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ADVANCES IN MICROWAVE COMMUNICATION AND RADAR*

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Introduction

The paper presents improvement in communication and radar technique for a mobile system. It is shown that continuous communication can be maintained with a moving vehicle through satellite for all angular orientations of the vehicle if array antennas with computer controlled phase shifters are used. The angular coordinates of a satellite looking from the array antenna change as the vehicle takes a turn, moves along an inclined road and up or down a hill. The change in angular co-ordinates recorded by an indicator initiates a command to the phase shifter through the computer.

Use of computer controlled phase shifter has the flexibility that the array antenna can be used for simultaneous multifunction purposes like simultaneous search, track and multitrack demanded from modern radar system. Phase-Only Control Method of beam shaping enables almost instantaneous change in beam shape from narrow to broad and vice versa. The phase distribution required for the generation of beam of different shapes is found by the method of stationery phase. The method of beam scanning is also presented.

Scenario Before Availability of Satellites

Before Availability

Before availability of satellites, the space between the earth's surface and ionosphere (Fig. 1) was used for radio communication upto short radio wave band[1]. VHF (used for TV and FM broadcasting) and Microwave are not reflected by and penetrate the ionosphere. The electromagnetic waves in these frequency bands are highly attenuated when attempt is made for gliding them along the surface of the earth. Thus the region of coverage[2] for signals in these frequency bands is restricted to the line of sight (Fig. 2). Microwave signal is used for point to point communication and generation of narrow beam in radar system while VHF is used for point to point communication as also for broadcasting. Coverage beyond the line of sight is obtained through relay stations.

Transmission of microwave fairly well beyond the line of sight can be realized using scattering from turbulences[2] in the upper layers of the troposphere (Fig. 3).

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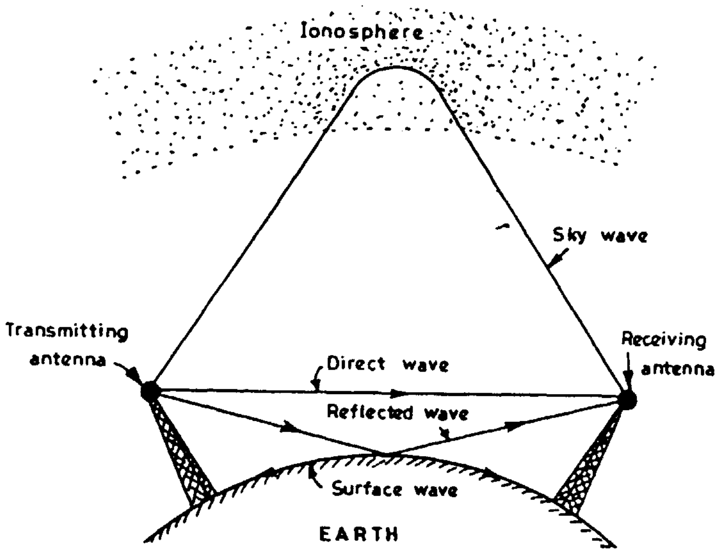

Fig 1 Wave components near the surface of the earth

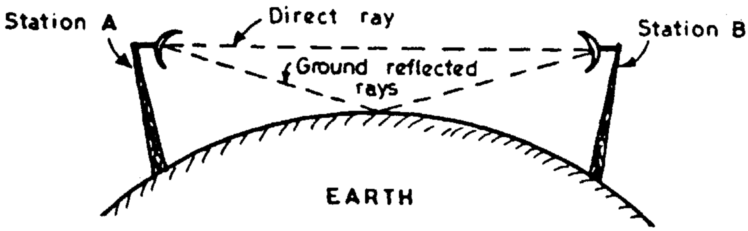

Fig 2 Line of sight propagation

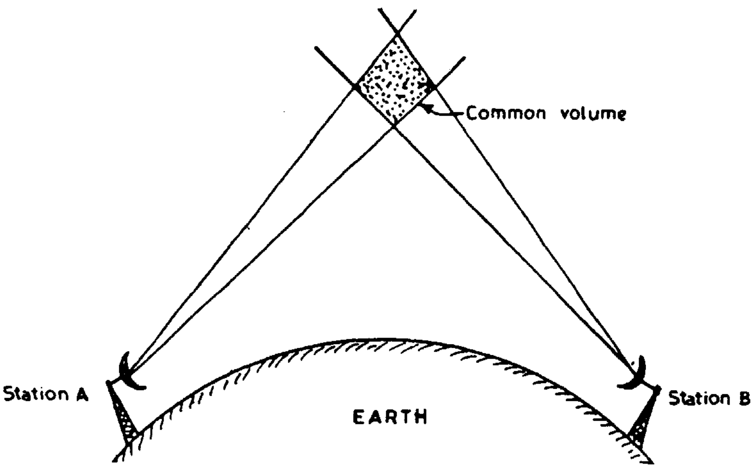

Fig 3 Troposcattered communication link

After Availability

After the availability of geostationary communication satellites, dish antennas mounted on towers are in use for transmission and reception of TV as well as communication (telephone and other messages) signals (Fig. 4). The axes of the dish antennas are pointed to the geostationery satellites. Reception of TV signals directly from satellite is obtained through a dish antenna on the roof top (Fig. 5).

Communication with a Moving Vehicle Through Satellite

Angular orientation of satellite seen from a moving vehicle with reference axes of the vehicle on the earth and zenith of the place (called earth co-ordinates) changes continuously depending upon the nature of the terrain and direction of the road. If a dish antenna is mounted on the top of such a vehicle, the antenna has to be continuously steered exactly in accordance with the change in orientation of its axes to maintain communication link with the satellite. The bulky and heavy mechanical steering arrangement cannot be recommended in the case of a light vehicle such as a car. The problem can be avoided through replacement

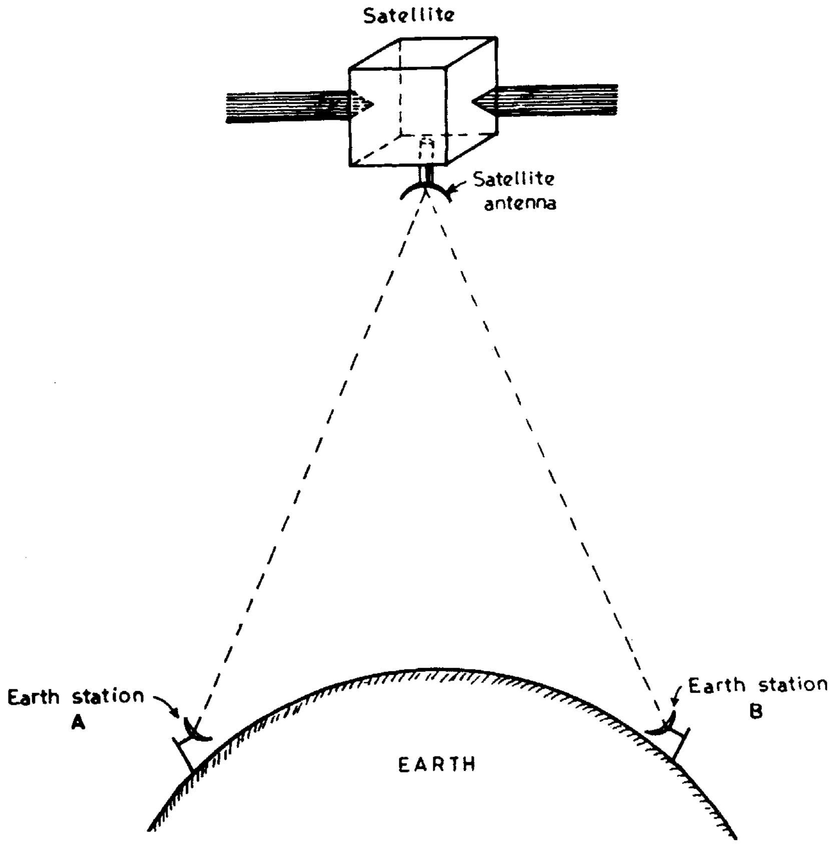

Fig 4 Communication using satellite

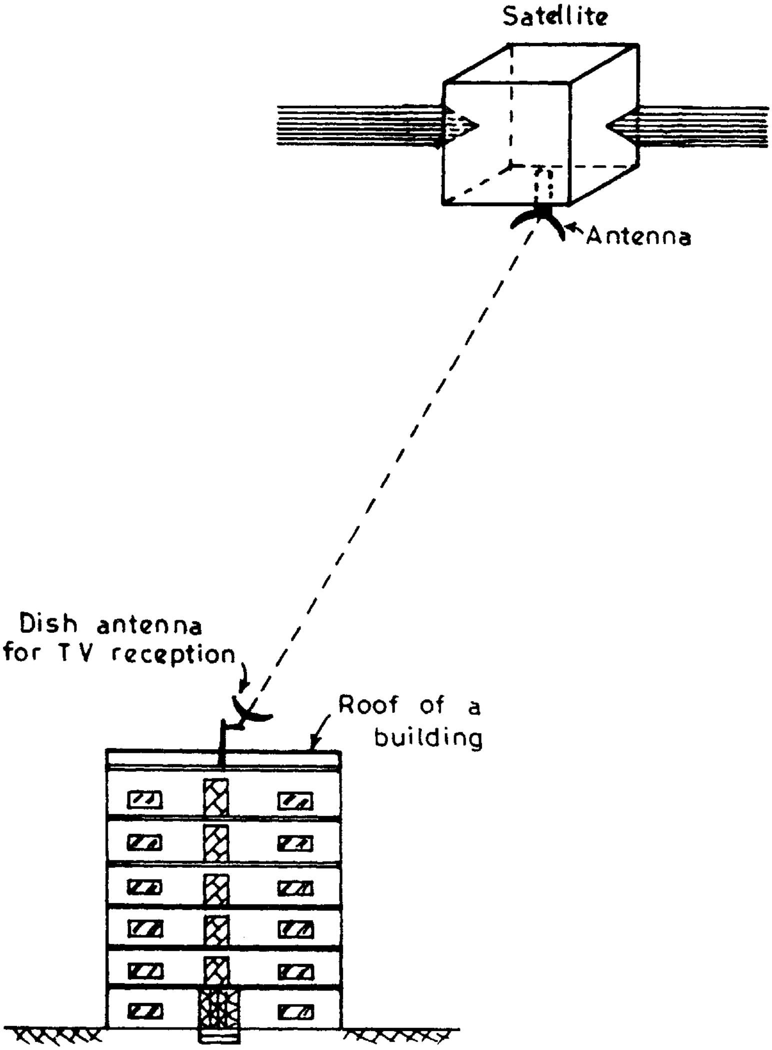

Fig 5 Dish antenna on the roof top for direct reception from satellite

of the dish antenna by an antenna array, in which use of computer controlled electronic phase shifters permits almost instantaneous positioning of the beam towards the satellite. The antenna remains fixed in position and only the beam moves[3].

The array antenna is fixed on the top of a car. It consists of circular waveguide radiators arranged periodically at the corners of equilateral triangles (Fig. 6). The circular waveguide radiators are in the form of integrated phase shifter and radiator. Phase shift is produced by a piece of ferrite material inside the circular waveguide. A change in magnetic field in the material causes a change in the phase shift. The magnetic field and hence the phase shift is altered by changing the current through a coil.

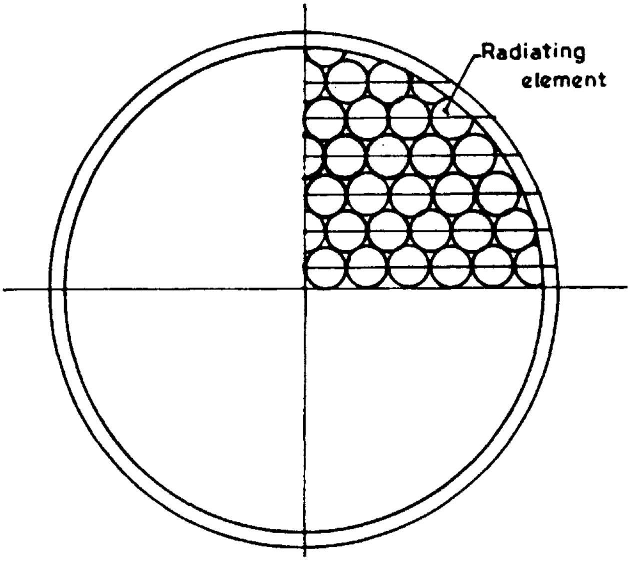

Fig 6 (a) Top view showing the radiating elements in one quadrant of the circular aperture

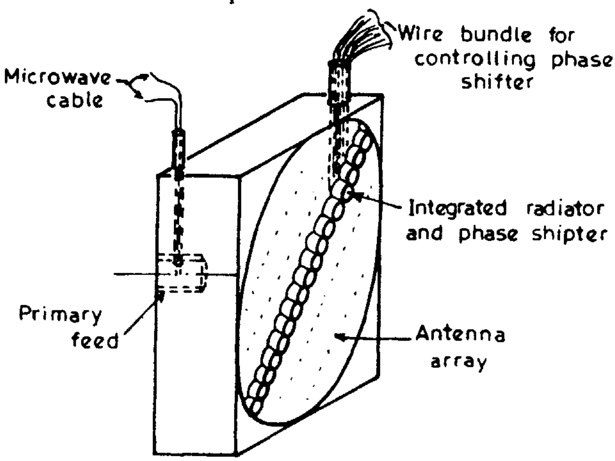

Fig 6 (b) Isometric view of the antenna phase shifter assembly array antenna on the top of the vehicle

ARRAY ANTENNA ON THE TOP OF THE VEHICLE

Positioning of the Beam Towards the Satellite

For a car located on a road in the horizontal plane, the azimuth and elevation coordinates of the satellite assuming the car located at the origin of the spherical polar co-ordinates (Fig. 7) have to be found. The electronically scanned antenna generates a search pattern, and then locates the satellite through tracking mechanisms. The procedure followed for finding the angular co-ordinates of the satellite by this mechanism is exactly the same as that used in locating a target in space by radar system. Thus mechanism of operation of microwave commu-

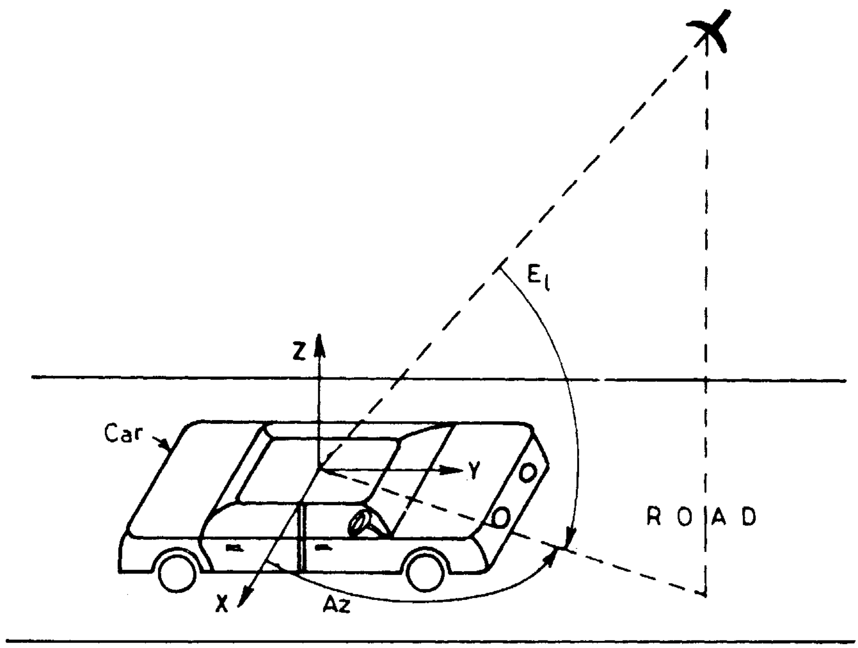

Fig 7 Co-ordinate system of a satellite seen from a car in the horizontal plane

nication system and radar system are identical. A closed tracking servo loop is generated in the computer and interpolative null tracking is used for finding azimuth and elevation co-ordinates.

If A_z, E_l are respectively the azimuth and elevation co-ordinates of the satellite as observed from the car, the interelement phase shift between the discrete radiators along the *x* and *y*-axes of the array aperture are given by

$$\phi_x = \frac{2\pi}{\lambda} d_x \cos E_l \cos A_z$$

$$\phi_y = \frac{2\pi}{\lambda} d_y \cos E_l \sin A_z \qquad \ldots (1)$$

where d_x and d_y are the spacing between the radiating elements with integrated phase shifters along *X* and *Y*-axes. $\mathrm{Cos} E_l \cos A_z$ and $\cos E_l \sin A_z$ are respectively the direction cosines of the line OP with respect to *X* and *Y* axes. Hence, the phase shifts ϕ_x and ϕ_y in eq. (1) are found from a knowledge of direction cosines. The cartesian co-ordinates of the satellite are

$$X = R\cos E_l \cos A_z$$

and $$Y = R\cos E_l \sin A_z \qquad \ldots (2)$$

$$Z = R\sin E_l.$$

The road along which the vehicle moves may (*i*) take a turn without any tilt (Fig. 8), (*ii*) be tilted along in width (Fig. 9) and/or (*iii*) be constructed up or down hill (Fig. 10). The position co-ordinates of the satellite as seen from the vehicle moving along the road changes as shown in Fig. 8-10. This change is described in terms of the rotation of the co-ordinate axes of Fig. 7 about X, Y, Z axes by T_x, T_y, T_z respectively[3]. For each rotation the new co-ordinates are related to the old co-ordinates by a 3×3 matrix. The final co-ordinates after 3 successive rotations are given by

$$\begin{bmatrix} X'' \\ Y'' \\ Z'' \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos T_x & -\sin T_x \\ 0 & \sin T_x & \cos T_x \end{bmatrix} \begin{bmatrix} \cos T_y & 0 & -\sin T_y \\ 0 & 1 & 0 \\ \sin T_y & 0 & \cos T_y \end{bmatrix} \begin{bmatrix} \cos T_z & -\sin T_z & 0 \\ \sin T_z & \cos T_z & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \quad \ldots (3)$$

Taking the matrix product and substituting (2) in (3), the modified direction cosines (α, β) with respect to X''' and Y''' axes required for finding interelement phase shift is given by

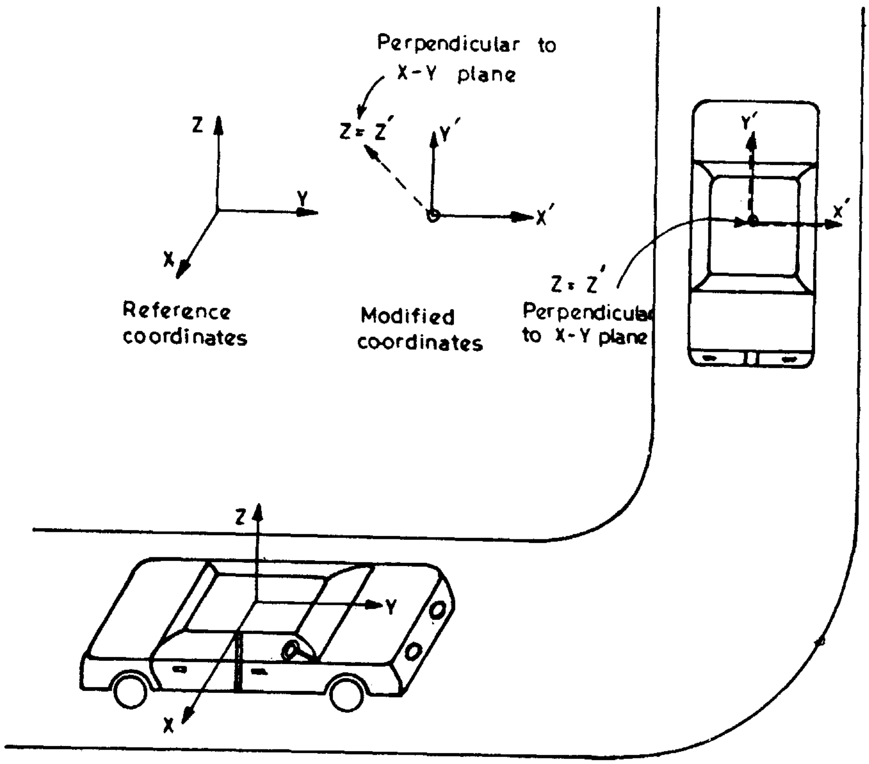

Fig 8 Modified co-ordinate system after the vehicle takes a turn in the horizontal plane

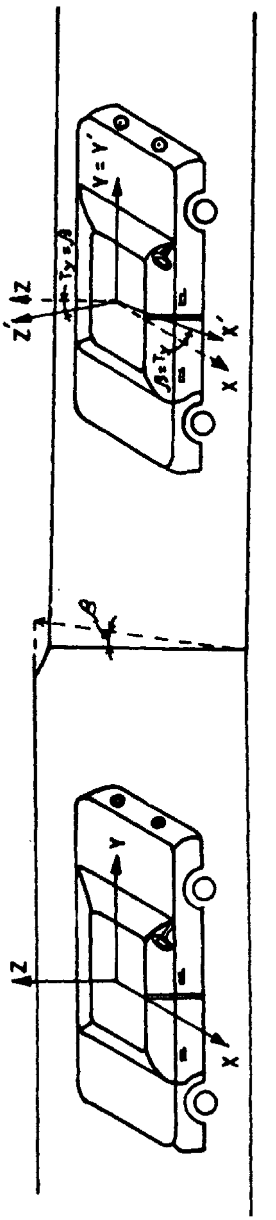

Fig 9 Modified co-ordinate system when the vehicle moves along a titled road

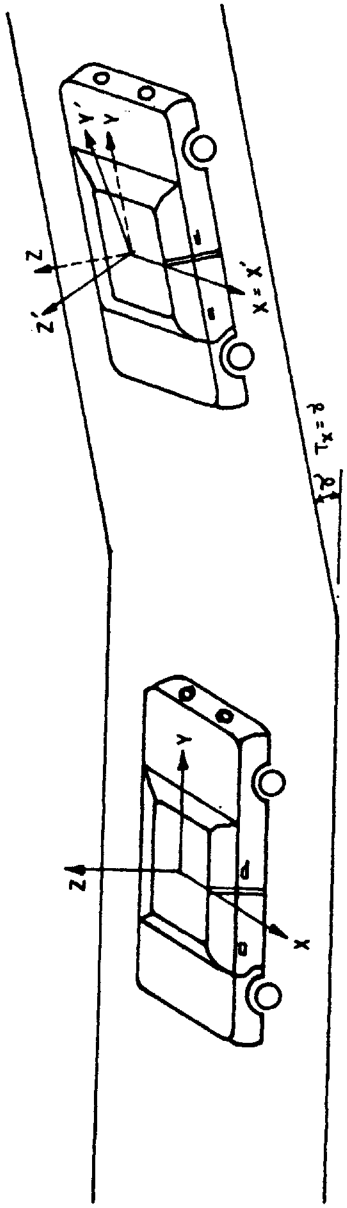

Fig 10 Modified co-ordinate system when the vehicle moves up-hill

$$\alpha=\frac{X'''}{R}=\cos T_y \cos T_z \cos E_l \cos A_z-\sin T_y \sin T_z \cos E_l \sin A_z-\sin T_y \sin E_l \qquad \ldots (4)$$

and

$$\beta=\frac{Y'''}{R}=(-\sin T_x \sin T_y \cos T_z+\cos T_x \sin T_z)\cos E_l \cos A_z+(\sin T_x \sin T_y \sin T_z + \cos T_x \cos T_z)\cos E_l \sin A_z-\sin T_x \cos T_z \sin E_l \qquad \ldots (5)$$

Locking of the Beam with Satellite

The interelement phase shifts along X and Y axes of the antenna array, required for positioning the beam to the satellite, when the car has taken shift from the normal course is given by

$$\phi'_x=\frac{2\pi}{\lambda} d_x \alpha \qquad \ldots (6)$$

and

$$\phi'_y=\frac{2\pi}{\lambda} d_y \beta \qquad \ldots (7)$$

where α, β are determined from (4) and (5) respectively. T_x, T_y, T_z which represent the change in orientation of the vehicle are recorded by a gyro. The electrical signal from the gyro generates a command to the computer, which controls the phase shifter for pointing of the beam to the proper direction.

When an indicator is available, the direction of the beam is altered in accordance with change in orientation of the vehicle, recorded by the same.

In the absence of an indicator, the angular co-ordinates of the satellite are found from search followed by track programme stored in the computer. For tracking a set of recursive equations generate a sampled data servo loop in the computer. The objective is to see that communication with a mobile vehicle is not interrupted.

Other Applications of Electronic Scanning

The discussion has so far been centred around the method of positioning the beam towards the satellite from a car in motion. This is one of many possible applications of electronic scanning, which has significant flexibility in its applications. One of the most important of the other applications is control of landing and take-off of a large number of air crafts in airports. This is made possible through simultaneous search and track and simultaneous tracking of a large number of aircrafts. Search followed by track discussed in connection with uninterrupted communication with a satellite is also the method followed in locating a target by radar system which may be either ground based or located in avionic system. Beam shapes required for search and track are different. Hence, in conventional radar using dish type of antenna, separate radars with different dish antennas are used.

If electronic scanning is used, the same radar can be used for simultaneous search, track and at the same time tracking a large number of objects. This enables such a radar installed in a civil air-port to handle simultaneously a large number of passenger aircraft during their landing[3].

Any passenger aircraft equipped with electronic scanning radar has to locate other aircrafts to avoid air collision. It has therefore to carry out simultaneous search and track operations. In addition, it has to be provided facilities for ground mapping and terrain avoidance. All the operations have to be carried out simultaneously on a time shared basis. These operations involve quick change in beam shape from broad to narrow and vice versa. A narrow beam is generated when all the elements are in the same phase. A linear phase progression never makes a beam broad. The method of generation of a broad beam with phase control is discussed below. The details of derivation are reproduced for completeness.

Phase Function of Circular Aperture for a Desired One-Dimensional Pattern

The two-dimensional Fourier Transform of the aperture function $f(x,y)$ of Fig. 6 is of the form[4]

$$g(k_x, k_y) = \int_{-R_0}^{R_0} \int_{-(R_0^2-x_0^2)^{1/2}}^{(R_0^2-x_0^2)^{1/2}} f(x, y)\, e^{(jk_x x + k_y y)}\, dx\, dy \qquad \ldots (8)$$

where R_0 is the radius of the circular aperture of Fig. 6 and $x^2+y^2 \leq R_0^2$ $K_x = 2\pi/\lambda \cos E_l \cos A_z$, $K_y = \cos E_l \sin A_z$ are the spatial frequency (spectral) components along x and y-axes.

For co-phasal excitation of the aperture, a narrow beam is obtained at $E_l = 90°$ i.e. $k_x = k_y = 0$. If there is no phase variation along y-axis but there is phase variation along x-axis, the beam is concentrated along $A_z = 0$ i.e. $k_y = 0$ in the spectral domain. In this case

$$f(x,y) = a(x, y)\, e^{j\psi(x)} \qquad \ldots (9)$$

The physical significance of equation (9) is that there is variation of amplitude along x,y axes. The phase function varies along x.

Using $k_y = 0$, it is found from (8) and (9) that

$$E(k_x, k_y) = \int_{x=-1}^{x=+1} \left[\int_{-(1-x^2)^{1/2}}^{(1-x^2)^{1/2}} a(x, y)\, e^{jk_y yR}\, dy \right] e^{j\{k_x Rx + \psi(x)\}}\, dx. \qquad \ldots (10)$$

The integral in square bracket is a function of x, say $b(x)$. Normalising the radius R_0 to unity, eq. (10) assumes the form

$$g(k_x, 0) = \int_{-1}^{+1} b(x)\, e^{\{k_x Rx + \psi(x)\}}\, dx. \qquad \ldots (11)$$

The stationary phase points[5,6] in the integrand of (11) are obtained from

$$R_0 K_x = \frac{2\pi R_0}{\lambda} \cos E_l = -\psi'(x)$$

If $\cos E_l = u$, then

$$\frac{2\pi R_0}{\lambda} u = -\psi(x). \qquad \ldots (12)$$

The major contribution to the value of the integral arises from the immediate vicinity of the end points of the interval and from the vicinity of those points for which $d/dx[(2\pi/\lambda)R_0ux - \psi(x)] = 0$ (stationary points). When the stationary points are present, their contribution is more significant than those of the end points. The value of the stationary point x is dependent on the value of $u = u$ and this dependence is given by eq. (12).

Expanding $\psi(x)$ in (11) in a Taylor's series about $x=0$ and substituting (12) in (11) and using the condition

$$\int_{-\infty}^{\infty} e^{(jyt^2)}\,dt = e^{j\pi/4}(\pi/y)^{1/2}$$

it can be shown that

$$|E(u)|^2 = \frac{2\pi}{R/\lambda|\eta''(x)|} b^2(x); \qquad \ldots (13)$$

where the point to point relation between u and x is given by eq. (12). Substituting the double derivative of $\psi(x)$ obtained from (12) in eq. (13), the relation between the pattern and aperture amplitude functions is obtained as

$$R/\lambda\, |E(u)|^2\, du = b^2(x)\, dx. \qquad \ldots (14)$$

Assuming that $[(2\pi/\lambda)R_0 \cos x + \psi(x)]$ has one stationary point for a particular value of u which changes continuously with change in x as given by eq. (12), the following integral relations are obtained from (13)

$$R/\lambda \int_{-\infty}^{u} |E(u)|^2\, du = \int_{-\infty}^{x} b^2(x)\, dx \qquad \ldots (15)$$

or

$$R/\lambda \int_{u}^{\infty} |E(u)|^2\, du = \int_{-\infty}^{x} b^2(x)\, dx. \qquad \ldots (16)$$

For an aperture extending from x_1 to x_2, it follows from eq. (15) and (16) that the corresponding pattern is in the range of u

$(2\pi R_0/\lambda)u_1 = -\psi'(x_1)$ and $(2\pi R_0/\lambda)u_2 = -\psi'(x_2)$. i.e.

In this case the total energy relation is given by

$$R/\lambda \int_{u_1}^{u_2} |E(u)|^2 \, \mathrm{d}u = \int_{x_1}^{x_2} b^2(x) \, \mathrm{d}x \qquad \ldots (17)$$

and the equations (15) and (16) assume the following forms

$$R/\lambda \int_{u_1}^{u} |E(u)|^2 \, \mathrm{d}u = \int_{x_1}^{x} b^2(x) \, \mathrm{d}x \qquad \ldots (18)$$

or

$$R/\lambda \int_{u}^{u_2} |E(u)|^2 \, \mathrm{d}u = \int_{x_1}^{x} b^2(x) \, \mathrm{d}x. \qquad \ldots (19)$$

The above approximations are valid as R/λ approaches infinity. The two possible relations between u and x obtained from the solutions of eq. (17) to (19) are $u = F_1(x)$ or $u_2 = F_2(x)$.

Substituting these relations in (13), the desired phase functions are obtained from the solution of following first order differential equations

$$\psi_1'(x) = -2\pi \frac{R}{\lambda} F_1(x) \qquad \ldots (20)$$

or

$$\psi_2'(x) = -2\pi \frac{R}{\lambda} F_2(x). \qquad \ldots (21)$$

In the following section the phase distributions required for the generation of sector beam and cosecant beam for two types of amplitude distributions (uniform and cosine on a pedestal) are presented[7].

Generation of Sector Beam

The angular spectrum of plane waves for a sector beam can be represented by an expression of the form

$$E(u,o) = A \text{ for } -u_0/2 \leq u \leq u_0/2 \qquad \ldots (22)$$

From (17) and (22), the constant A is obtained as

$$A^2 = \frac{1}{R/\lambda \, u_0} \int_{-1}^{+1} b^2(x) \, \mathrm{d}x \qquad \ldots (23)$$

From (18), (22) and (23) the relationship between u and x is given by

$$u = -\frac{u_0}{2} + u_0 \frac{\int_{-1}^{x} b^2(x) \, \mathrm{d}x}{\int_{-1}^{+1} b^2(x) \, \mathrm{d}x} \qquad \ldots (24)$$

where $u = \sin\theta$.

Substituting (24) in (12) the derivative of the phase function is given by

$$\psi'(x) = \frac{R}{\lambda}\,\eta'(x) = 2\pi\frac{R}{\lambda}\,u_0\left[0.5 - \frac{u_0}{2} + u_0\frac{\int_{-1}^{x} b^2(x)\,dx}{\int_{-1}^{+1} b^2(x)\,dx}\right] \qquad \ldots (25)$$

The phase function required for any aperture amplitude function $a(x, y)$ can, in general, be found from the numerical solution of the above differential equation. In the particular case of uniform amplitude distribution $[a(x, y) = 1]$, the expression for $\psi(x)$ is obtained in the closed form and is given by

$$\psi(x) = 2\pi\frac{R}{\lambda}\,v_0\left[-\frac{3}{8}x^2 + \frac{1}{16}x^4\right] \qquad \ldots (26)$$

All integrals appearing in (25) are numerically evaluated. On evaluating the integrals by this numerical procedure, the differential equation (25) is also solved numerically. Substituting the values of $\psi(x)$, so obtained in (10), the radiation pattern is calculated.

The phase functions and the corresponding radiation patterns calculated for $R/\lambda = 15$, 25 and $u_0 = 0.25$ are presented in Figs 11 and 12.

Generation of Cosecant Beam

The plane wave spectrum for a cosecant beam in the $k_y = 0$ ($\phi = 0°$) plane can be expressed in the form

$$E(u, 0) = A/u \text{ for } u_0 \leq u \leq u_1 \qquad \ldots (27)$$

where the constant multiplier A is evaluated from (17) and (27) as

$$A^2 = \frac{\int_{1}^{+1} b^2(x)\,dx}{\frac{R}{\lambda}\left[\frac{1}{u_0} - \frac{1}{u_1}\right]} \qquad \ldots (28)$$

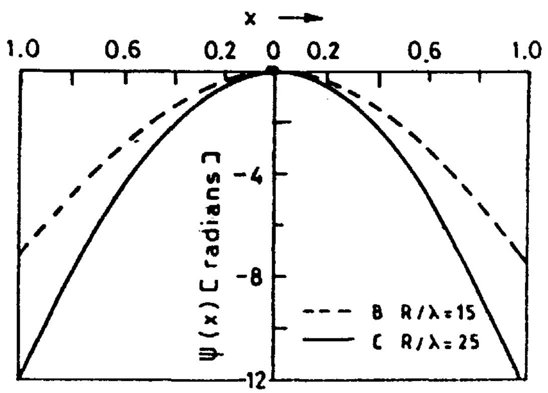

Fig 11 Phase distribution for sector beam

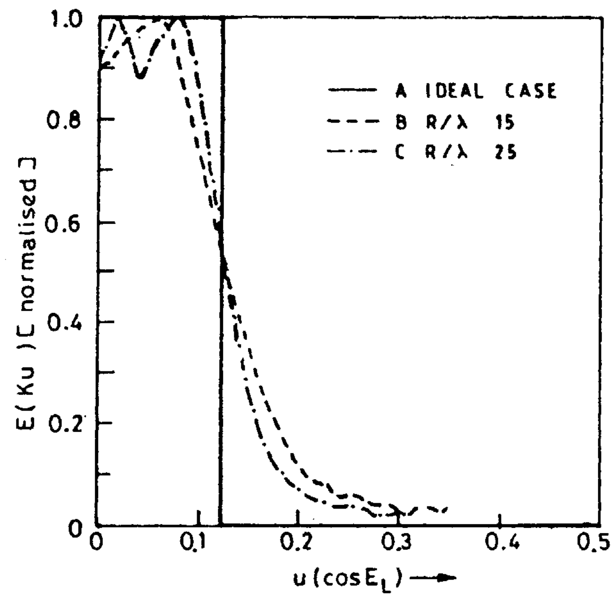

Fig 12 Radiation patterns produced by phase distribution of Fig. 11

From (18), (27) and (28) the relationship between u and x is given by

$$-\frac{1}{u} = -\frac{1}{u_0} + \left[\frac{1}{u_0} - \frac{1}{u_1}\right] \frac{\int_{-1}^{x} b^2(x)\,dx}{\int_{-1}^{+1} b^2(x)\,dx} \qquad \ldots (29)$$

Substituting (29) in (12) the derivative of the phase function is expressed as

$$\psi'(x) = \frac{R}{\lambda}\,\eta'(x) = 2\pi \frac{R}{\lambda} \frac{1}{-\frac{1}{u_0} + \left[\frac{1}{u_0} - \frac{1}{u_1}\right] \frac{\int_{-1}^{x} b^2(x)\,dx}{\int_{-1}^{+1} b^2(x)\,dx}} \qquad \ldots (30)$$

The integrals appearing in (30) are solved numerically and the differential equation of (2.26) is also numerically solved. The values of $\psi(x)$ numerically evaluated.

The phase functions $\psi(x)$ and the corresponding radiation patterns calculated for $R/\lambda = 15, 25$, $u_0 = 0.25$ and $u_1 = 0.85$ are presented in Figs 13 and 14.

Scanning of Expanded Beam

A beam which is narrow in one plane and broadened in other plane provides illumination in a particular plane. When this beam is generated from a mobile platform the plane of illumination has to be kept unaltered in spite of change in angular orientation of the mobile platform. In this case the Fourier Transform is two dimensional and is of the form[7]

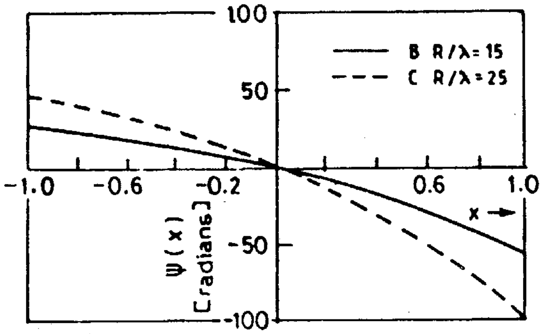

Fig 13 Phase distribution function along x-direction for uniform amplitude distribution and cosecant beam generation

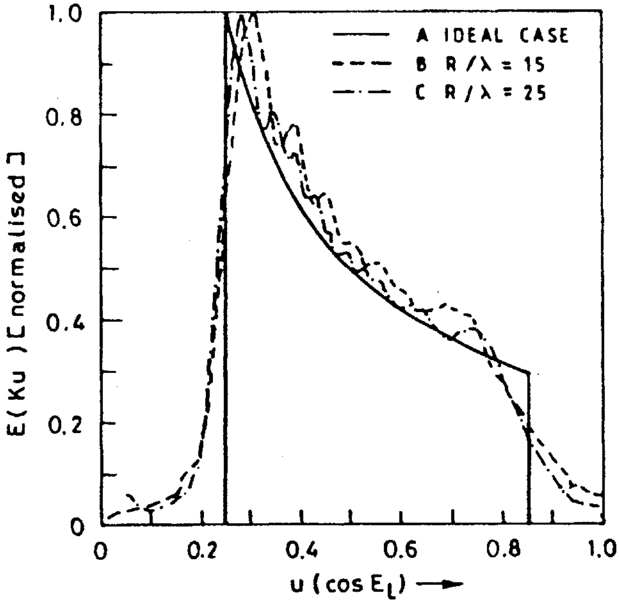

Fig 14 Radiation patterns produced by phase function of Fig. 13 for uniform amplitude excitation

$$g(k_{xy},k_{yt})=\int_{x=-1}^{x=+1}\left[\int_{y=-(1-y_t^2)^{1/2}}^{(1-y_t^2)^{1/2}} f(x_t, y_t)\,dy\right] e^{(jk_{yt}y_t+(R/\lambda)\eta(y_{yt})}\,dy_{yt}\,e^{j(k_{xt}+gy_tx_t)}\,dx_t \quad \ldots (31)$$

The direction cosines k_{xt}, K_{yt} are found from eq. (3). In (31) $\eta(y_t)$ is the nonlinear phase distribution along y-axis of the aperture. $g(y_t)$ is the slope of the linear phase function along x-axis. These quantities are found from the following equations using the method of stationary phase described in the earlier sections:

$$K_{yt} = -(R/X)\,\eta'(y_t), \quad \ldots (32)$$

$$K_{xt} = -g(y_t) \quad \ldots (33)$$

and

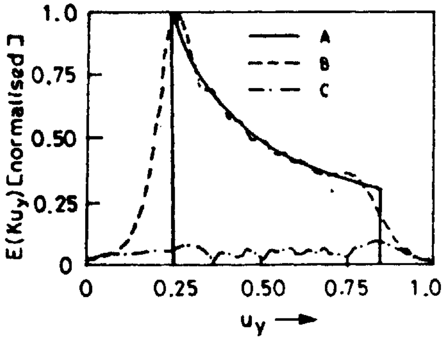

Fig 15 Radiation patterns of cosec beam for scanned plane Az = 0, Curve A-Desired Pattern, curve B-Realised pattern at Az = 0, curve C-Realised patterns at + 5°

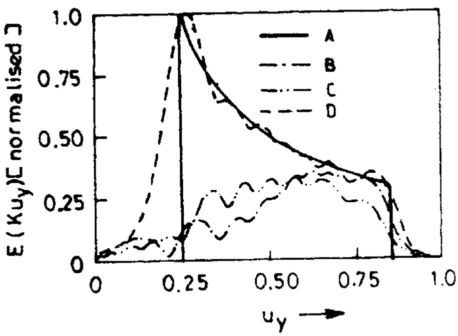

Fig 16 Improved radiation patterns of cossec beam for scanned plane Az = 45, curve A-Desired pattern, B-Realized pattern at Az = 45, C-Realised pattern at Az = 40, D-Realised pattern at Az = 50°

$$\psi_1'(t) = -(R/\lambda)\, \eta'(y_t).$$

The normalised radiation patterns are given in Figs 15 and 16.

Discussion

Use of electronic scanning permits positioning of the beam in the same pointing direction for any orientation of the moving vehicle. The computer controlled phase shifter automatically maintains the beam in any desired direction. This has an added flexibility of carrying out simultaneous search and tracking operations. The control of beam shape by changing the phase distribution is a completely new idea which was formulated in the post eighty period. Solution of different equation obtained from the asymptotic evaluation of the radiation integral yields the desired phase function required for generation of a broad beam. Scanning of this broad beam in a direction perpendicular to its plane is achieved from linear phase progression in a particular direction. The slope of the line representing the linear phase progression is a function of position along the corresponding direction.

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