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A SPECIAL THEORY OF BEAM SCANNING IN THE TIME DOMAIN

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Introduction

In a previous paper[1], the author has reported on a Non-Uniform Time Delay and Integrate (NUTDI) charge coupled device for a high-resolution within-pulse sector scanning sonar application. This paper is aimed at explaining in more detail and from first principles the special concept of beam scanning in the time domain on which the NUTDI device is based. The theory is developed for plane wavefronts incident on a line array. This premise of plane wavefronts , which is pertinent to farfield responses, is not restrictive as electronic focusing can be used to shift the farfield response from infinity to the near-field[2]. Such focusing can be achieved by an array of CCD delay lines having a quadratic length variation[3] . A special feature of the concept is the common control of the multi-channel delays which are required to cancel out the medium propagation delays for successive angles of look as the beam is swept across the sector within the duration of the transmitted pulse. It is this common increment of the channel delays which not only results in the desirable simplicity of beam scanning control but also leads to the important stipulation of a constant speed of scan.

Constant speed of scan

A conventional time-delay-and-integrate device (TDI) is a multi-input/single-output delay line and is shown schematically in Fig 1. On each clock pulse, the signal on each input tap is sampled, delayed and then added to the accumulating sum of signal samples obtained on preceding input taps at different past instants in time depending on the clock history. The instantaneous differential delay between adjacent inputs is equal to the current clock period. If the TDI is connected to an equally spaced array and is operated with a constant period clock, then coherent summation of the transducers' signals occurs for plane wavefronts incident at an angle such that the propagation delay between adjacent transducers equals the differential delay introduced by the TDI between adjacent input taps. A fixed beam is therefore formed in a direction determined by the constant period clock.

However, with a scanning clock, the period changes from one cycle to the next. A scanning law can therefore be defined as a mathematical function which determines the variation of the instantaneous clock period with time and thus governs the manner in which the beam is swept across the sector. Consider a TDI connected to an N-element line array with as yet undetermined spacings d_1, d_2, ...d_{N-1} (Fig 2). Let the instantaneous period of the scanning clock be an arbitrary but monotonically increasing function of time so that the beam is swept from small to large angles. Why this is a desirable direction of scan is explained later. In this discrete-time approach, the continuous scanning law actually represents a time series of successive discrete clock periods, the sum total of which equals the scan period. For repetitive scanning, the same

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series of clock periods is repeated for each scan. Consider a time history comprising any N successive clock periods such as $\tau_{p-N+1}, \tau_{p-N+2}$, ... τ_{p-2}, τ_{p-1} & τ_p with τ_p as the most recent clock period. At the instant when the clock period is τ_p, the TDI output is to represent a coherent summation of signal samples taken from a plane wavefront incident at an angle θ_p given by $\tau_p = (d_1 \sin \theta_p / c)$ where c is the speed of sound in water. Coherent summation occurs only if the spacings and the clock periods are related thus :-

$$\tau_{p-N+1} : \tau_{p-N+2} : \ldots\ldots : \tau_{p-1} : \tau_p = d_{N-1} : d_{N-2} : \ldots\ldots\ldots : d_2 : d_1 \qquad \text{Eq 1}$$

It is to be noted that so far the array spacings and clock periods are completely arbitrary though one set specifies the other. However, such arbitrariness disappears when it is additionally required that coherent summation of signal samples from the next wavefront θ_{p+1} is to occur at the next clock period τ_{p+1} where $\tau_{p+1} = (d_1 \sin \theta_{p+1}/c)$ (Fig 3). With a common scanning clock, this further constrains the clock periods and the spacings to be related by :-

$$\tau_{p-N+2} : \tau_{p-N+3} : \ \ldots \ : \tau_p \ : \tau_{p+1} = d_{N-1} : d_{N-2} : \ \ldots \ : d_2 : d_1 \qquad \text{Eq 2}$$

From Eqs 1 and 2 , it is deduced that the clock periods must be related by :-

$$\frac{\tau_{p-N+2}}{\tau_{p-N+1}} = \frac{\tau_{p-N+3}}{\tau_{p-N+2}} = \ldots\ldots = \frac{\tau_p}{\tau_{p-1}} = \frac{\tau_{p+1}}{\tau_p} = \gamma = \text{constant} \qquad \text{Eq 3}$$

Extending the argument to all the other clock periods in one scan, it can therefore be concluded that the successive clock periods must follow a geometric series with a common ratio γ if coherent summation is to be achieved for each direction corresponding to each clock period. The following simple analysis shows that the continuous scanning law giving rise to this geometric series of discrete clock periods is a linear function of time. Fig 4 is a plot of any three successive clock periods τ, $\tau\gamma$, and $\tau\gamma^2$ against time. The instant in the scan t marks the beginning of the clock period τ (point A). The next clock period $\tau\gamma$ starts at the instant $t+\tau$ (point B). Similarly, the third clock period $\tau\gamma^2$ starts at the instant $t+\tau+\tau\gamma$ (point C). Points A, B and C therefore represent the instantaneous variation of the scanning clock period and it is to be shown that they form a straight line.

$$\text{gradient AB} = \frac{\tau\gamma - \tau}{\tau} = \gamma - 1 \qquad \text{Eq 4}$$

$$\text{gradient BC} = \frac{\tau\gamma^2 - \tau\gamma}{\tau\gamma} = \gamma - 1 \qquad \text{Eq 5}$$

Since gradients AB and BC are equal and B is a common point, ABC is hence a straight line. The proof being valid for any three successive clock periods, it therefore follows that the instantaneous clock period $\tau(t)$ varies linearly with time within a scan. Such a clock generator is called a linear period clock (Fig 5). Since the rate of change of clock period is constant, the beam is swept at a constant speed over the sector. Therefore, a constant speed of scan is a necessary condition for distortionless time delay beam scanning.

Geometric series array

It can be deduced from Eq 1 that the array spacings must also follow a geometric series with a common ratio $1/\gamma$:-

$$\frac{d_{N-1}}{d_{N-2}} = \frac{d_{N-2}}{d_{N-3}} = \;\dots\dots\dots = \frac{d_3}{d_2} = \frac{d_2}{d_1} = \frac{1}{Y} \qquad \text{Eq 6}$$

The value of Y is significant in that it is a measure of the constant speed of scan. Taking as an example, a reference spacing d_1 of 2λ and a linear period clock sweeping from 0.2 (maximum device clock frequency limit) to 2.2 (ambiguity limit for sonar frequency of 500 KHz) microseconds, the scanning beam pattern for a single target is computed and shown in Fig 6 for N=32 and T=125 μsec. An inherent feature of scanning in the time domain which can be observed in Fig 6 is the "buildup time" at the beginning of the scan. This is the initial time during which the output samples are not fully constituted from valid input samples but contain some inputs from the previous scan. The actual buildup time is given by the total duration of a number of initial clock periods equal to the number of delay stages from the first input tap to the device output. It is to minimize the buildup time that the linear period clock is swept from small to large periods.

The TDI by itself can only scan a "squinted sector" in one quadrant. A similar sector in the complementary quadrant can be scanned by another TDI which is driven by a linear period clock sweeping in the opposite direction from large to small periods and whose inputs are connected to the array elements in the reverse order (Fig 7). With such an arrangement, there exists a central blind region, the size of which is determined by the maximum clock frequency and the interelement spacing. This blind region may be significant in some applications. However, the unambiguous sector scanned can be centred on the boresight direction by inserting appropriate fixed delays between the transducers and the TDI. These delays effectively predeflect the on-axis sector by a certain angle off the boresight. The predeflected sector is then scanned by the TDI. The fixed delays required in the various channels depend on the desired predeflection angle and the element spacings. Fig 8 shows how these delays can be exactly calculated. In practice, such delays can be implemented approximately by a set of parallel serial-in/serial-out CCD delay lines with a non-uniform variation in length. Such a device can be called a Non-Uniform Time Wedge.

Equally spaced arrays

It is advantageous to extend the concept of fast time delay beam scanning to the more general case of equally spaced arrays. This will not only widen the range of applications, but also allows the fixed predeflection to be performed with a uniform Time Wedge device which may have more general applications than the special non-uniform Time Wedge required for the geometric series array and which a manufacturer may therefore be more easily persuaded to fabricate !

A specified equally spaced array can be approximated to by selecting those element positions in an associated geometric series array which are closest to the given equally spaced element positions. A scanning TDI structure for the equally spaced array can then be constituted by selecting the particular device input taps which correspond to the "best fit" element positions. Since such specially selected element positions are not necessarily successive or consecutive positions in the geometric series array, the resulting device will have input taps which are not uniformly distributed and which are separated by a varying number of delay stages depending on how many geometric series spacings are "skipped" before the next element is selected. The term NUTDI (for Non-Uniform TDI) will be used to distinguish this new scanning device configuration for the equally spaced array from the conventional uniform TDI.

It will now be shown how, given any N-element array with equal spacing D operating at a sonar frequency f and a specified scan period T, an associated geometric series array can be derived and how a special selection of its element positions can be performed to yield the appropriate NUTDI structure. It has already been noted that in order to reduce the buildup time, the linear period clock is swept from small to large periods. This being so, the geometric series spacings increase down the array in the direction of the wavefront propagation as shown in Fig 9. It can be qualitatively deduced that, the nearer the input taps of the NUTDI are to the output point, the smaller the number of delay stages between them. This is because less of the larger geometric series spacings are required to make up an equal spacing D. Hence, the number of delay stages between adjacent NUTDI input taps is minimum between the last two inputs. Let this minimum number be α . The design constraints on the choice of α are explained later. But once α has been defined, the detailed NUTDI structure can be quantitatively derived from the given sonar specifications as follows :-

unambiguous sector size $\theta_D = \lambda / D$ rad. (Eq 7)

nominal size of largest geometric series spacing $d_1 = D/\alpha$ (Eq 8)

If the minimum clock period is τ_L , then lower limit of sector is

$$\theta_L = \arcsin (c\, \tau_L / d_1) \qquad \text{Eq 9}$$

upper limit of sector is $\theta_U = \theta_L + \theta_D$ (Eq 10)

upper limit of linear period clock is $\tau_U = d_1 \sin \theta_U / c$ (Eq 11)

Given scan period is T, the rate of change of clock period is

$$r = (\tau_U - \tau_L)/T \qquad \text{Eq 12}$$

common ratio of geometric series is $\gamma = 1 + r$ (Eq 13)

The exact value of d can then be calculated from :-

$$D = d_1(1-1/\gamma^{\alpha})/(1-1/\gamma) \qquad \text{Eq 14}$$

Knowing α, d and γ , the associated geometric series array is therefore completely defined. The next step is to select those element positions that are closest to the given equally spaced elements and hence obtain the NUTDI structure. If m_n represents the element position in the geometric series array that is closest to the n th element in the given equally spaced array (Fig 9), then m_n is also the effective number of delay stages from the n th input of the NUTDI to the output point. Thus, equating corresponding element positions ,

$$(n-1) D = d_1 \left(1-\frac{1}{\gamma^{m_n-1}}\right) / \left(1-\frac{1}{\gamma}\right) \qquad \text{Eq 15}$$

Substituting Eq 14 into Eq 15 and solving for m_n gives

$$m_n = 1 + \log\{\gamma^{\alpha}/[\gamma^{\alpha}-(n-1)(\gamma^{\alpha}-1)]\}/\log(\gamma) \qquad \text{Eq 16}$$

The value of m_n calculated from the above equation for each value of n from n=1 to n=N are in general not integers. This is because the equally spaced elements do not always exactly coincide with element positions in the geometric series array. A non-integral value of m for a particular value of n therefore implies that the n th element in the equally spaced array lies somewhere in between the (m_n) th and the (m_n+1) th element positions in the geometric series array, where (x) represents the integer part of x. As m_n represents an element number as well as the effective number of delay stages between the n th input and the output of the NUTDI device, it can only take integral values and the calculated values are therefore corrected to the nearest integers. The difference between the calculated and the corrected values of m therefore represents the discrepancy in position between an equally spaced element and the nearest geometric series element. Though these positional discrepancies are fixed, they result in angle-dependent time errors in the computation of the scanning NUTDI beam pattern which is therefore distorted differently at different angles. In fact, these "quantisation time errors" are larger for larger angles (or correspondingly, larger clock periods) as is illustrated by the high level of the far-out side-lobes in the computed beam pattern shown in Fig 10. Obviously, these positional discrepancies are reduced if the geometric series array has more densely distributed elements, thus allowing a closer mapping with the equally spaced elements. This can be achieved by choosing a larger value of α , which effectively means splitting each geometric series spacing into a number of smaller spacings. The resulting NUTDI device is consequently longer, i.e. has a larger number of delay stages. With the larger number of delay stages between adjacent inputs, the device needs to be clocked at a range of correspondingly higher clock frequencies in order to obtain the same range of differential delays and thus to scan over the same sector as before. In principle, the value of α can be increased until the quantisation time errors become so small that the beam distortions are negligible. However, in practice, the value of α is limited by the maximum clock frequency, which together with the length of the device determine the buildup time. The detailed structure of a specific NUTDI device designed for a 32-channel 500 KHz sonar with a 1° beam swept over a 30° sector at 8 KHz scanning rate and for α=2 is given in reference 1. Fig 10 shows the computed beam pattern obtained using a first version of the three phase device in which all the inputs are sampled simultaneously on the same phase. The use of a uniform Time Wedge to introduce the appropriate predeflection is assumed. In a second version of the device, each input is sampled on an appropriately chosen clock phase so that m_n in Eq 16 can effectively be corrected to the nearest one-third rather than the nearest integer. The modified input structure is described in more detail in reference 1. The improvement resulting from the very much reduced quantisation errors can be seen in Fig 11. This input modification is of practical significance because it allows beam pattern of reasonable quality to be obtained without requiring unrealistically high clock frequencies and thus makes the concept an engineering pr position. The NUTDI device and a 32-channel Uniform Time Wedge device have now beeen fabricated and are currently under evaluation. It is to be noted though designed for a particular set of sonar specifications, the specific NUTDI can also be used for other suitably chosen sets of sonar parameters.

Summary

A special theory of beam scanning in the time domain is developed from the the two premises of plane wavefront and common incremental control of the multi-channel delays. It stipulates a constant speed of scan if beam distortions are to be avoided throughout the sector. In the first instance, the theory shows that a conventional TDI can be used to fast scan a line array whose interelement spacings follow a particular geometric series related to the scanning speed. The theory is then extended to cover the more generally useful case of equally spaced arrays. Extension to equally

spaced arrays involves an approximation procedure, which though in principle can be made more exact, is however limited by practical considerations at high clock frequency operation. To reduce such approximation errors, a new input feature is incorporated in the NUTDI device. Work is currently proceeding to incorporate the NUTDI and the Time Wedge devices in a prototype within-pulse sector scanning sonar. It is envisaged that the present work will be extended to two-dimensional scanning of an N X N transducer matrix array, where the significant system simplicity and compactness resulting from the use of such devices will be particularly advantageous.

References

1. ONG L. H. " A novel CCD for time delay within-pulse sector scanning sonars" Proceedings of the Institute of Acoustics Conference on Transducer Arrays and Array Processing pp 61 - 70 Dec 13/14 th 1978

2. WELSBY V.G. "Electronic scanning of focused arrays" Journal of Sound and Vibration 8 (1968) pp 390 -394

3. MELEN R., et al " CCD dynamically focused lenses for ultrasonic imaging systems " 1975 CCD Applications Conference , San Diego, California pp 165 - 171

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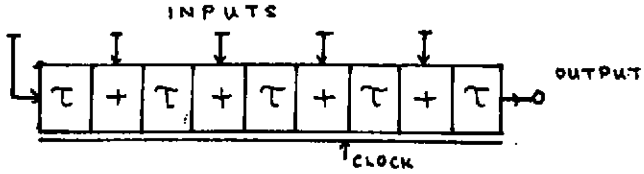


Fig 1 TDI Schematic
[τ] delay stage

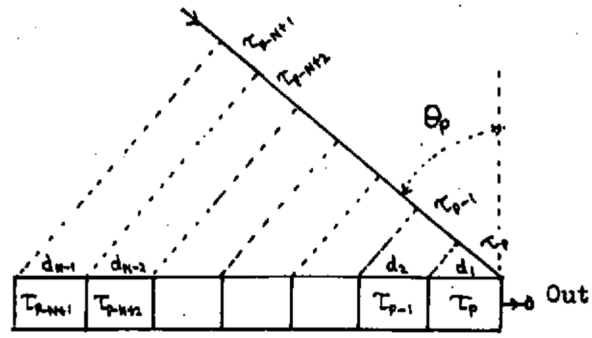


Fig 2 Time history of N clock periods ending in Coherent summation for Θ_p

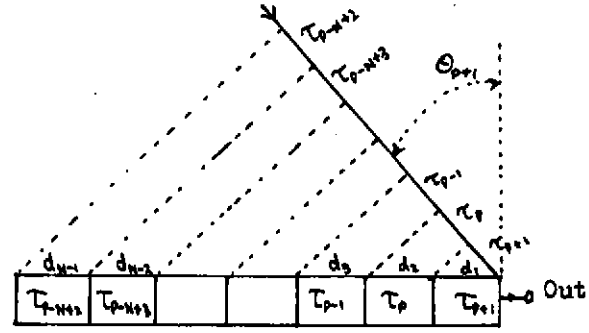


Fig 3 Time history of N clock periods ending in Coherent summation for Θ_{p+1}

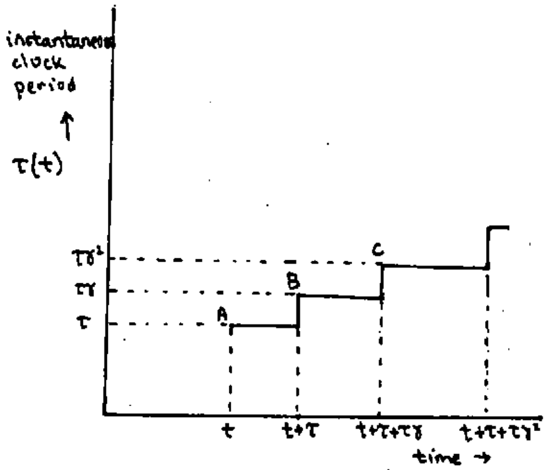


Fig 4 To prove geometric series of clock periods results from linear period scanning law

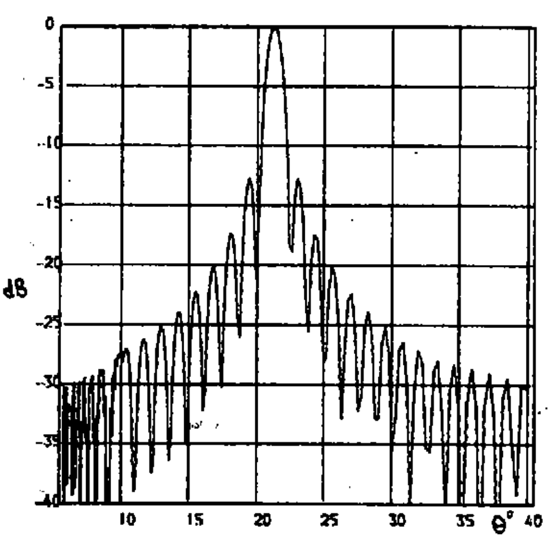


Fig 6 Beam pattern for geometric series array scanned by TDI
N=32 f =500 KHz d =2λ
τ_L =0.2μs τ_u=2.2μs T=125 μsec

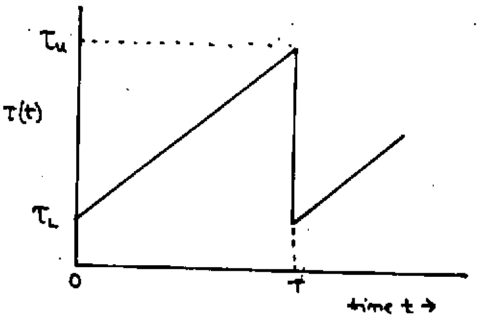


Fig 5 Linear Period Clock

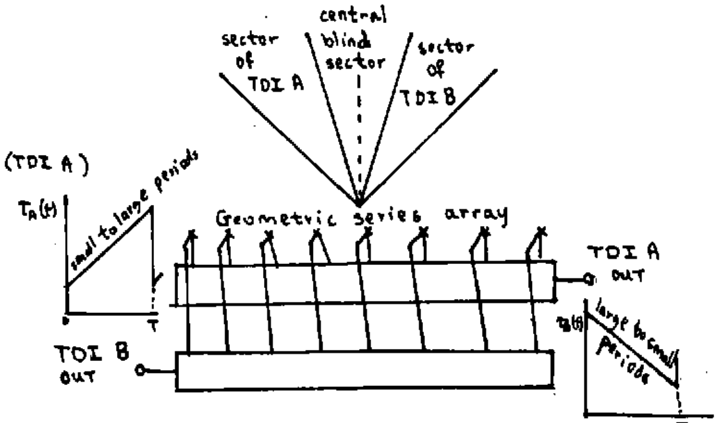


Fig 7 Complementary sectors using two TDIs scanned in opposite directions

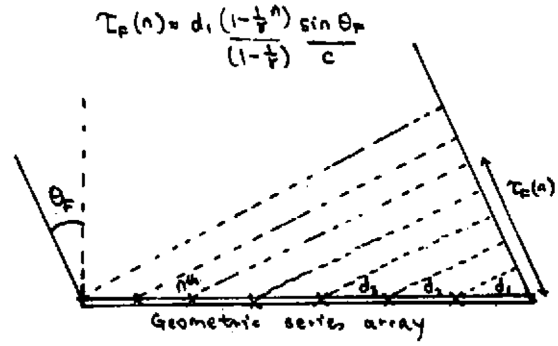


Fig 8 Calculation of the fixed predeflection delays for a geometric series array

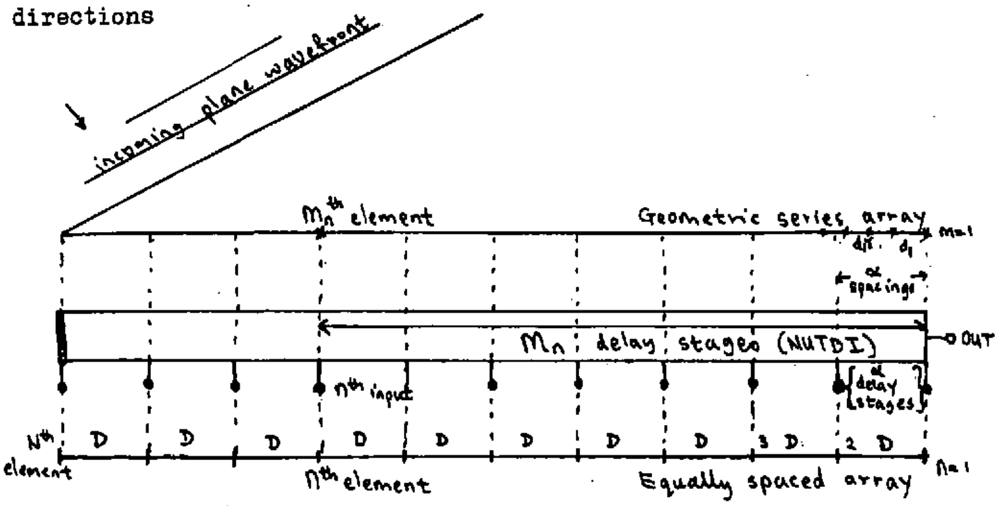
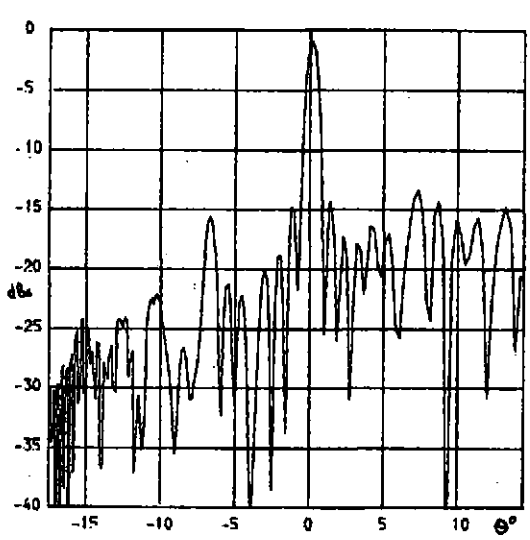


Fig 9 Mapping between the equally spaced array and an associated geometric series array to find the NUTDI structure



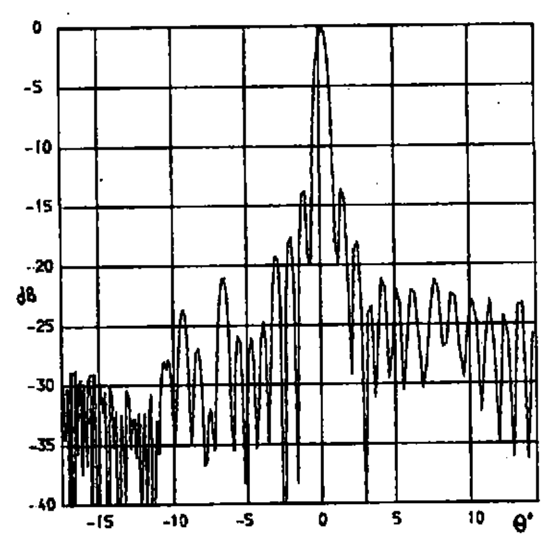


Fig 10 Beam pattern for equally spaced array scanned by NUTDI with common input clock phase

Fig 11 Beam pattern for equally spaced array scanned by NUTDI with individual input clock phase

N=32 f=500 KHz D=2λ α=2 τ_L=0.2μs τ_u=1.3μs T=125 μs