International Journal of Engineering and Technical Research (IJETR)
ISSN: 2321-0869 (O) 2454-4698 (P) Volume-7, Issue-6, June 2017

Analysis of a Radar system for UAV Tracking using MATLAB

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***Abstract*— The ultra-modern technologies maintain creating advanced methods for refining the performance of the ancient systems. Array antennas are one of the constantly improving technologies, carried numerous benefits to our daily life. The developers of array antennas remove the drawbacks of the ancient technology radars such as great side-lobes, degradation effect of the clutter, and vulnerability to the jammers. Array antennas discovered several applications on different areas.**

Now a days, unmanned aerial vehicles (UAVs) have arisen to be a part of our life more frequently than before. UAVs avoid pilot loss of life. They succeed in multiple of military and civilian missions such as battle damage assessment, surveillance and reconnaissance, target recognition, search and rescue, and monitoring of traffic. A significant practise of the UAVs is, carrying out reconnaissance and surveillance missions, troop support which needs to maintain a data-link with troops with the intention of send any data collected, such as video images, or audio. In the course of operations it is essential to uninterruptedly sustain a data and control link with the operator. This necessitates the ground station antenna to track the UAV so the antenna beam is pointed correctly. The aim of this research is to calculate essential design parameters for a radar system of a phased array antenna to angle-track a UAV and finally propose suggestions to construct an accurate tracking system.

***Index Terms*—Ultra-modern technologies, UAV, Tracking.**

I. INTRODUCTION

Radars can explore the airspace and then track the anticipated targets in order to extract the elevation, azimuth, speed and course information from the moving.

It allows the operator to forecast where the target will be next. There are many kinds' radar applications of tracking. Tracking antennas can also be utilised by weapon systems to target the weapons or to guide the missiles. The search radars identify the target through their wide beam-width and once the target is chosen, the tracking radar, which could be alternative mode of the same radar system, tracks the target by means of its narrow beam-width (i.e. pencil beam) of the tracking antenna. The aim of this paper is not radar applications however the tracking of signals from UAVs, and hence of the UAV by its own. It can be assumed as the receiver side of radar. Proposed tracking system is processing the signal, which was sent by the UAV transmitter.

Therefore, it is essential to indicate tracking principles to examine the performance of UAV tracking system.

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II. DESIGN PARAMETERS & ESSENTIALS FOR TRACKING SYSTEM

i) Elimination of Grating Lobes

Grating lobes are the maxima of the main beam, as predicted by the pattern multiplication theorem. When the array spacing is less than or equal to $\lambda/2$, only the main lobe exists in the visible space, with no other grating lobes. Grating lobes appear when the array spacing is greater than $\lambda/2$. For large spacing, grating lobes can appear in the visible space even at a zero scan angle.

The phased-array tracking antenna operates in the band from 2.4 to 2.5 GHz. The lowest frequency, which is 2.4 GHz, is selected for the calculation of most parameters. The wavelength is 0.125 m. One of the biggest concerns is the occurrence of grating lobes. Grating lobes might limit the performance of the antenna system. Grating lobes can be avoided if element spacing satisfies: [8]

$$d < \frac{\lambda}{1+\left|\sin\theta_{S_{\max}}\right|} \quad (1)$$

Where $\theta_{S_{\max}}$ is the maximum beam scan angle with respect to the axis of the array.

The maximum scan angle will be a function of the operating conditions. That is, the UAV velocity and distance from the tracking array, its angle off bore-sight, and range. A graph shown in Fig. 1, shows the element spacing vs. scan angle. This graph is based on the highest frequency within the operating bandwidth. This graph gives an idea about the element spacing for no grating lobes for each scan angle. To estimate the required maximum scan angle the UAV range and velocity must be specified.

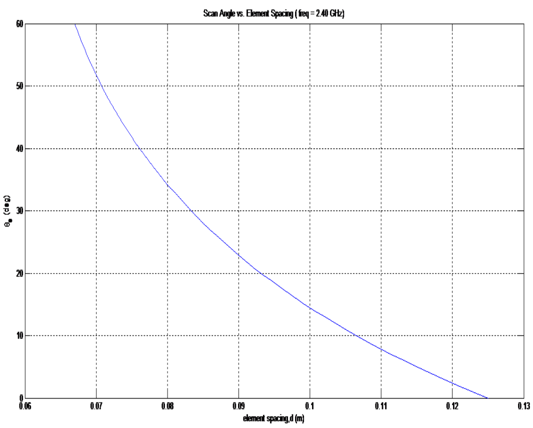

Fig. 1. Element Spacing (d) for no grating lobes vs. Scan Angle (θs)

ii) Elements Spacing & Number of Elements

The element spacing and number of elements both affect the gain. More elements means higher gain and narrower beam width, but it also makes the design more expensive. To minimize cost, the fewest possible elements should be used. The signal that will be tracked needs to fall on the main null in the difference array pattern. To have a symmetric difference beam, the number of elements must be even.
The directivity of the linear array can be calculated with the following formula: [8]

$$D=\frac{1}{\frac{a_0}{N}+\frac{2}{N^2}\sum_{m=1}^{N-1}\frac{N-m}{m\beta d}\left(a_1\sin m\beta d+a_2\cos m\beta d\right)\cos m\alpha} \quad (2)$$

Where N is the total number of elements in the array and α is inter-element phase shift (which is zero for broadside). The factors in the formula above: a_0 a_1 and a_2 are given in Table 1 for several element patterns. The array will be using parallel dipoles, which are placed above a ground plane. The addition of the ground plane increases the gain about 3 dB above that predicted by Eq. (2).

Fig.3 shows a comparison between the element spacing and directivity, which is equal to gain for a lossless antenna. It can aid in a decision to define the element spacing.

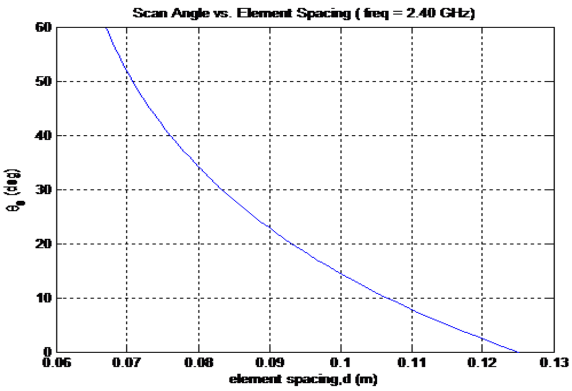

Fig. 2 Element Spacing (*d*) for no grating lobes vs. Scan Angle (θs)

The vertical axis in Fig.2 gives the maximum allowed element spacing for each scan angle to avoid grating lobes. We can take any of the values below these maxima as the element spacing of the system, however, spreading the elements out (larger *d*) gives a narrower beam-width. The directivity curves as a function of N for parallel short dipoles, shows a sudden decrease near one and two wavelengths (Fig. 3). This is the result of the grating lobes appearing in the visible region at the spacing of 1λ and 2λ, respectively.
The directivity of a broadside array of isotropic elements when there are no grating lobes is approximated by: [8]

$$D\approx 2\frac{L}{\lambda}=2\frac{Nd}{\lambda} \quad (3)$$

Where $L = Nd$ is the array length. The directivity of long arrays ($L >> \lambda$) is primarily controlled by the array factor if the element pattern is of low directivity and its major lobe is aligned with that of the array factor. In cases such as these, Eq. (3) can be used. The actual array will have a small ground plane under the dipoles, giving a gain about 3 dB higher than predicted by Eq. (2) and (3).

TABLE 1.PARAMETERS FOR USE IN COMPUTING THE DIRECTIVITY OF UNIFORM CURRENT AMPLITUDE.EQUALLY SPACED LINEAR ARRAYS. [8]

Element Type	$\lvert g_a(\theta,\phi)\rvert^2$	a_0	a_1	a_2
Isotropic	1	1	1	0
Collinear Short Dipoles	$\text{Sin}^2\theta$	$\frac{2}{3}$	$\frac{2}{(mbd)^2}$	$\frac{-2}{(mbd)}$
Parallel Short Dipoles	$1-\sin^2\theta\cos^2\phi=\sin^2\gamma$	$\frac{2}{3}$	$1-\frac{1}{(mbd)^2}$	$\frac{1}{(mbd)}$

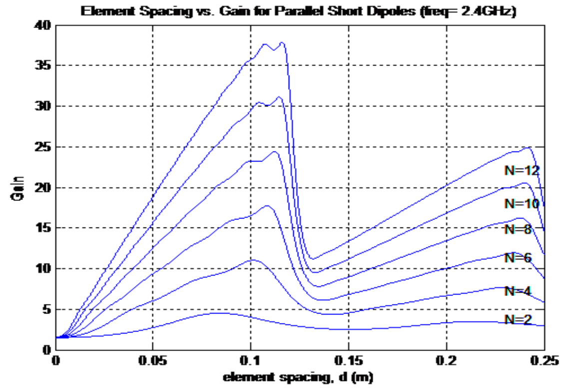

Fig. 3 Element spacing (*d*) vs. gain for isotropic elements (no scan) based on Eq. (2).

Figures 2 and 3 can be used to make a decision on what the element spacing should be based on initial estimates of the UAV range and velocity, the maximum scan angle was estimated to be 40 degrees. This scan angle corresponds to a maximum spacing of approximately 0.073 m. Any value of element spacing below this prevents grating lobes in the visible region. The determination of the element spacing does not only depend on the desired scan angle but also the gain and certainly on the economical considerations as discussed above. Taking into account all these considerations, the number of elements was decided to be between 8 and 12.

The determined element spacing corresponds to a gain of approximately 16 for parallel short dipoles. Fig. 4 shows that 8 elements give a gain of around 12 dB. With a ground plane, the gain will increase 2 to 3 dB.

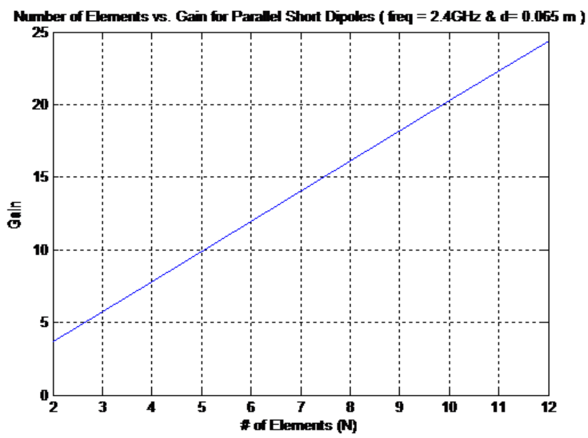

Fig. 4 Gain vs. number of elements.

iii) Half Power Beam Width (HPBW)

HPBW is another important parameter to consider. Fig. 5 shows a graph giving the half power beam width vs. scan angle for various N. Beam broadening will affect the achievable accuracy of the tracking antenna at wide beam angles. In order to determine the half power beam-width for various values of the number of elements, the element spacing and the scan angle was inserted in the MATLAB program. For a long (*Nd*>>λ) uniformly excited and equally spaced linear array, the HPBW is approximately: [8]

$$HPBW \approx 0.886\frac{\lambda}{Nd}\sec\theta_S$$, near broadside (4)

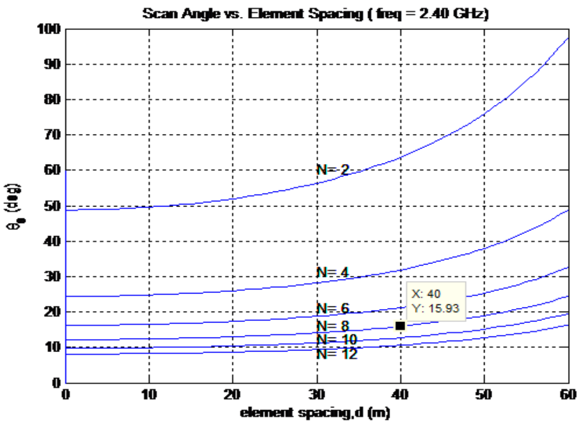

Fig. 5 Scan angle (θs) vs. half power beam-width.

The graph in Fig. 5 consists of curves for even values of N from 2 through 12. A scan angle of 40 degrees with eight elements gives a half power beam width of about 16 degrees. This half power beam-width is a good starting point for analysis. Hence, the initial values for the scan angle, element spacing, and number of elements have been determined for proposed design.

The frequency is set at 2.4 GHz by the fact that this is the frequency used by the communication systems on the UAV. The scan angle was determined to be 40 degrees, and the half power beam-width approximately 16 degrees, giving more than 12 dB of a gain for eight vertical dipole elements in the linear array. With a ground plane, the gain will increase to about 15 dB.

iv) Accuracy of Tracking System

Based on all of these parameters, another MATLAB program was written to find the accuracy of our tracking system. The MATLAB code gives the difference between the tracking angle and actual angular position of the UAV over time. Nonetheless, the speed of UAVs depend on the type of mission. Although the specific type of UAV for the system has not been defined yet, its desired purpose is troop support, carrying out reconnaissance and surveillance missions, and maintaining a data-link with troops in order to send any data collected such as video, image, or audio. In light of this mission context, the UAV speed is likely to be between 10 and 90 m/sec. Initially, a UAV speed of 30 m/sec is assumed. From Figure 6, the range of the UAV is decided to be 1000 meters. When UAV is at θ =0, the range from the antenna to UAV is *R*= 1000 m. The antenna is stationary and UAV is assumed to be moving on a route perpendicular to the array. This short range puts more demand on the tracking system because the UAV moves through the beam rapidly.

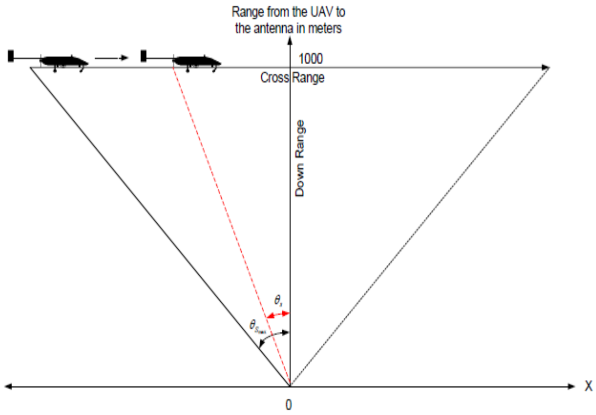

Fig. 6 UAV tracking by the array located at x=0.

The MATLAB code uses the slope error constant formula, which is given by

$$\frac{\Delta}{\Sigma} \approx k_S\theta, |\theta| \le \theta_B / 4 \qquad (5)$$

The computed mono-pulse slope constant of the antenna is k_S = -0.12003 per degree. The resulting graph for the initial parameters (element spacing, number of elements, HPBW, frequency, scan angle) is seen in Figure 7. It takes approximately 44 seconds for a UAV with a speed of 30 m/sec to travel over a path the length of approximately 1700 m that is a function of the scan angle that was determined before; i.e. 40 degrees. The tracking error is the difference between the scan angle of the antenna and the actual angular position of the UAV is a maximum 2.305 degrees when the target is near θ=0°.

In order for a mono-pulse tracking system to track the target, it is supposed to be within the difference beam null, which is the region where the sum beam crosses over the difference beam on its each side. The sum pattern is used only on transmitter while both sum and difference pattern are used on receiver. As it can be seen in Fig.8, at the moment the error signal reaches its greatest value, e.g. when tracking (scan) angle is zero, the difference beam crossover is found to be 7 degrees. The linear region is less than this, so in the MATLAB code the difference beam linear region is limited to one-fourth of the sum beam HPBW on each side, i.e. -4 to 4 degrees. Consequently, the target is considered to be tracked by the antenna as long as the angular error is kept within these limits.

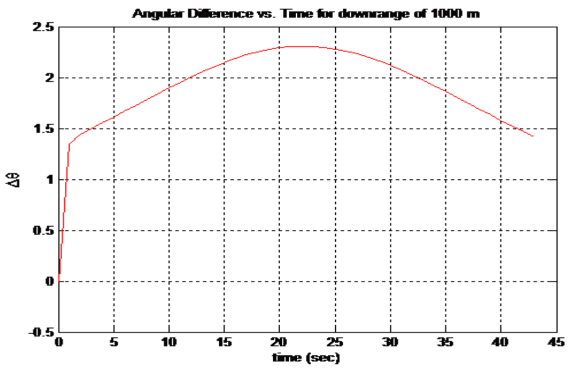

Fig. 7 Angular difference (tracking error) vs. time for a UAV 1000 m downrange at a speed of 30 m/sec.

When the MATLAB code is examined, it can be seen that the time increment for the system to follow the target is one second. When the time increment is reduced to one tenth of a second, the angular error gets much smaller, i.e. for UAV speed equal to 30 m/sec, the maximum angular error becomes 0.23 degrees. This makes sense because as the update rate is increased, the tracking system will refresh its scan angle more frequently.

With the help of Fig.5, the HPBW has been found to be approximately 16 degrees. On the other hand, Figure 8 shows that it is actually around 13 degrees. This difference arises from the approximations made in obtaining Eq. (4), an equation to calculate HPBW. The difference encountered is expected for small arrays. [8]

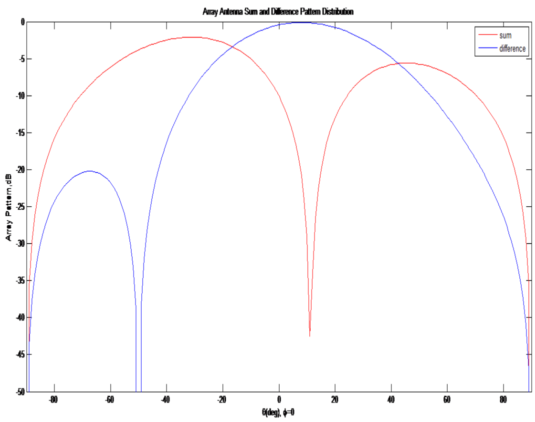

Fig.8 Array antenna sum and difference pattern distribution.

v) Crossover Loss

Gain is another concern for tracking a target. If the angular position of the target is squinted with respect to the peak of the main beam, a loss in gain called *crossover loss* occurs. Crossover loss is calculated as follows for a Gaussian beam: [8]

$$G(\Delta\theta) = G_0 e^{-K(\Delta\theta)^2/(\theta_B)^2} \quad (6)$$

$$L_{CO} = 10\log\left(\frac{G(\Delta\theta)}{G_0}\right) \quad (7)$$

Where G_0 is the gain of the beam peak, $\Delta\theta$ is the angular difference between the beam and the position of the target with respect to the antenna bore-sight, θ_B is HPBW, $K = 4\ln(2) = 2.773$, and L_{co} is the crossover loss in dB. The SNR is obtained from the Friis equation:

$$SNR = \frac{P_r}{N} = \frac{P_t G_t G_r \lambda^2 pq}{(4\pi R)^2 L_S} \cdot \frac{1}{k_B T_S B} \quad (8)$$

Where P_r is the received power, N is the noise generated in the system, P_t is the transmitter power on the UAV, G_t and G_r are the antenna gains of the transmitting and receiving antennas, respectively, λ is the wavelength, R is the range, L_s is the system loss, p is the polarization efficiency (or polarization mismatch factor) and *q* is the input mismatch factor, k_B is Boltzman's constant, T_s the temperature of the system and B is the bandwidth of the receiver.

Eq. (8) reveals the fact that SNR is proportional to gain, meaning that the smaller the gain, the smaller the SNR. As seen in the equation, the reduction in gain also causes loss in receiver power. If the system does not have sufficient receiver power, it cannot have the necessary bit rate to maintain the data link and it suffers loss of information. If range is computed based on a given SNR:

$$R_{\max}^2 = \frac{P_t G_t G_r \lambda^2 pq}{(4\pi)^2 (SNR) L_S} \cdot \frac{1}{k_B T_0 B} \quad (9)$$

It is seen that range of the tracking system is dependent on gain as well. Losses in gain reduce the range of the system and cause loss of track.

The noise level can be changed with receiver hardware. A more appropriate quantity that is independent of the receiver noise is the received power P_r. In order to examine the range performance of our tracking system, a MATLAB program, based on Eq. (8) and (9) was written. It is assumed that our system does not have any polarization or feed mismatch losses. Moreover, the sensitivities according to bit rates of Cisco Aironet 350 cards are used in the program. The bit rates and sensitivities are summarized in Table 2. [8] The P_t is entered as 1 Watt and G_t is 1. The G_r is 12 dB and the increase in receiver gain due to ground plane element factor effects is neglected.

III. RESULTS

The results of the MATLAB program are shown in Table 2. The higher the bit rate, the less range we will have. These bit rates can be determined in accordance with the operation type. The results seen in Table 2 are overly optimistic, because the calculation does not take the losses into account. The FCC limits the Effective Radiated Power (ERP) = ($P_t G_t$) to 4 Watts. If the ERP of the transmitter antenna on the UAV is increased to 4 Watts, the range increases to double the range values seen in Table 2.

TABLE 2. BIT RATES AND MINIMUM SENSITIVITY LEVEL EQUIVALENTS VS. RANGE FOR AN ERP OF 1 W.

Bit Rate Level	Minimum Sensitivity	Range
1 Mbps	-94 dBm	62.76 km
2 Mbps	-91 dBm	44.43 km
5.5 Mbps	-89 dBm	35.29 km
11 Mbps	-85 dBm	22.27 km

Using the antenna parameters of Fig. 7 and taking $\Delta\theta$ as 2.305 degrees (because it is the maximum angular error), the maximum crossover loss of the system is calculated at approximately -0.25 dB. Fig. 4 has shown that an 8-element system needs a gain of more than 12 dB. A loss of 0.25 dB in gain does not cause a big decrease in SNR of the system.

If the UAV travels the path in 22 seconds at speed of 60 m/sec (as opposed to 30 m/sec), the maximum tracking error is

4.323 degrees, as seen in Fig. 9. Even though this angular error is not within the approximated limits of the MATLAB code, it is still within the limits of the system design, as seen in Fig. 7. Consequently, the system does not lose the track with a UAV at the speed of 60 m/sec.

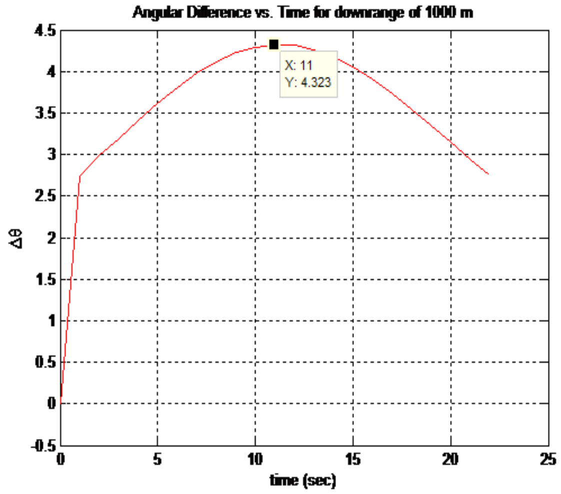

Fig. 9 .Angular difference (Tracking Error) vs. time for a UAV 1000 m at a speed of 60 m/sec.

Crossover loss is calculated from Eq. (6) and (7) as 0.879 dB. Again, this loss is much less than the required gain of the tracking antenna, so much less so that it can be ignored. This result also shows that the system does not lose the track.

As far as the maximum speed is concerned, the maximum angular error for a UAV with the speed of 90 m/sec is 5.943 degrees, as seen in Fig. 10. Crossover loss is calculated as 1.66 dB. These parameters are still within the acceptable limits. As a result, the system does not lose the track of a UAV flying with maximum speed at 1 km and can maintain the data link between the UAV and the tracking system.

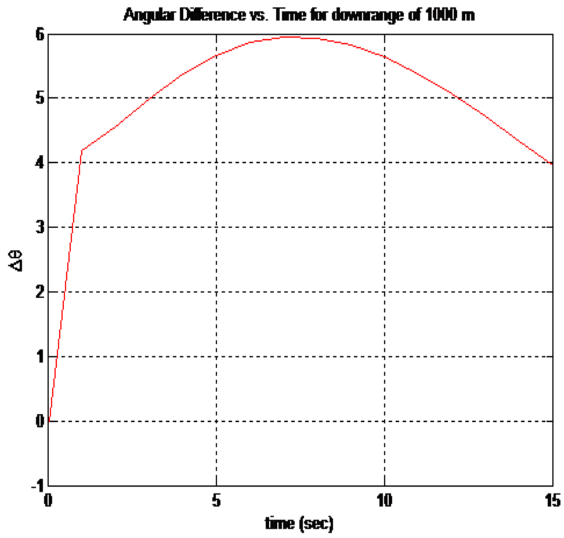

Fig. 10 Angular difference (Tracking Error) vs. time for a UAV downrange 1000 m at a UAV speed of 90 m./ sec.

A comparative analysis between published research work [1] and proposed work is shown in Table 3.

TABLE 3. COMPARISION BETWEEN PROPOSED WORK AND PREVIOUS WORK

S. No.	Technique/ parameters/Type	Base Paper	Publishing Paper
1	Antenna	Uniform circular Array	Phased Array Antenna
2	Technique	OFDM	Analytical
3	Software Used	NA	MATLAB-2012
4	Pitch Angle φ	φ=45°	NA
5	Scan Angle θ_s	NA	θ_s=40°
6	No.of Antennas	4,16,32,128	2,4,6,8,10,12
7	Antenna elements suggested	16	8
8	Velocity Range of UAV (m/sec)	[70 120]	[30 60 90]
9.	Max. Crossover losses	NA	[0.25 0.879 1.66] dB for 30,60,90 m/s UAV speed respectively
10.	Bit Rate/ Sensitivity/ Range of Tracking Signal	NA	Varied (Table 2)

IV. CONCLUSION

In this research paper different parameters and essential conditions i.e. elimination of grating lobes, number of elements, element spacing, HPBW, accuracy of tracking system, crossover losses are calculated using MATLAB software and suggestions to design an accurate tracking radar system containing phased array are given.

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