the echoes, which is a free open-source software development toolkit that provides signal processing blocks to implement in radio projects. Then, the simulation determines the azimuth and elevation of the meteors. An improved Multiple Signal Classification (MUSIC) algorithm has been suggested to analyze these echoes. The detected power of each meteor echo has a Doppler frequency shift due to the high speed of the meteors, which impacts the accuracy of the Direction of Arrival (DOA) estimation. The Doppler shift was considered in this simulation, and the results showed that the suggested method has low complexity and high resolution and can estimate the meteors' position with the minimum error.

Keywords: Meteors, Improved Music algorithm, Doppler shift, L-shaped array antenna, GNU Radio.

تقدير اتجاه وصول أصداء الشهب باستخدام مصفوفة هوائيات راديوية

عماد كسار عكيب* ، ياسر جاسب بخيت، محمد ناجي ال نجم
قسم الفلك و الفضاء، كلية العلوم، جامعة بغداد، بغداد، العراق

الخلاصة
يعتبر هوائي المصفوفة من الادوات المهمة جدا في الفلك الراديوي. تسمح هوائيات المصفوفة للفلكيين بالحصول على إشارات عالية الدقة ذات حساسية عالية للإشارات الضعيفة. في هذا البحث قمنا بحساب مواقع الشهب التي تدخل الغلاف الجوي للأرض باستخدام برنامج مختص بمعالجة الاشارات الراديوية بالإضافة الى تطوير محاكاة لرادار الراديوي لغرض تحليل أصداء الشهب. لقد تم استخدام برنامج الراديو GNU في معالجة الأصداء و هو عبارة عن مجموعة أدوات مجانية لتطوير البرمجيات مفتوحة المصدر توفر مجموعة معالجة الإشارات لتنفيذها في المشاريع الراديوية. ومن ثم، تحدد المحاكاة سمت وارتفاع الشهب. تم اقتراح خوارزمية محسنة لتصنيف الإشارات المتعددة (MUSIC) لتحليل هذه الأصداء. تتمتع القدرة المكتشفة لكل صدى الشهب بتأثير تردد دوبلر بسبب السرعة العالية للشهب، مما يؤثرعلى دقة تقديرنتائج اتجاه الوصول

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(DOA). أظهرت النتائج أن الطريقة المقترحة ذات دقة عالية وقادرة على تقدير موقع الشهب بكفاءة عالية بأقل خطأ.

1. Introduction

Estimating the direction-of-arrival (DOA) of multiple signals using array antennas is of great interest in many fields, such as radio astronomy, radar, sea surveillance, and wireless communications. Many researchers investigated and suggested methods to estimate the DOA [1-6]. In general, when Meteoroids enter the earth's atmosphere with a high velocity, they burn up and this fireball is called a meteor [7-8]. The meteors were divided into two parts: hard and trailing. The hard part consists of dense plasma, and the trial involves diffusing plasma left in the Earth's atmosphere, and each part generates echoes [9-13].

Meteor positions can be measured by array radio radar. The radio radar receives the echoes from meteors and can be used to determine their positions by estimating the direction of arrivals (DOA). Due to the moving of the meteors, the transmitted signal is affected by Doppler shift, which is related to radial speed [14-19 and its DOA is related to the orthoradial speed. This Doppler shift appears as an additional phase in each element of the array antennas for this reason the Doppler shift has to be considered in the DOA estimation algorithm.

The configuration of the array antennas is essential to avoid an ambiguity problem [20-24]. This ambiguity happens when the response for the signals is the same for different targets. The distance between two adjacent antennas has to be less than or equal to the observed wavelength. The traditional 2D MUSIC algorithm is used to estimate the DOA. Implementing the MUSIC algorithm method directly leads to solving large complex systems of equations. A fast algorithm has been suggested by W. Nie et al. by searching on specific rounds without the need to search the total spectrum [25-28].

The real-time data for meteor observation can be obtained from Meteor radar systems such as Enhanced Meteor Detection Radar (EMDR). Four radar systems provide these data, like the Middle Atmosphere Alomar Radar System radar in Norway, the Middle and Upper Atmosphere (MU) radar in Japan, the Program of the Antarctic Syowa Mesosphere Stratosphere Troposphere Incoherent Scatter (PANSY) radar in the Antarctic. This paper suggests an improved 2D MUSIC method to estimate the DOA of reflected echoes from the meteors trial. The suggested method separates the received signal into two channels using an L-shaped array antenna and removes the effect of Doppler phases. For simulation, the used software is called GNU Radio software which is a free open-source software development toolkit that supplies signal processing blocks to implement in radio projects. GNU simulates the DOA estimation of meteors trial within the radio frequency range (10 MHz - 30 MHz).

1.1 **DOA estimation without Doppler shift**

Consider a reflected signal from a faraway target in the sky. The far-field plane wave is received by an array of antennas arranged linearly on the x-axis, as shown in Figure (1). Thus, the plane wave incident on all the array elements with the same angle. The distance between the array elements (d) must be less than or equal to half the wavelength of the source frequency. Otherwise, an aliasing effect occurs.

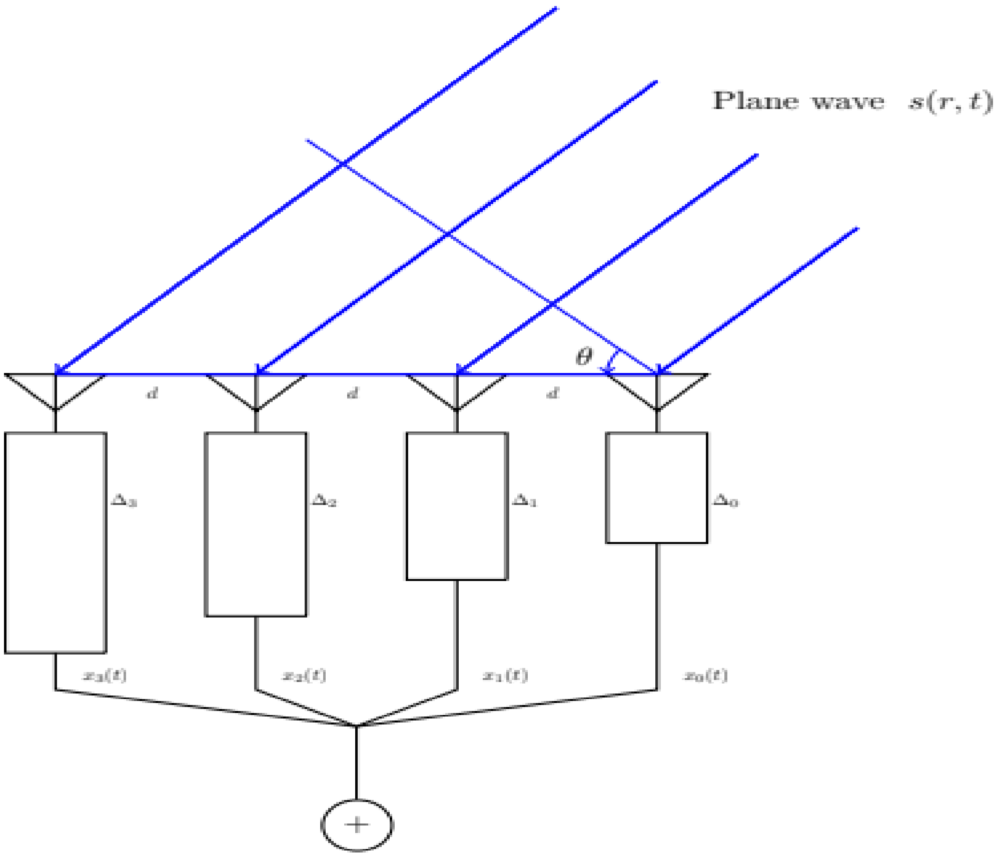

Figure 1: Direction of arrivals of reflected signal from a target.

Assume that the received signals are reflected from a static target and have the angular frequency ω_p. The Doppler phase is ignored in this case (f_D=0). The angle θ_p is the Direction of arrival (DOA). The signal s_p(r, t)=exp$\left[j\left(\omega_p \text{t}+\vec{k}.\vec{r}\right)\right]$ arrives at each array element $\left(x_m, \text{y}_m\right)$, where (r, t) is the coordinates of the signal in space and time respectively, (k) is the wave number of the signal, (m=1,2,.., M) with a path difference equals to [6]:

$$\Delta_{\text{m}}=\text{d} \sin\left(\theta_p\right)/\lambda \quad (1)$$

The complex factor corresponding to phase difference is calculated as [6]:

$$a_{\text{m}}\left(\theta_p\right)=\exp\left[j\left(\vec{k}.\vec{r}\right)\right]=\exp[-j2\pi(m-1)\Delta_{\text{m}}] \quad (2)$$

The output signal of the m-th element is [6]:

$$x_m(t) = \sum_{\text{p}=1}^{P} s_p\,(t)a_m\left(\theta_p\right)+\text{n}_m(t)\ , \quad (3)$$

where the complex envelope $s_p(t)$ is given by [6]:

$$s_p(t)=\exp\left[\text{j}\omega_p t\right]\ , \quad (4)$$

and $n_m(t)$ is the additive white Gaussian noise (AWGN). This expression can be described in matrices form [6]:

$$\text{X}=\text{D}^H\text{S}+\text{N}\ \ , \quad (5)$$

where,

$$D^H = \left[a_m(\theta_1), a_m(\theta_2), \cdots, a_m(\theta_P)\right]^H \quad (6)$$

$$\begin{bmatrix} 1 & 1 & \cdots & 1 \\ e^{-j2\pi\Delta_1/\lambda} & e^{-j2\pi\Delta_2/\lambda} & \cdots & e^{-j2\pi\Delta_P/\lambda} \\ \cdots & \cdots & \cdots & \cdots \\ e^{-j2\pi\Delta_{(M-1)}/\lambda} & e^{-j2\pi\Delta_{(M-1)}/\lambda} & \cdots & e^{-j2\pi\Delta_{((M-1))P}/\lambda} \end{bmatrix},$$

and,

$$S=\left[s_1(t), s_2(t), \cdots, s_P(t)\right] N=\left[n_1(t), n_2(t), \cdots, n_M(t)\right]$$

1.2. Eigendecomposition of array covariance

The correlation matrix for X can be then written as:

$$R=X.X^H \quad (7)$$

The eigenvalues and eigenvectors for the noise subspace are determined from the correlation matrix. The spatial spectrum $P(\theta)$ is [6]:

$$P(\theta) = \frac{1}{a_m(\theta).E_n E_n^H.a_m(\theta)^H} \quad (8)$$

When $a_m(\theta)$ is orthogonal with each column of E_n, the value of this denominator is close to zero because of the existence of the noise. As the denominator gets a minimum value, the power spectrum $P(\theta)$has a peak value. Make θ change in equation (8) and estimate the arrival angles by finding the peak.

2. Doppler effect on MUSIC algorithm

Multiple Signal Classification (MUSIC) is an algorithm used for radio detection finding. It searches the orthogonality between the signal and the noise subspaces to achieve a high-resolution DOA estimate. Because those two subspaces are perfectly orthogonal to each other when the signal-to-noise ratio (SNR) is high, the MUSIC algorithm can resolve close sources. Another advantage of the algorithm over the other methods is that it can be used with arbitrary array geometries.

This paper uses an improved 2D MUSIC algorithm to estimate the elevation and azimuth angles for signal echoes of two meteors. Implementation of 2D Music algorithm directly leads to high complexity. To reduce the complexity, special L-shaped array antennas receive the signals. Eight array antennas are used in this method. Four antennas are arranged on the x-axis and four antennas on the z-axis. The L-shaped antenna separates the received signal into two channels. One channel estimates the azimuth angle (x-axis), and the other is used for elevation (z-axis).

For meteors, one has to include the Doppler frequency shift $\omega_D$to the phase of received signals,

$$s_p(t)=\exp\left[j\omega_D t\right] \quad (9)$$

The complex factor corresponding to phase difference is calculated as:

$$a_m(\theta_p)=\exp\left[j(\vec{k}.\vec{r})\right]=\exp[-j2\pi(m-1)\Delta_m]$$

The output signal of the m-th element is

$$x_m(t) = \sum_{p=1}^{P} s_p(t) a_m(\theta_p) + n_m(t)$$

where the complex envelope $s_p(t)$ is given by,

$$s_p(t) = \exp\left(j\omega_p t\right) \exp\left(j\omega_D t\right) \tag{10}$$

To estimate the azimuth and elevation angles, equations (5,6,7,8) can be used.
The distance between two adjacent elements in the array antennas has to be less than or equals to the half wavelength of the source signal. If the distance exceeds this limitaliasing affects the MUSIC algorithm. The Doppler frequency affects the source wavelength of the received signals. So, the algorithm must consider the Doppler frequency to get the correct method. The frequency shift block is included in the simulation, as shown in the next section.

3. Flow graph of DOA estimation

In this section, we will explain the implementation of the MUSIC algorithm using GNU radio software and how it can be used in array radio radar.

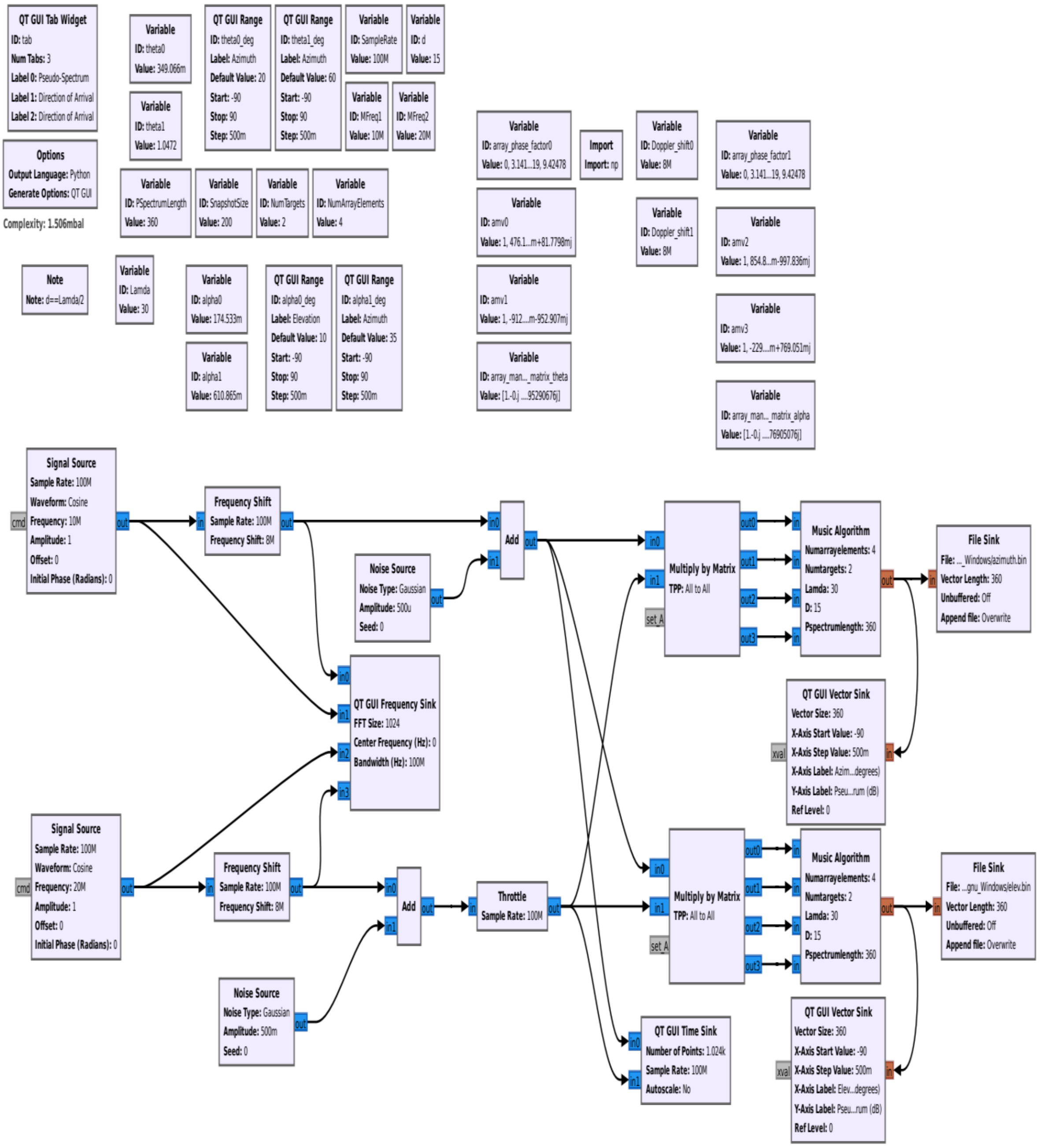

Figure 2: Flow graph of DOA estimation of meteors using an improved music algorithm.

Figure (2) shows a flow graph of the direction of arrival estimation of two meteor echoes. Blocks signal source (10MHz and 20MHz) represents the echoes received from the array antenna. All the blocks are coded in Python and C++. Each flow graph block has properties that can be coded with Python or set the values.

In this section and from the flow graph, some block details can be clarified. For example, the source signals block properties like frequency, amplitude, and sample rate can be adjusted, as shown in Figure (3). The Frequency shift block adds Doppler shift (8 MHz) to the received signals. The Block noise source adds (AWGN) to the signal, and array phase factors are separated in a variable block called array_phase_factor0 and array_phase_factor1. The Multiply by matrix¨ block job calculates $X_m(t)$in Equation (3). We have coded a Python block called MUSIC Algorithm to calculate the pseudo-spectrum of the echoes from the input $X_m(t)$, and the output spectrum is then sent as input to the QT GUI Vector Sink block to plot it. The block's vector size and other properties can be set, as shown in Figure (4). Finally, the File Sink block saves the pseudo-spectrum data as a binary file for further manipulation or sharing. A subprogram is written in Python to read the binary file data.

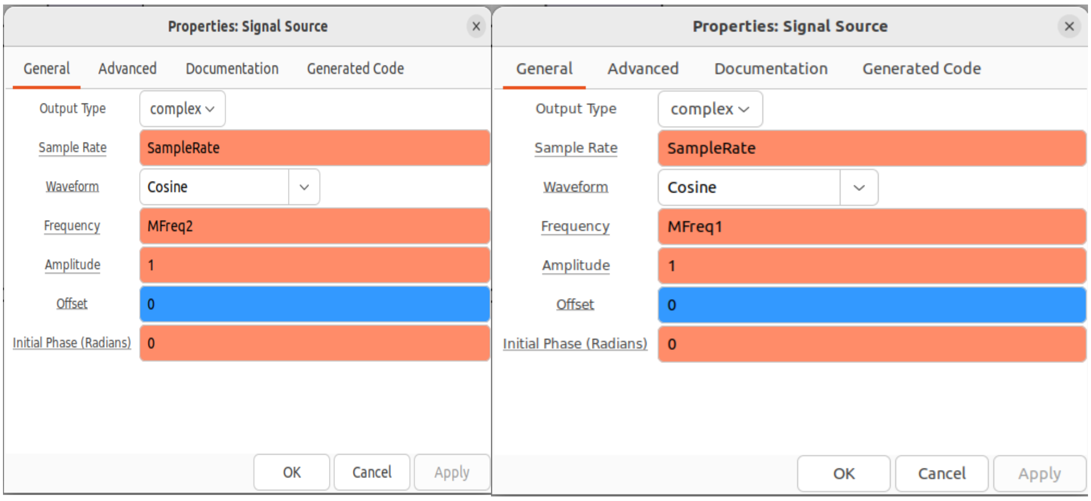

Figure 3: Meteors echoes blocks properties.

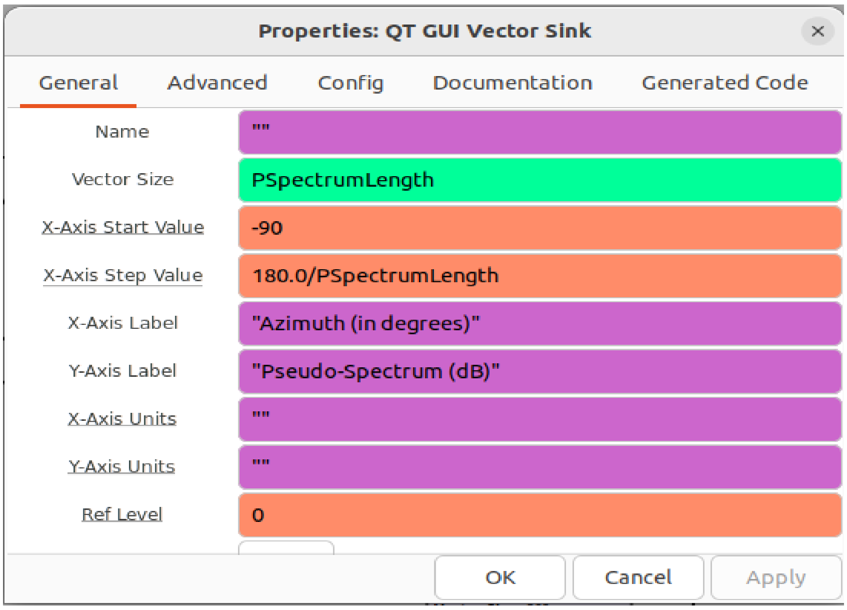

Figure 4: QT GUI Vector Sink block properties.

4. Simulation results and analysis

Figure (5) shows the received complex signals from meteors. The real and imaginary parts are shown together. The frequency of these signals was selected to be in the radio range (10 MHz - 30 MHz). This range of frequency can be used in Over-the-Horizon (OTH) scattering method of meteors detection. The advantage of using OTH radar instead of the traditional VHF radar is that the OTH is more sensitive to meteors than the VHF radar. We assume that all the received signals are incoherent. If the signals are coherent, they will unite into one signal, reducing the covariance matrix's rank. This will affect the linear system; thus, the MUSIC algorithm will fail to estimate the correct DOA. To deal with coherent signals, one has to remove the correlation between the signals. The coherent signals are out of the scope of this research. The Gaussian noise source is added to these signals by connecting the signal and noise blocks with the add block. The Gaussian noise corresponds to the thermal noise generated from the system hardware. Figure (5) shows the complex echoes received by the array antennas.

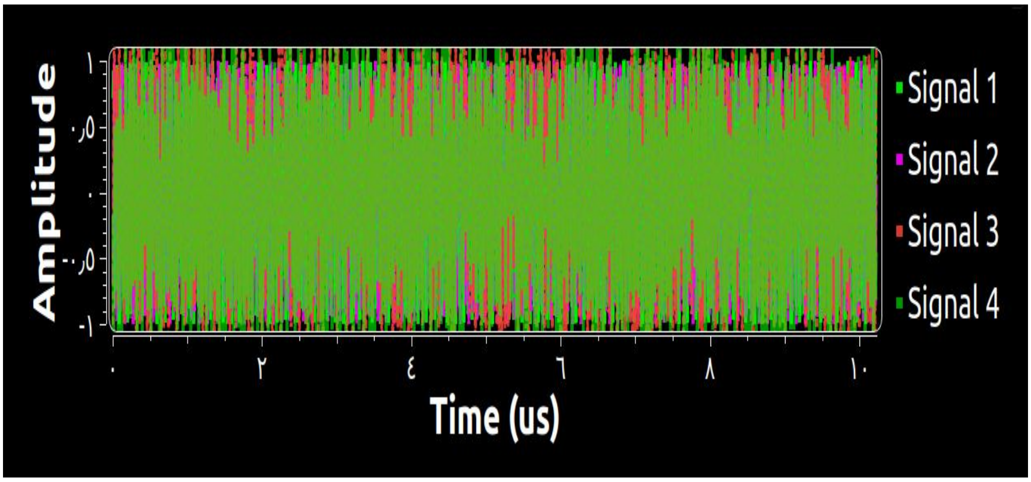

Figure 5: Simulation for the received signal (10 MHz and 200 MHz) from two meteors in time domain. Real and imaginary parts for both of them

Figure (6) and Figure (7) show the pseudo-spectrum of the echoes using an improved MUSIC algorithm to estimate the azimuth and elevation angles. Each peak in the figures is related to the DOA of the meteors. One can see the high resolutions of the peaks, and no overlapping is noticed, even for very close echoes. The noise has no major effect since the algorithms are not sensitive to noise, as explained in the previous sections. The peak of Figure (6) points to Azimuth angles 20^0 and 60^0, which is exactly the azimuth angle of the incoming signal from the target. Same thing with Figure (7) points to elevation angles 10^0 and 35^0. The result shows the efficiency of the new method. No ambiguity problem was noticed in the results.

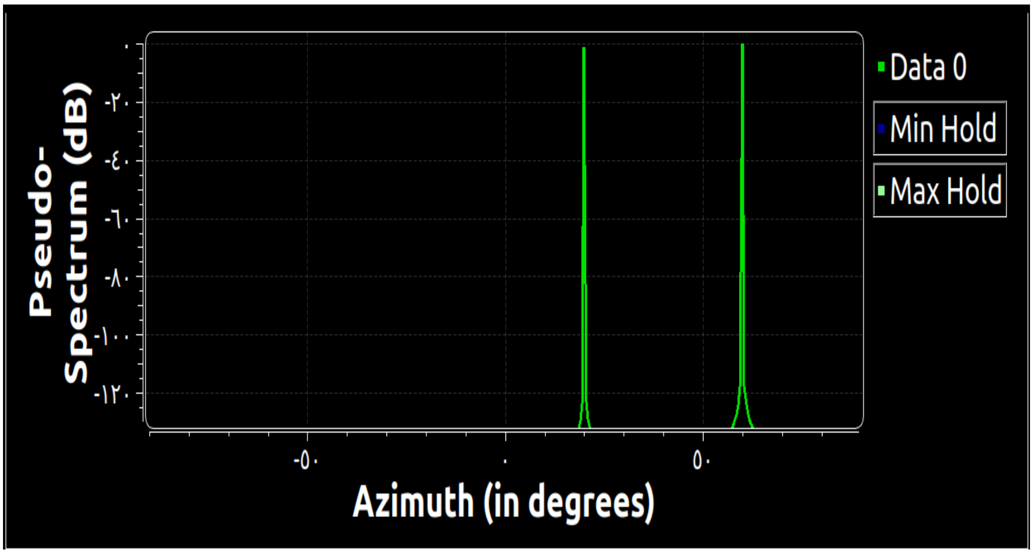

Figure 6: Pseudo-spectrum of the meteors echoes. The peaks correspond to the azimuth angles of the meteors.

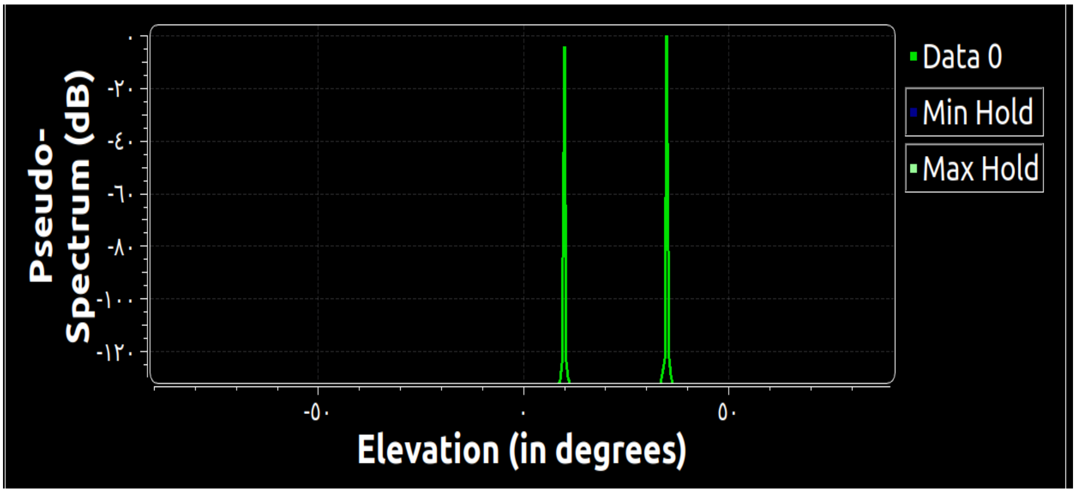

Figure 7: Pseudo-spectrum of the meteors echoes. The peaks correspond to the elevation angles of the meteors.

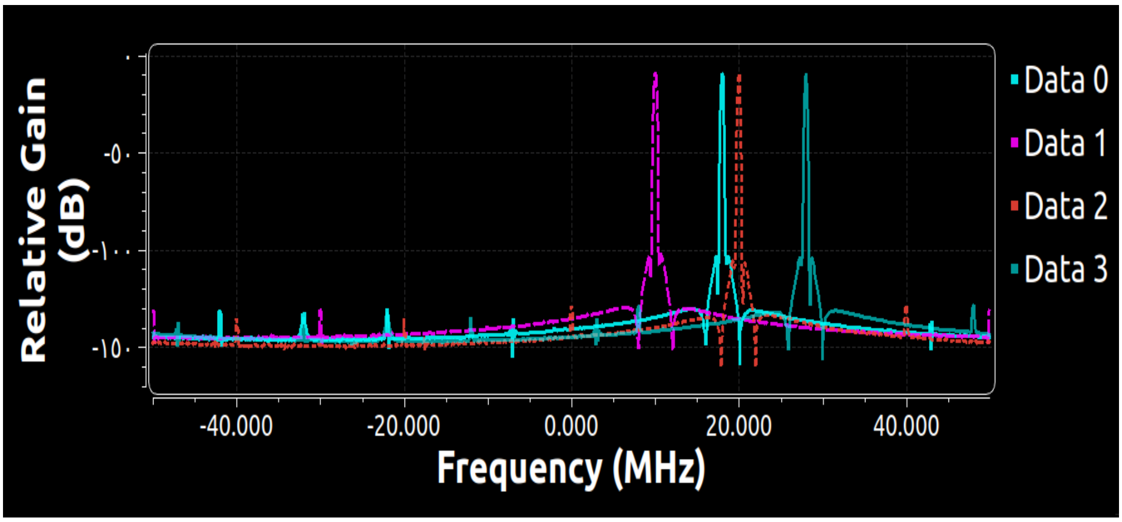

Figure 8: The Doppler shift effect (8 MHz) on the received signals.

Figure (8) shows the Doppler shift effect on the received signals. The dashed line represents the received signals, and the solid line represents Doppler-shitted signals. As mentioned in the previous sections, the transmitted radio is directed at meteors and is affected by the Doppler effect. The frequency of the reflected waves becomes lower or higher depending on the direction of the transmitted wave. In Figure (8), it was assumed that the meteors moving in the same direction as the reflected wave. Thus, we added Doppler frequency in block frequency shift to the signal source. The Doppler shift value was set to 8 MHz, as shown in variables Doppler_shift0 and Doppler_shift1. The distance (d) between two adjacent array elements has to be adjusted according to the Doppler-shitted frequency. As mentioned, (d) must not exceed half the source wavelength. 5. Conclusions

Through the steps of this paper and from the obtained results, one can conclude that the array elements configuration is important to reduce the MUSIC algorithm complexity in 2D, and arranging the elements on x and z-axes reduces the computational time significantly. Also, the findings in Figures (6, 7, and 8) showed that the improved method gives correct azimuth and elevation angles for moving targets. The results revealed that the new algorithm can distinguish between very close objects. In addition, it proved the effectiveness of GNU radio in evaluating signal processing algorithms. Finally, this simulation can be used for further investigating real data received from meteors.

References

[1] S. Cui-zhen, “The application of MUSIC algorithm in the planar array antenna”, *IEEE International Conference on Signal Processing*, Communications and Computing (ICSPCC), 2015.

[2] Qi. Zi-sen, G. Ying, W. Bu-hong and G. Cheng, “The performance analysis of MUSIC algorithm based on Conformal array antenna”, *Journal of Electronics and Information Technology*, 2008.

[3] Z. Guang-yi, “Phased array radar system [M]”, *Beijing: National Defence Industry Press*, 1994.

[4] J. J. Lee, E. M. Ferren, D. P. Woollen, and K. M. Lee, “Near-field probe used as a diagnostic tool to locate defective elements in an array antenna”, *IEEE Transactions on Antennas and Propagation*, vol. 36, no. 6, pp. 884-889, June 1988.

[5] Q. Yuan, Q. Chen, and K. Sawaya, “Accurate DOA estimation using array antenna with arbitrary geometry”, *IEEE Transactions on Antennas and Propagation*, 2005.

[6] Y. Liu, and H. Cui, “Antenna Array Signal Direction of Arrival Estimation on Digital Signal Processor (DSP)”, *Procedia Computer Science*, vol. 55, pp. 782-791, 2015.

[7] M. M. Zamal, and M. N. Al Najm, “Computation of the Relationships of X-ray to Radio Luminosities of a Sample of Starburst Galaxies”, *Iraqi Journal of Science*, vol. 64, no. 6, pp. 4076-4093, 2023.

[8] Z. Ceplecha, J. Borovička, W. G. Elford, D.O. Revelle, R.L. Hawkes, V. Porubčan, and M. Šimek, “Meteor Phenomena and Bodies”, *Space Science Reviews*, vol. 84, pp. 327-471, 1998. https://link.springer.com/article/10.1023/A:1005069928850

[9] S. Z. Khalaf, K. Abrahim and I. K. Akeab, “A Calculation real abundance of gaseous elements of the comet PanSTARRS C/2011 S4”, *Iraqi Journal of Physics*, vol. 18, pp. no. 45, 2020.

[10] A. H. Abdullah, P. Kroupa, P. Lieberz, and R. A. González-Lópezlira, “On the primordial specific frequency of globular clusters in dwarf and giant elliptical galaxies”, *Astrophysics and Space Science*, vol. 364, no. 86, 2019.

[12] S. E. Sandström, “On Sparsity Related to the Integral Equations of 2D Electromagnetic Scattering”, *Radio Science*, vol. 58, no. 4, pp.1-7, 2023. https://doi.org/10.1029/2022RS007598.

[13] M.N. Al Najm, H. H. AL-Dahlaki, and B. A. Alkotbe, “Investigation of the Baryonic Mass Tully–Fisher Relationship for Normal and Barred Spiral Galaxies”, *Iraqi Journal of Science*, vol. 64, no. 12, pp. 6620-6637, 2023.

[14] Haydar R. Al-baqir, Abdullah K. Ahmed and D. Gamal, "Surface Photometry of NGC3 Lenticular Galaxy", *Iraqi Journal of Science*, vol. 60, no. 9, pp.2080-2086. 2019. DOI: https://doi.org/10.24996/ijs.2019.60.9.23

[15] Y. Dong, C. Dong, W. Liu, M. Liu, and Z. Tang, "Robust DOA Estimation for Sources with Known Waveforms Against Doppler Shifts via Oblique Projection", *IEEE Sensors Journal*, vol. 18, no. 16, pp. 6735-6742, 2018.

[16] H. L. Van Trees, "Detection, estimation, and modulation theory, optimum array processing", *John Wiley & Sons*, 2004.

[17] Y. Luo, X. Xin, F. Du, X. Tang, and Y. Li, "Comparison of DOA algorithms applied to ultrasonic arrays for PD location in oil", *IEEE Sensors Journal*, vol. 15, no. 4, pp. 2316-2323, 2015.

[18] J. Shi, G. Hu, B. Zong, and M. Chen, "DOA estimation using multipath echo power for MIMO radar in low-grazing angle", *IEEE Sensors Journal*, vol. 16, no. 15, pp. 6087-6094, 2016.

[19] S. Marcos, A. Marsal, and M. Benidir, "The propagator method for source bearing estimation", *Signal Processing*, vol. 42, no. 2, pp. 121-138, 1995.

[20] U. E. Jallod, H. S. Mahdi, and K. M. Abood, "Simulation of Small Radio Telescope Antenna Parameters at Frequency of 1.42 GHz", *Iraqi Journal of Physics*, vol. 20, no. 1, pp. 37-47, 2022.

[21] D. Kastinen, J. Kero, A. Kozlovsky, and M. Lester, "Resolving the ambiguous direction of arrival of weak meteor radar trail echoes", *Atmospheric Measurement Techniques*, vol. 14, no. 5, pp. 3583-3596, 2021.

[22] J. Kero, D. Margaret, Campbell-Brown, G. Stober, J. L. Chau, J. D. Mathews, and A. Pellinen-Wannberg, "Radar Observations of Meteors", *Cambridge University Pr*ess, 2019. https://doi.org/10.1017/9781108606462.

[23] A. Kozlovsky, S. Shalimov, S. Oyama, K. Hosokawa, M. Lester, Y. Ogawa, and C. Hall, "Ground Echoes Observed by the Meteor Radar and High-Speed Auroral Observations in the Substorm Growth Phase", *Journal of Geophysical Research: Space Physics*, vol. 124, no. 11, pp. 9278-9292, November 2019. https://doi.org/10.1029/2019JA026829.

[24] A. Kozlovsky, R. Lukianova, and M. Lester, "Occurrence and Altitude of the Long-Lived Nonspecular Meteor Trails During Meteor Showers at High Latitudes", *Journal of Geophysical Research: Space Physics*, vol. 125, no. 8, pp. 1-17, August 2020. https://doi.org/10.1029/2019JA027746, 2020.

[25] D. Kastinen, J. Kero, "Probabilistic analysis of ambiguities in radar echo direction of arrival from meteors", *Atmospheric Measurement Techniques*, vol. 13, no. 12, pp. 6813-6835, 2020.

[26] J. Ni, and J. Yang, "Variable step-size diffusion least mean fourth algorithm for distributed estimation", *Signal Processing*, vol. 122, pp.93-97, 2016.

[27] B. R. Karthikeyan, G.R. Kadambi, and Y. A. Vershinin, "A formulation of 1-D search technique for 2-D DOA estimation using orthogonally polarized components of linear array", *IEEE Antennas and Wireless Propagation Letters*, vol. 14, pp.1117-1120, 2015.

[28] F.M. Han, and X. D. Zhang, "An ESPRIT-like algorithm for coherent DOA estimation", *IEEE Antennas and Wireless Propagation Letters*, vol. 4, pp.443-446, 2005.