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Upgrading Two Dimensional Search Radar to Three Dimensional Search Radar Based on SDR

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Abstract

This paper presents an exploitation of the existing two dimensional radars (2D) which have two identical antennas for reception to be upgraded to a three dimensional radar (3D) in order to measure the height as well as the slant range and azimuth direction. The height measurement is important for preliminary information for reducing the time required for acquisition. Software Defined Radio (SDR) is chosen for the implementation of height finder processor is given in this paper. Design parameters are selected for the proposed height finder processor in order to accommodate SDR requirement. This work is also concerned with the analysis of the parameters which affect the accuracy of height finding. These parameters include the refraction index, smooth surface reflection, divergence and rough surface reflection. The results of the analysis show the feasibility of this proposal to upgrade the 2D to 3D radars.

Keywords: Radar, Height finder, V-Beam, Elevation angle measurement.

تطوير رادار الكشف ثنائي الأبعاد إلى رادار كشف ثلاثي الأبعاد باستخدام (SDR)

الخلاصة

يتضمن هذا البحث استثمار الرادارات الثنائية الأبعاد(2D). التي تستخدم هوائيين متماثلين للاستلام بتطويرها لتكون ثلاثية الأبعاد لغرض قياس ارتفاع الأهداف إضافة إلى قياس مدى الهدف المائل وزاوية الاتجاه الأفقية. قياس الارتفاع مهم لتامين المعلومات الأولية لغرض تقليل الزمن أللازم لمتابعة الهدف. تقنية البرامجيات المعرفة راديويا (SDR) تم اختيارها لبناء وحدة معالج إيجاد الارتفاع. المخطط الكتلي لوحدة معالج إيجاد الارتفاع المقترحة تم تضمينه في هذا البحث. القيم التصميمية لوحدة إيجاد الارتفاع تم اختيارها بما يتلاءم مع متطلبات تقنية(SDR). كذلك يتضمن هذا البحث تحليل للعوامل المؤثرة في إيجاد الارتفاع. هذه العوامل تتضمن الانكسار ومعامل الانعكاس من السطوح الملساء والانفراج ومعامل الانعكاس من السطوح الخشنة. نتائج التحليل بينت معقولية تطوير الرادارات الثنائية إلى رادارات ثلاثية.

1. Introduction

The principle of the radar operation is based on generating pulses of radio frequency energy and transmitting these pulses via a directional antenna, as shown in Fig.(1). When a pulse hits a target in its path, a small portion of the energy is reflected back to the antenna. The radar receives a reflected pulse if it is higher than a certain optimized threshold. The radar indicates the range to the target as a function of the time required of the pulse travelling to the target and returning [1, 2]. The

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radar indicates the direction of the target by the direction of the antenna at the time of the received reflected signal.

The basic requirement, to measure the range, bearing and other attributes of a target remains the same for all radar applications. The radar systems must obtain certain information from the radar signal. The kinds of radar information that can be extracted include range, azimuth angle, elevation angle(height finding), target size and target shape. To obtain various kinds of information, different techniques must be used to optimize the desired kind of information.

Developments trends in radar systems are the system design, the method and speed of processing the return radar signals, the amount of information which can be obtained, and the way that the information is displayed to the operator. The heart to modern radar systems is the digital computer and its data processing capability, which can extract avast amount of information from the raw radar, signals [2]. It is expensive to upgrade and maintain a radar system each time a new requirement comes into existence. Radar systems are gravitating towards minimal hardware designs using flexible soft architecture software. Recently, Software Defined Radio (SDR) have become highly configurable hardware platforms that provide the technology for realizing the rapidly expanding new radar systems[3]. Many sophisticated signal processing tasks are performed in a SDR, including advanced

compression algorithms, power control, power spectral analysis, digital filters and protocol management.

This paper aims at exploiting the existing two dimensional (2D) radar (azimuth and range information that can be extracted from 2D radar) which have two separate antennas and upgraded to three dimensional(3D) radar to evaluate the height of the target as well as the azimuth direction and range which are given by two dimensional radar. This work includes an analysis and a simulation of the elevation error due to the surface reflections in addition to a proposed implementation technique of the height finding processor based on SDR.

2. Description of the proposed height finder radar

Target height found by ground radar is based on calculation rather than a direct measurement because the basic information from radar includes range and angular measurements. Height evaluation is carried out by computations, utilizing the range of the target and its elevation angle.

The proposed height finder radar is based on the earliest three dimensional radar concept used in civilian and military air surveillance operations utilizing the V-beam principles [4]. V-beam principle employs two antenna beams with 45°seperation between them, radiated from a common rotating antenna structure as shown in Fig(2).The V-beam technique is used because of the compatibility and simplicity to upgrade the available two dimensional radars in service. Fig (3) shows the block diagram of the proposed height finder.

The steps of upgrading process can be summarized as follows:

1. Rotating one of these two antennas by 45° with respect to the other antenna in order to form two V-beams

(vertical beam and slant beam). The two beams are energized by either two or single transmitter.

2. Converting the received two signals to an intermediate frequency and then applied to analog to digital converter (ADC). These two signals applied to SDR unit as shown in Fig. (3).

3. The azimuth position of the two centers of the vertical and slant beam blips and their angular separation can be measured (the angle θ) by using synchro converter and synchro to digital converter (SDC). A synchro converter is a transducing instrument to measure shaft angle and positioning systems. The rotor winding of a synchro converter is excited by an AC voltage. The voltage induced in stator winding terminals (S_1, S2, S3) will be proportional to the cosine of the angle between the rotor coil axis and stator coil axis. The induced voltages in terminals (S_1, S2, S3) will be converted into digital format by SDC. The code for the digital output of SDC is binary and the word lengths range from 10 to 18 bits (12 bits is chosen for this proposed system which gives accuracy 0.088^{0}). The signal of synchro to digital converter applied to SDR unit as shown in Fig. (3).

3. Target Height Elevation Analysis

The height of the target (h), as shown in Fig (2), is given by [4]:

$$h = D \sin\theta \qquad \text{…. (1)}$$

where

D = Ground range from radar to the target

θ = Angle between centers of the vertical and slant beam blips is measured when the antenna rotates, the vertical beam intersects the target first and then after that, by angle θ, the slant beam intersects the target.

But $$D^2 = R^2 - h^2 \qquad \text{.... (2)}$$

where R = slant range of the target Substitute eq (2) by (1)

$$h = \frac{R \sin\theta}{\sqrt{1+\sin^2\theta}} \qquad \text{……. (3)}$$

Equation (3) describes the height of target which is determined by radar in term slant range and angle θ. However, the target height is determined as function of elevation angle ϕ. The relationship between angle θ and elevation angle ϕ can be found as follows. The target height (h_f) for the flat earth case, as shown in Fig (4), is given by:

$$h_f = R \sin\phi \qquad \text{...... (4)}$$

Substituting equation (3) by equation (4) yields:

$$\sin \emptyset = \frac{\sin\theta}{\sqrt{1+\sin^2\theta}} \text{..... (5)}$$

Substituting equation (5) by equation (4) for flat case yields:

$$h_f = \frac{R \sin\theta}{\sqrt{1+\sin^2\theta}} \qquad \text{…… (6)}$$

The target height for the spherical earth case, as shown in Fig(4), can be derived from the law of the cosines[4].

$$(r + h_s)^2 = R^2 + r^2 - 2R\,r\cos\left(\phi + \frac{\pi}{2}\right)$$

$$(r + h_s)^2 = R^2 + r^2 + 2R\,r \sin\phi$$

$$h_s = \frac{R^2+2R\,r\sin\phi}{2r+h_s}$$

But $2r >> h_s$

$$h_s = \frac{R^2}{2r} + R\sin\phi \quad \text{...... (7a)}$$

Substituting equation (5) by equation (7a)

where

$$h_s = \frac{R^2}{2r} + \frac{R\sin\theta}{\sqrt{1+\sin^2\theta}} \quad \text{... (7b)}$$

$h_s =$ Target height above earth surface

r =Radius of earth =6370.88Km

Equations (6 and 7a) expressed the height of the target as a function of the angle θ. The effect of the radar antenna height is neglected since the height of the radar antenna is small if compared with target height and to simplify the analysis [4].

4. Accuracy Analysis of Height Finding

All height finding techniques accuracy are based on the accuracy of elevation angle measurements. The main source of the error is the surface reflection and atmospheric reflection. Surface reflections combine vectorially with direct path signals by antenna, produce an error in the elevation angle measurement due to the variation in the amplitude and phase of the received signals.

Propagation factor (*F*) is used to express the relationship between the direct and indirect signals. The propagation factor, also accounts for the radar antenna pattern effects, is given by [5]:

$$F = \left|\frac{E_d}{E_d+E_i}\right| \quad \text{...... (8)}$$

where

E_d = direct signal received via a direct path.

E_i = indirect signal received via an indirect path.

However, the relationship between the radar range and propagation factor is given by:

$$R = R_o F \quad \text{....... (9)}$$

Where

R_o= radar detection in free space.

Equation (9) shows that if $F \neq 1$, then an error is introduced in the value of the slant range (R) but the height of the target depends on the value of (R) according to equations (6,7b).Thus the error in the height finding radar is a function of the propagation factor.

Assume the two beams (A and B) of the antenna are identical and have the same propagation factor. Fig (5) shows the geometry for analysis of elevation errors due to ground reflections. The relative received field strength of either beam A or B arriving along the direct path at elevation angle (ϕ) is given by [4, 5]:

$$E_d == \frac{\sin[\pi(z/\lambda)\sin\phi]}{\pi(z/\lambda)\sin\phi]} \quad \text{... (10)}$$

where:

z= Antenna Aperture = 40λ

λ= Wave length

Then net received field strength at the feed point of each antenna direct and indirect fields are given by [4]:

$$E = E_d + \Gamma E_{(2\phi)} e^{-j(2D\sin\phi)} \quad \text{….. (11)}$$

where

$E_{(2\phi)}$ = Relative received field strength of antenna beam A from reflected path at $2\emptyset$ from peak of antenna beam A

Γ = Reflection coefficient.

= $1 < \pi$ for horizontal polarization over an infinite conducting plane

D = 40λ the height of radar antenna

The magnitude of propagation factor can be obtained by substituting equation (10, 11) in equation (8). Yield:

$$F = \left| \frac{E_d}{E_d + \Gamma E_{(2\phi)} e^{-j(2D\sin\phi)}} \right| . \quad (12)$$

To improve the accuracy of height determination the following effects must be taken into consideration

-Atmospheric reflection

- Ground reflection

4.1 Atmospheric Refraction

In free space, radio waves travel in straight lines. However, in the presence of the earth atmosphere, they bend (refract). Refraction is a term used to describe the deviation of radar wave propagation from straight line caused by the variation of the index of refraction [4]. The index of refraction is defined as the ratio of the electromagnetic wave in free space to the velocity of electromagnetic wave in the medium.

The general method of accounting for atmospheric refraction in radar height calculations is to replace the actual earth radius (r), by an equivalent earth radius r_e which is given by:

$$r_e = K\, r \quad \text{..(13)}$$

where $K = \frac{4}{3}$ (factor K by which the earth radius must be multiplied). Equation (13) is used to replace r by r_e in order to change the actual atmosphere by a homogenous atmosphere in which electromagnetic wave travels in straight lines rather than curved lines. This method is used only for approximating calculation in short range height finding, otherwise the factor K is given by [8]:

$$K = \frac{1}{1 + r(dn/dh)} \quad \text{.. (14)}$$

where dn/dh is the rate of change of reflective index n with height.

4.2 Ground Reflection

The characteristics of the reflected radar waves from the earth's surface are changed in amplitude and phase. Three factors that contribute to these changes are the reflection coefficient for a smooth surface, the divergence factor due to earth curvature and the surface roughness [5].

4.2.1 Smooth Surface Reflection Coefficient

For parallel and perpendicular polarizations, the smooth reflection coefficients are given by[7]:

$$\Gamma_{sh} = \frac{-\epsilon_r \sin\gamma_i + \sqrt{\epsilon_r - \cos^2\gamma_i}}{\epsilon_r \sin\gamma_i + \sqrt{\epsilon_r - \cos^2\gamma_i}} \quad \text{…. (15a)}$$

$$\Gamma_{sv} = \frac{\sin\gamma_i - \sqrt{\epsilon_r - \cos^2\gamma_i}}{\sin\gamma_i + \sqrt{\epsilon_r - \cos^2\gamma_i}} \qquad \text{………..(15b)}$$

where

$\Gamma_{sh} =$ Smooth surface reflection coefficient for horizontal polarization.

$\Gamma_{sv} =$ Smooth surface reflection coefficient for perpendicular polarization.

$\gamma_i =$ Grazing Angle

$\epsilon_r =$ Relative Dielectric constant

4.2.2 Divergence

When an electromagnetic wave is incident on a round earth surface, the reflected wave diverges, because of the earth's curvature and energy is defocused. The divergence factor D) is given by [7]:

$$D = \frac{1}{\sqrt{1 + \frac{2r_1r_2}{r_e r \sin\gamma_i}}} \qquad \text{….(16a)}$$

where

$r_1 r_2$ = Sectors length between the projection of the radar and targets, respectively, over round earth and earth center.

$$r - r_1 + r_2 \qquad \text{… (16b)}$$

However, the divergence factor can be extracted from curves presented by Blake [8].

4.2.3 Rough Surface Reflection

Surface roughness strongly influences the strength of radar returns. Surface roughness (S_r) is given by[9]:

$$S_r = e^{-2\frac{(2\pi h_{rms}\sin\gamma_i)^2}{\lambda}} \qquad \text{… (17)}$$

where h_{rms} is the rms surface height irregularity.

The total reflection coefficient Γ_t can be expressed by combining the above three factors as follows [5]:

$$\Gamma_t = \Gamma_{(sh,sv)} D\, S_r \qquad \text{... (18)}$$

where $\Gamma_{(sh,sv)}$ is the surface reflection coefficient for horizontal or vertical polarization.

Γ_t is used instead of Γ in equation (11) to introduce the effect of ground reflection. The Γ_t parameters are calculated for small grazing angle by using equations (13a, 14a, 15) as follows:

1. The value of Γ_{sh} is approximately -1.

2. The value of D is approximately 1 (since $r_1 r_2 << r_e$)

3. The average value of S_r is approximately 0.97 for $h_{rms} = \frac{\lambda}{2\pi}$

Thus the value of Γ_t is approximately (-0.95). Fig (6) shows the flow chart which is used for analysis and calculation.

5. Software Defined Radio (SDR)

SDR is a collection of hardware and software technologies that enable reconfigurable system architectures for wireless networks and user terminals to reduce the amount of signal processing in radio application [10,11]. It is expensive to upgrade and maintain a radar system each time a new requirement comes into existence. Radar systems are gravitating towards minimal radio hardware designs using flexible architecture software radio. SDR can greatly simplify the design of a radar system since typical hardware radio components are replaced by software design. SDR uses programmable digital devices to perform the signal processing necessary to transmit and receive information at radio frequency. Devices such as digital signal processing and field programmable gate array (FPGA) uses software to provide them with required signal processing functionality. This technology offers greater flexibility to perform different functions, potentially longer life, reduce the size and complexity and power consumption and cost[12]. For these advantages, SDR is selected to implement the proposed height finder processor to upgrade the existing 2D search radar to 3D radar.

The ideal SDR architecture consists of a digital subsystem and a simple analog subsystem. The analog functions are restricted

to those that cannot be performed digitally. The architecture pushes the analog conversion stage right up as close as possible to the antenna, in this case prior to power amplifier in the transmitter and after the low noise amplifier in the receiver [13]. SDR technique is used to implement height finder processor, as shown in Fig (3) according the steps in article (2).

6. Results

Fig (7) shows the variation of $\boldsymbol{E}$ as function of elevation angle according to the equation (11). The difference in the amplitude of $\boldsymbol{E}$ is the results of the vector summation of the signals through direct path and reflected path. Fig (7) also shows the effects of divergence and surface roughness according to equation (18) by substituting $\boldsymbol{\Gamma_t}$ instead of $\boldsymbol{\Gamma}$ in equation (11).

Fig (8) shows the relationship between the height of the target and elevation angle for different slant ranges for both cases of flat and spherical ground according to equations (6,7b). Fig(8), also shows the effects of divergence and surface roughness according to equations (18) by substituting $\boldsymbol{\Gamma_t}$ instead of $\boldsymbol{\Gamma}$ in equations (6, 7b).

Fig (9) shows the variation of propagation factor $|\boldsymbol{F}|$ as a function of elevation angle according equation (12). This variation is due to the reflected received signal which is a function of the incident angle of the returned echo. Fig (9), also shows the small effects of divergence and surface roughness on the propagation factor, by substituting $\boldsymbol{\Gamma_t}$by using equation (18). Fig (10) shows the effect of the propagation factor$|\boldsymbol{F}|$upon the value of the height of the target for both flat and spherical cases ($\boldsymbol{h_f}^{-}, \boldsymbol{h_s}^{-}$)according to equations (6, 7b) after multiplying the value of *R* by factor $\boldsymbol{F}$ for each value of elevation angle according to equations (8 and 9).

7. Conclusions

Upgrading the existing 2D radar to 3D based on SDR is proposed. This proposal can be also used to replace the main processing hardware units by using a software based on SDR to increase capability and reduce both size and cost.

Theoretical analysis shows that the error in the height measurement is within acceptable error for normal 3D radar.

8. References

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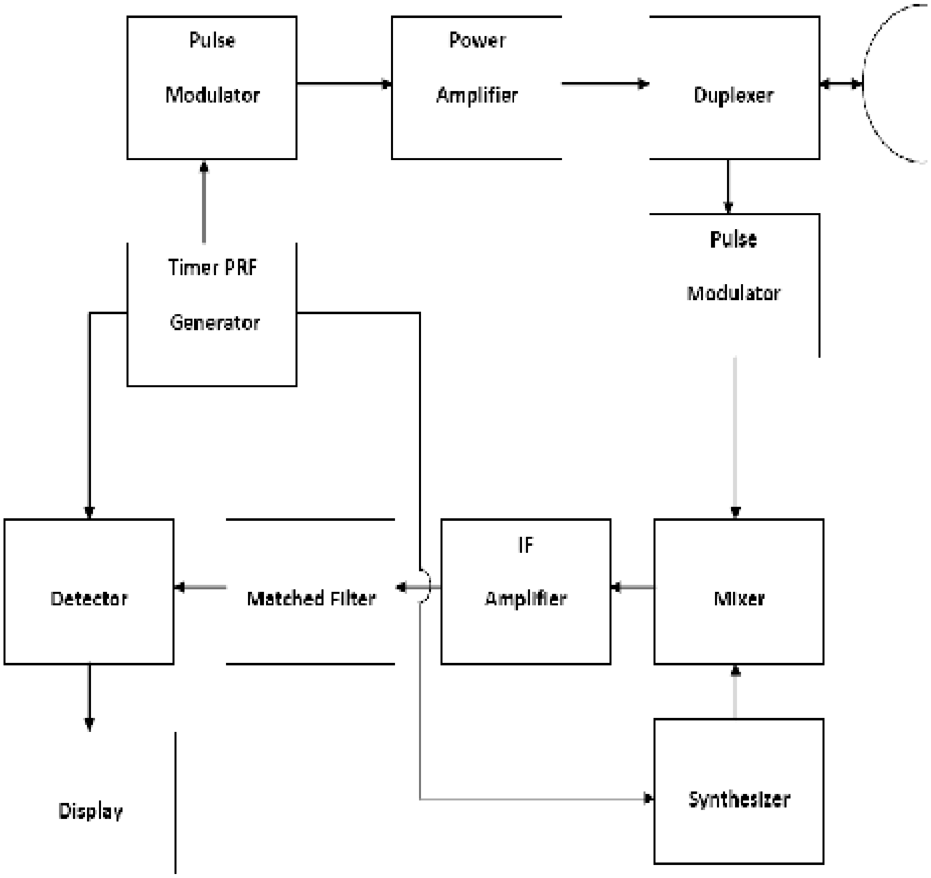

Fig. (1) The Basic Radar Working Principles

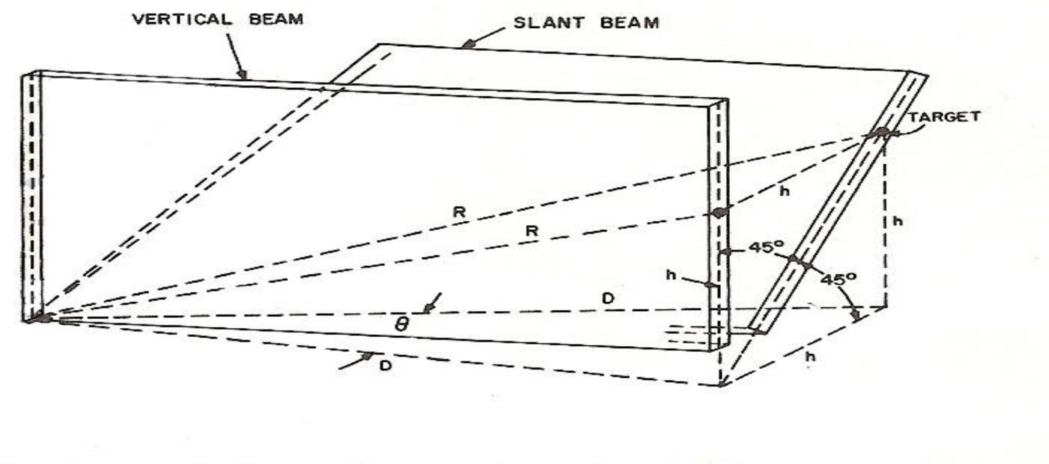

Figure (2) Two V- beam geometry

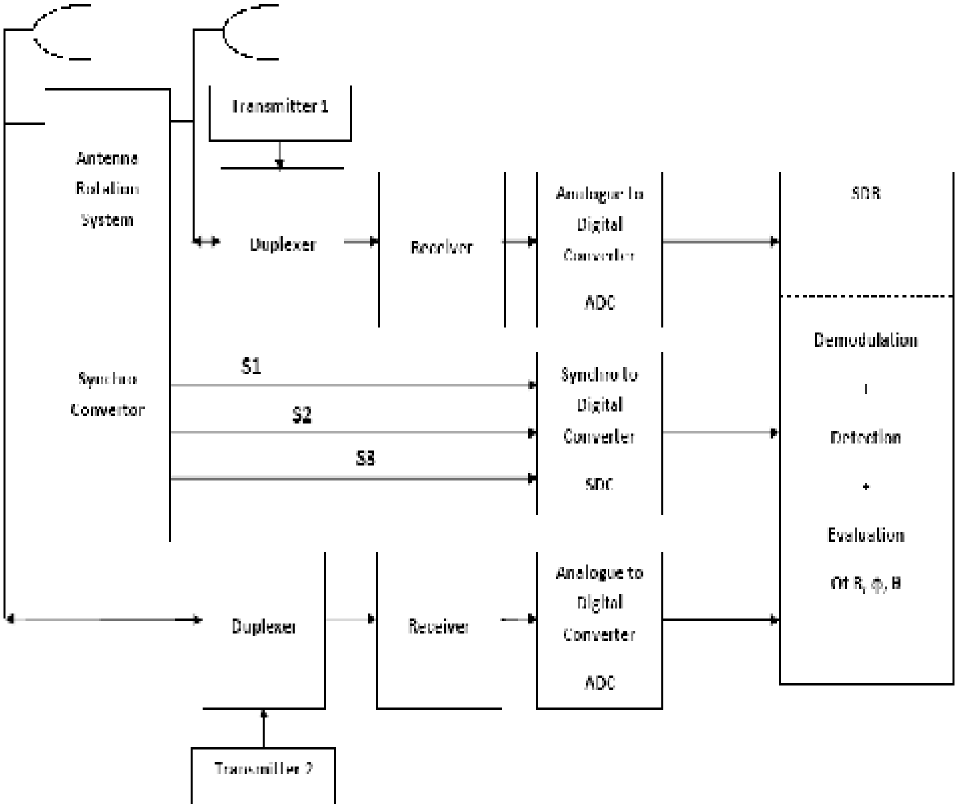

Fig. (3) Proposed System.

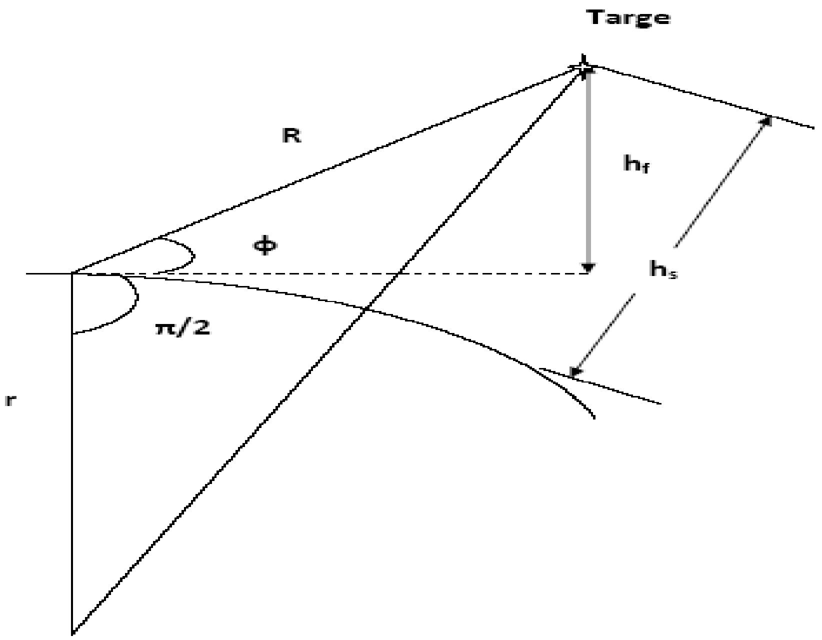

Fig. (4) Flat and Spherical Earth Geometry

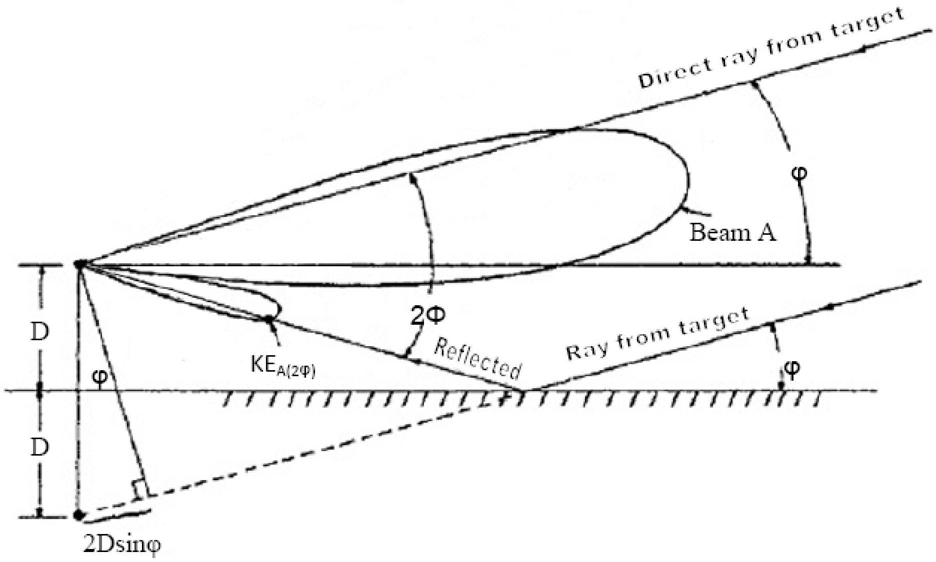

Fig. 5 Geometry for the analysis of radar height finding error due to ground reflection

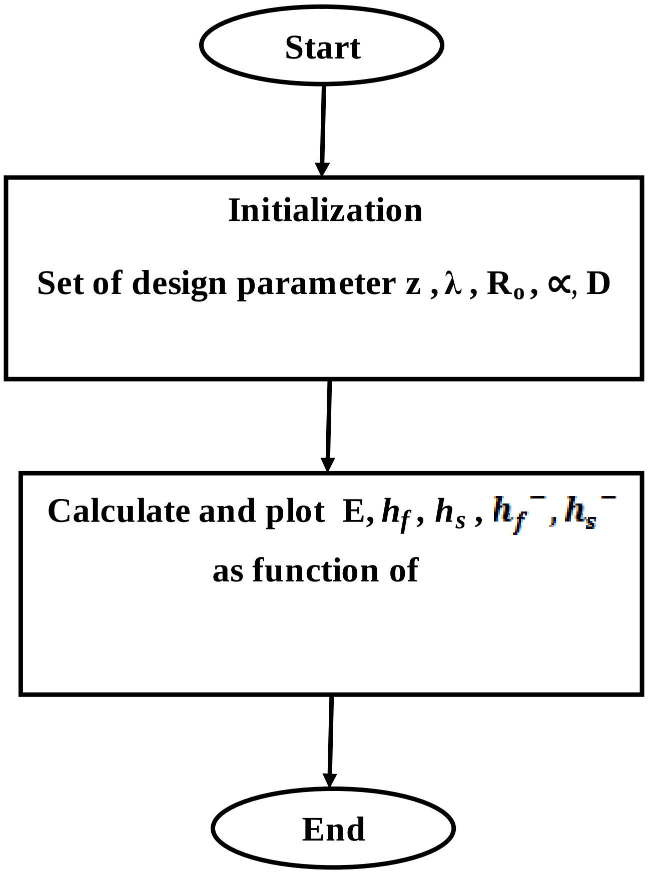

Figure (6) Flow chart of the analysis and calculation

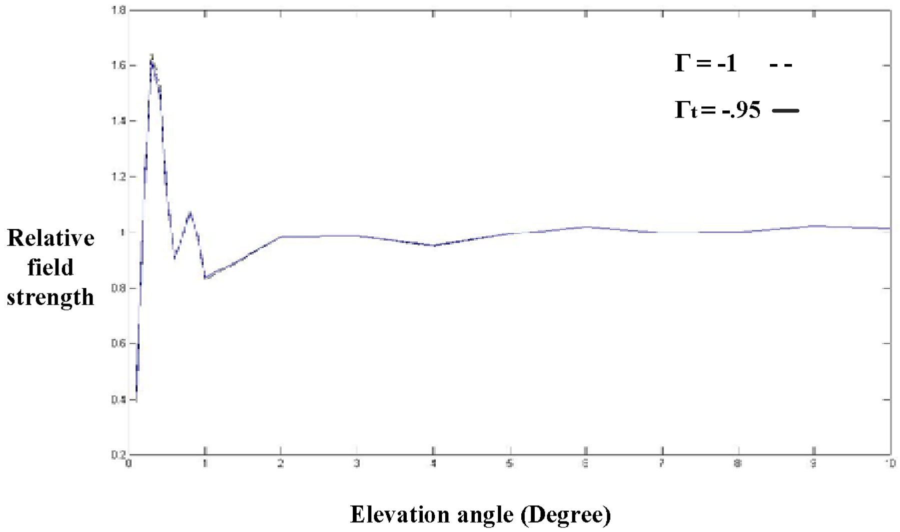

Figure (7) Relative field strength received in beams (A or B) due to ground reflection as a function of the elevation angle

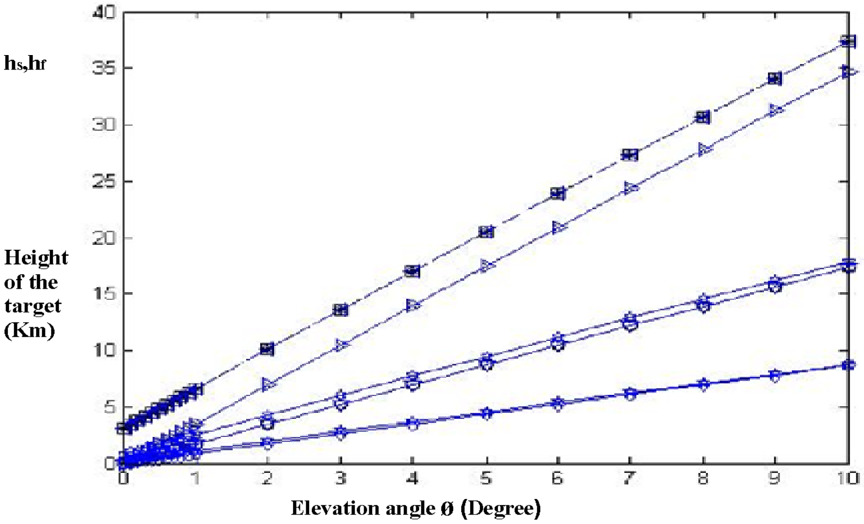

Figure (8) Variation of the height of the target with elevation angle for different slant ranges for |F|=1.

- variation h_f with Γ= -1 , R=50 km ; + variation h_s with Γ= -1 , R=50 km

–o variation h_f with Γ= -1 , R=100 km ; * variation h_s with Γ= -1 , R=100 km

–x variation h_f with Γ= -1 , R=200 km ; –□ variation h_s with Γ= -1 ,R=200 km

-◊ variation h_f with Γ= - .95 , R=50km ; ☆ variation h_s with Γ= - .95, R=50 km

▽ variation h_f with Γ= - .95, R=100 km ; ✡ variation h_s with Γ= - .95, R=100 km

◁ variation h_f with Γ= - .95, R=200km ; ▷ variation h_s with Γ= - .95,R=200km

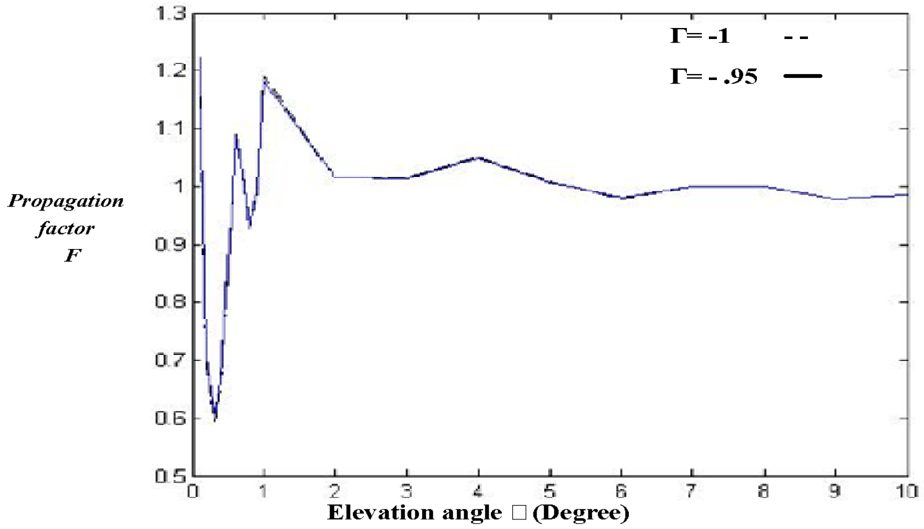

Figure (9) Variation of the propagation factor with elevation angle

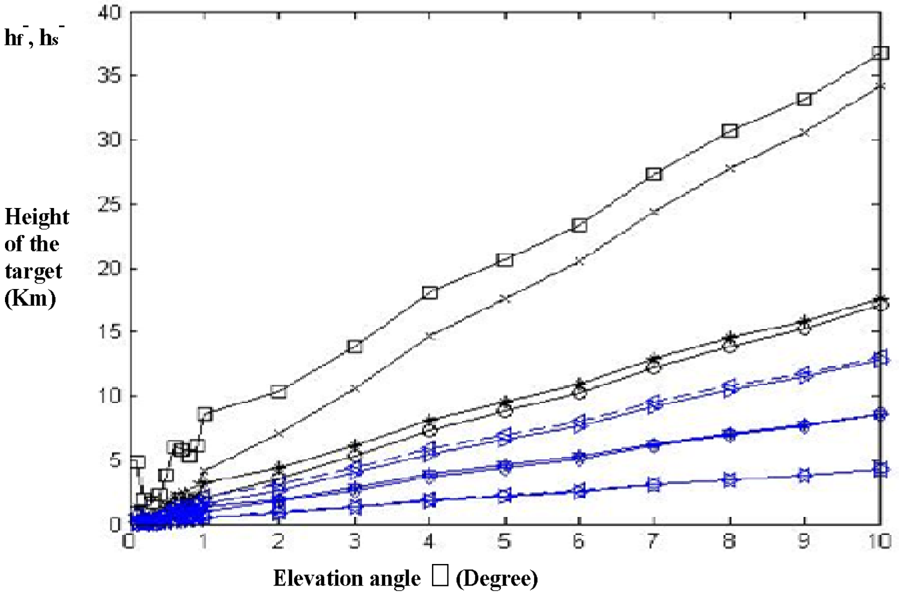

Figure (10) Variation of the height of the target with elevation angle for different slant ranges for |F|≠1.

- variation h_f^- with Γ= -1 , R=50 km ; + variation h_s^- with Γ= -1 , R=50 km

–o variation h_f^- with Γ= -1 , R=100 km ; * variation h_s^- with Γ= -1 , R=100 km

–x variation h_f^- with Γ= -1 ,R=200 km ; –□ variation h_s^- with Γ= -1 , R=200 km

-◊ variation h_f^- with Γ= - .95 , R=50 km ; ☆ variation h_s^- with Γ= - .95, R=50 km

▽ variation h_f^- with Γ= - .95 , R=100 km ; ✡ variation h_s^- with Γ= - .95, R=100 km

◁ variation h_f^- with Γ= - .95, R=200km ; ▷ variation h_s^- with Γ= - .95, R=200 km