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Multiple Base-Line Interferometry (MBLI) for Position Determination in the Land Mobile services.

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1. Introduction

The art of direction finding and position location has taken giant steps forward in recent years with the advent of satellite systems, most notably the Global Positioning System (GPS). However, the need arises from time-to-time to locate the position of radio transmitters, operating legally or otherwise, in circumstances where such systems provide little in the way of assistance. The purpose of this study is to look into the problem of accurate determination of the position of such a transmitter within a reasonably restricted area using ground based interferometric techniques.

The specific technique that we are asked to evaluate is outlined in fig.1 in which the

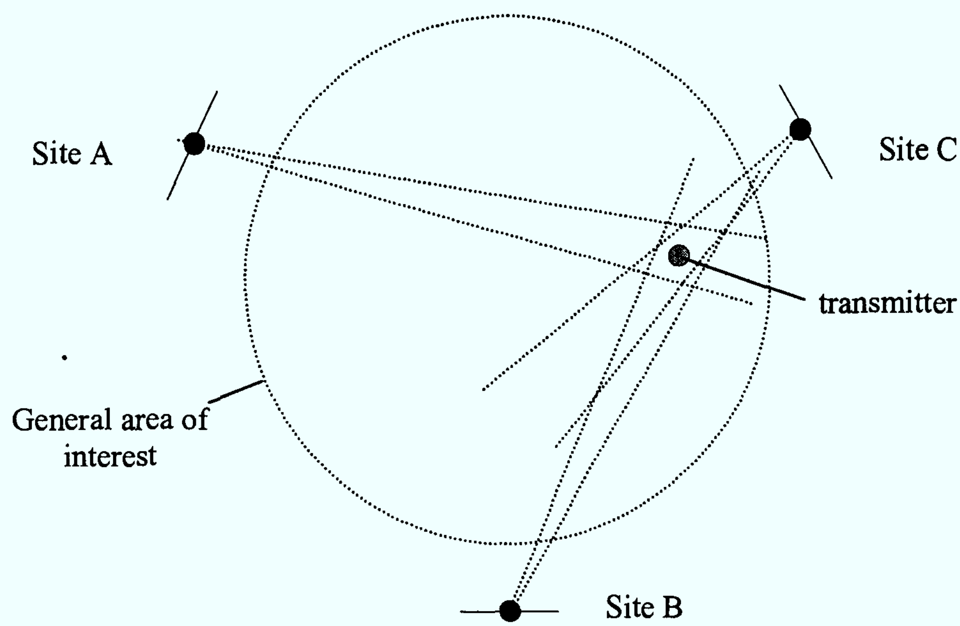

Fig.1.1 The basic layout of the position determining system.

expectation is that initial estimates based on angular estimates from each of three sites are refined by some means using the long base line established between the sites. Because of the inherent limitations of any system, due to noise in one form or another, the initial angular estimates from the individual sites have some uncertainties (indicated by the dotted lines) which leads to the generated uncertainty in position as illustrated. It will be noted that provided that the receiving antennas are looking broadly in the direction of the area of interest, just two sites can provide an estimate of the position. The third site adds further information which reduces the area of uncertainty; this is especially important if the transmitter is close to the base line joining two of the sites.

In examining the problem, some initial assumptions are necessary regarding such things as the overall dimensions involved, the general propagation conditions and the general characteristics of the transmitter and receiver in order to generate reasonable estimates of the likely performance of such a system. Accordingly, the following will be taken as a representative configuration:

i. The sites form an equilateral triangle with sides equal to 5km.

ii. The area of interest is within a circle of radius 2km centred within the above triangle as illustrated in fig.1.

iii. The line of sight from the transmitter to each receiver is unobstructed and no multi-path propagation is generated by nearby buildings etc.

iv The signal arriving at the receiver is essentially contained in a horizontal plane so that measurement only of the azimuthal angle-of-arrival is required.

v. The transmitter operates at a frequency in the range 150MHz (λ = 2m.) to 1GHz (λ = 0.30m) and has some arbitrary modulation with bandwidth of ≤150kHz. In particular, it is assumed that no specific timing information is available.

vi. The transmitted power is 1W and the antenna gains (G_D) at both transmitter and receiver are 0dB.

vii. Vertical polarization is assumed (most systems in fact use this)

These assumptions allow some constraints on some initial derived estimates to be made:

a. The angular range at each site is limited to about $\pm 60^0$ relative to the direction towards the centre of the area of interest.

b. The distance (d) from transmitter to receiver ranges between about 1km and 5km with a typical value of 3km.

c. A good estimate of typical receiver antenna temperature (T_A) is given by $T_A = 10^8 / f_{MHz}^2$ leading to a receiver antenna temperature ranging from about 4500K to 100K. Note, though, that a wide angle antenna will "see" the Earth at T ~ 300K over much of its main beam leading to a minimum noise temperature of this order.

Taking a typical example of a 450MHz transmitter at a distance of 3km and using the Friis transmission formula:

$$P_R |_{dBm} = P_T |_{dBm} + G_{DT} |_{dB} + G_{DR} |_{dB} + 20 \log \lambda - 20 \log d - 20 \log 4\pi = -65\,\text{dBm}$$

The noise power will depend directly on the bandwidth of the receiving system that will range, perhaps, from a high of 300kHz or so down to 300Hz, say, if the receiver is designed to isolate the carrier. Using noise power $P_N = k T_R B$, where Boltzmann's constant k = 1.38×10^{-23} J.K^{-1} and B is the bandwidth in Hz, leads to a noise power range of –107dBm to -149dBm.

Given the initial assumptions, then, there is an ample signal:noise ratio in the range 40 to 80dB. However, it is stressed that these are *initial* assumptions and it is recognized that in the expected practical situations, the signal level is likely to be significantly less than that quoted above due to the presence of various structures, etc. These effects will be considered later as the need arises.

2. Angle-of Arrival Measurement.

Techniques for measuring the angle-of-arrival of an incoming signal are many and varied, and a brief review of some of them will be attempted here. Broadly speaking, the techniques may involve measurements on signal amplitude or on signal phase or both.

2.1 Signal Amplitude measurements.

Arguably the simplest technique to estimate the angle-of-arrival (AOA) is to employ a moderately directive antenna and orient this to produce a maximum (or minimum) signal level at the output of a suitable receiver. One of the first examples of this approach is the Adcock array [1] in which the received signals from two identical antenna elements (often dipoles), separated by approximately $\lambda/2$, are added in antiphase producing a sharp null broadside to the array; this is illustrated in fig. 2.1. Since the nulls are much sharper than the maxima, the general idea is to rotate the array until a null is indicated with the orientation then giving the AOA. The obvious 180^0 ambiguity may need to be resolved if the direction is totally unknown and one way to achieve this is to introduce a sensing element in the centre of the array with its output shifted by 90^0 and added to the main signal (from the original two elements). This produces a cardioid pattern, as shown in fig.2.2, which may be used directly,

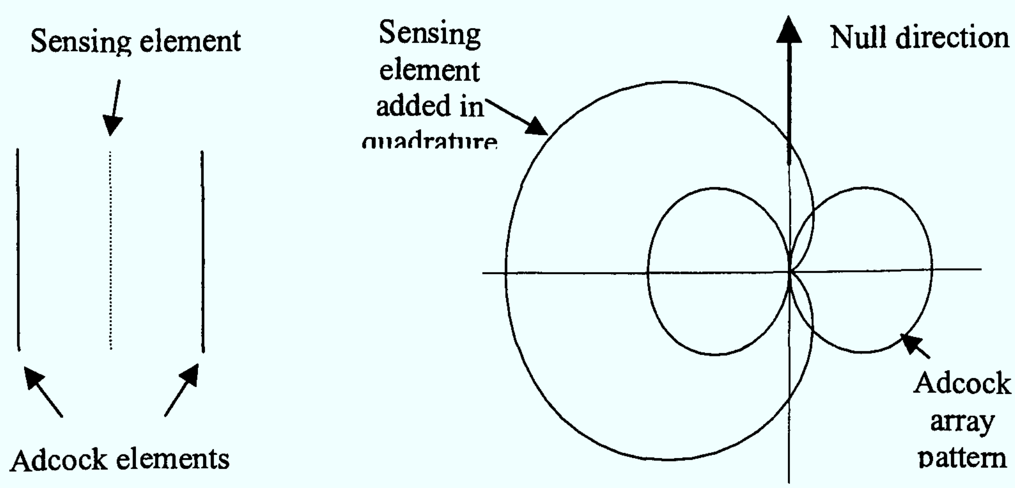

Fig. 2.1 The array pattern for an Adcock array composed of identical dipole elements in the plane perpendicular to the array

or as an indicator for the sharper pattern from the original array using the increase or decrease of signal strength as the whole array is rotated.

In order to avoid mechanical rotation of the array, if this is inconvenient, a system of orthogonal arrays, plus the sensing element for a total of 5 elements, has been used. The original Adcock system used a goniometer consisting of a coil connected between the terminals of each antenna pair and suitably oriented. with a rotatable coil in the centre to provide signal pickup. An improvement by Watson-Watt et al [2] utilized a cathode ray oscilloscope presentation for direct display of the direction of the source. Other variants on this simple approach used a small (compared with a wavelength) vertical loop as a substitute for the Adcock array and this still provides one of the simplest means for a fairly crude measure of the angle-of-arrival. Shielded loops [3] are often used at HF, though sensitivity to both vertical and horizontal polarizations can be a disadvantage.

Sharper lobes and nulls may be obtained by using a linear array with more elements as illustrated in fig. 2.2. Here the signals from each half of the array are added together in

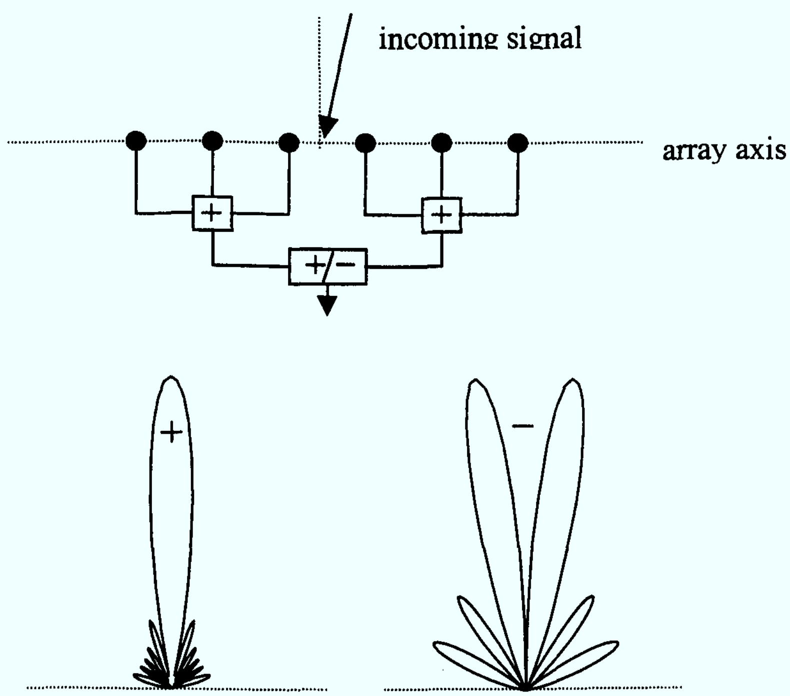

Fig 2.2. A simple multi-element array which produces either a sharp main lobe or a sharp null as the two halves are added in phase or in antiphase respectively.

phase and these two signals then added either in phase or in antiphase to produce a sharp main lobe or a sharp null perpendicular to the array. The dimensions of the array must be such that multiple main lobes are not formed which in turn means that the spacing of the elements must not be much larger than one half wavelength, depending on the directivity of the individual elements. Rotation of the array to zero-in on the incoming signal then allows reasonably accurate measure of the AOA of the incoming signal.

As before, it can be awkward to physically rotate an array, especially if the dimensions are significant. An interesting adaptation of the above is the Wullenweber system [3] which uses a circular array and goniometer pattern rotation to measure the amplitude of the incoming signal. The principle is shown in fig. 2.3. Again, the dimensions must be such that multiple main lobes are avoided.

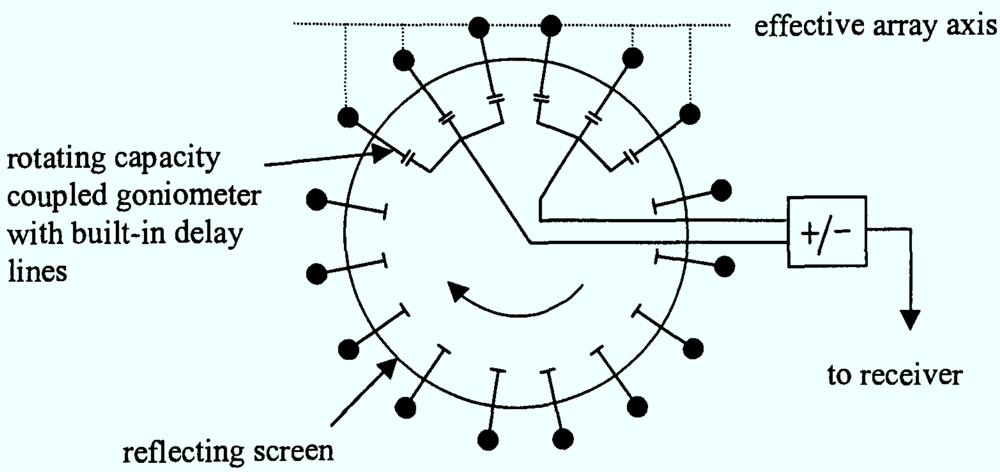

Fig. 2.3 Wullenweber rotating array. Note the use of suitable delay lines to form a broadside array.

2.2 **Signal Phase Measurements.**

All of the above involve essentially measurement of signal amplitude alone. Various other techniques are available which involve phase measurements in one form or another in addition to, or instead of, amplitude measurements. An oft-used technique generates a Doppler shifted signal at the receiver using an antenna rotating in a circle. Since it is sometimes difficult to rotate the antenna at high angular velocity ω, a variant pioneered by

Earp et al [5, 6] is often used as shown in fig. 2.4. The basic idea is that the component of velocity in the direction of the incoming varies in a sinusoidal fashion which thus

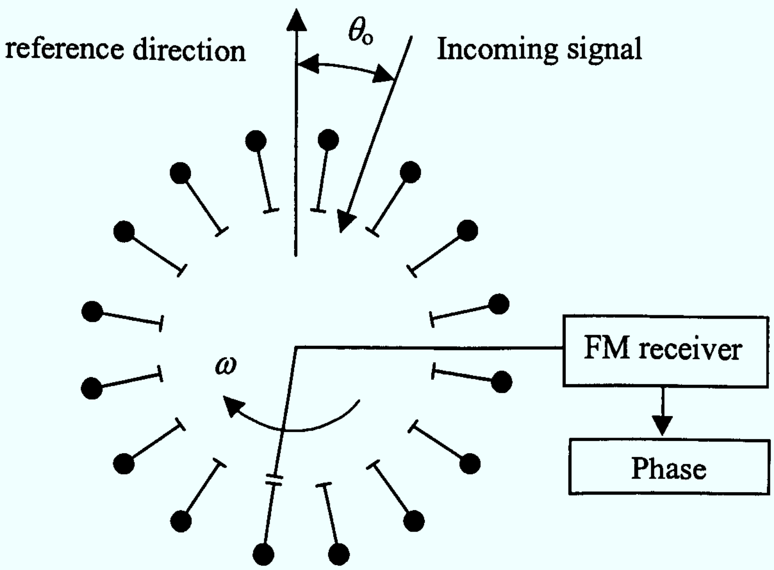

Fig. 2.4 A commutated pseudo-Doppler direction finding system.

frequency modulates the signal with instantaneous frequency shift Δf given by,

$$\Delta f = \frac{\omega R}{\lambda_0} . \cos(\phi_0) . \sin(\omega t - \theta_0)$$

where R is the radius of the array and λ_0 is the signal wavelength. The $\cos(\phi_0)$ term allows an estimate of the elevation angle, ϕ_0, from the amplitude of the FM signal in addition to an estimate of the azimuthal angle, θ_0, from the phase.

Such circular arrays are also used in a more conventional manner by sampling the complex amplitude at each location around the array (using a separate antenna element as a phase reference). As mentioned above, the array can be synthesized by using a physically rotating single element at higher frequencies (UHF and above) where the physical dimensions involved make the approach practicable. This approach has been used, together with estimates of time delays to investigate the directional properties of a signal from which multipath has been generated due to the presence of buildings, etc. [7, 8, 9, 10].

Perhaps the most common arrangement of elements to form an array is the familiar uniform linear array. In this, n elements, spaced distance d, form an effective aperture $L = nd$ as shown in fig. 2.5. If the outputs from the elements are added in phase, then a radiation (or reception) pattern similar to that shown is produced. The widths of the principal maxima are determined by the aperture in wavelengths L_λ, and the number of principal maxima by the spacing, d. If a

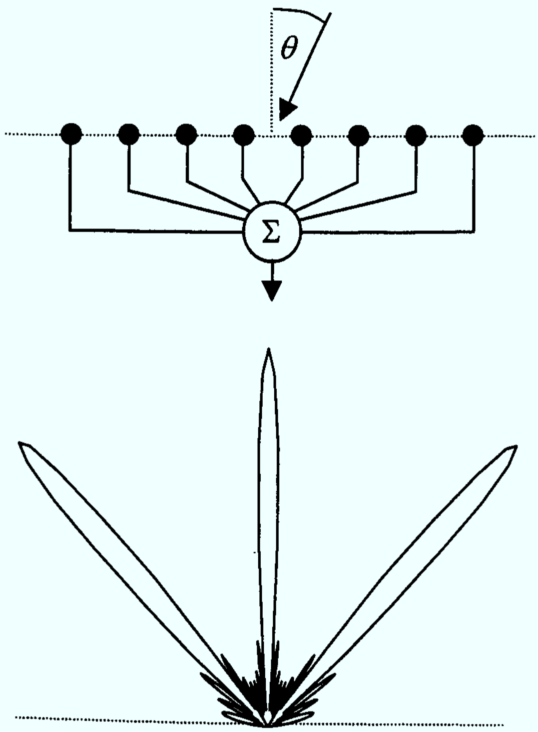

Fig.2.5 Illustrating the basic uniform linear array with 8 elements spaced $3\lambda/2$ to produce 3 principal lobes with null-to-null broadside lobe beamwidth = $114/L_\lambda{}^0 = 9.5^0$.

single principal lobe is required, then the element spacing is restricted to $\sim \lambda/2$. Such an array can be adapted readily to beam forming and to AOA determination. A simple way to "steer" the beam is to introduce progressive linear phase shifts in the signals from the individual elements using phase-shifting hardware. The required phase shifts may be generated from appropriate processing of the incoming signals. In the context of determining the AOA of the incoming signal, then simple measurement of the complex amplitude across the array (i.e., amplitude and phase at each element) allows accurate determination of the angle since the angular spectrum is simply the Fourier transform of this linear complex amplitude data set. An example of this is to be found in Webster and Merritt [11] in which a 16-element array with total aperture L = 667λ provides a resolution ~ 0.1^0; furthermore, multipath signals are resolved by this approach provided that the separation in AOA is greater than this limit. It might be noted in passing, that if the expected range in AOA is restricted by the propagation paths, as in this case, or the elements themselves have significant directivity in the broadside direction, then the spacing limitations can be appropriately relaxed to produce a wider overall aperture with a given number of elements.

The above represents a summary of some of the basic techniques which may be used in angle-of-arrival determination. Many variants on these approaches have been used, for example, switching between separate overlapping patterns from directive antennas and searching for the direction which gives equal amplitudes on the two has some attractions. Further information and discussion may be found in a number of sources [12,13,14].

The uncertainty in the estimated angle-of-arrival using any of the above approaches depends on several factors. Fundamentally, the measurement is limited by the signal to noise ratio and the integration time available to make it. If several estimates can be made then the uncertainty is reduced, so that indefinite improvement might be obtained as more measurements are made, the details depending on the nature of the signal and the noise. Having got to this point, though, a question now arises concerning the accuracy of the estimate from the point of view of errors, systematic or otherwise, introduced by the measuring system itself. The presence of objects close to the source or the receiver is likely to produce a perturbing influence on the final estimate through the generation of multipath signals and/or phase distortion. Mutual coupling between elements in an array will also produce errors in the final estimate of the angle-of-arrival and great care is needed in matching each of the individual elements.

3. Interferometric Techniques.

3.1 Introduction.

If a linear broadside array is to be used to estimate the angle-of-arrival of an incoming signal, then several criteria should be met. First, the answer should be unambiguous and second, there should not be significant errors introduced by the system itself. Further, if the system is to be readily deployable, it should be relatively simple. We start with a 2-element version as shown in fig.3.1. By measuring the phase difference, ϕ_{10}, between the two elements an estimate for ξ is available from,

$$\phi_{10} = -2\pi.\frac{d}{\lambda}.\sin\xi$$

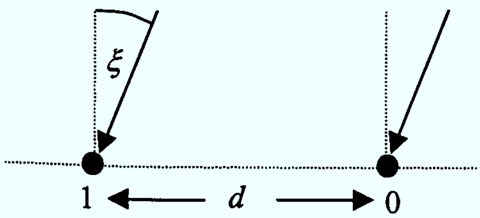

Fig. 3.1 Measurement of angle-of-arrival, ξ, from signal phase difference between two spaced elements.

Since ϕ_{10} is measured in the range $\pm\pi$, the value of ξ is determined unambiguously in the range $\pm\pi/2$ only if $d \leq \lambda/2$. Further, if d *is* set equal to $\lambda/2$, then mutual coupling between the two elements results in perturbed phase measurements leading in turn to the errors in angle-of-arrival. This is illustrated in fig. 3.2 for $\lambda/2$ dipoles placed end-to-end and side-by-side (the usual arrangement).

Similar effects are to be expected in an array that has several closely spaced elements, and appropriate allowance becomes increasingly difficult especially if the array is mounted close to ground.

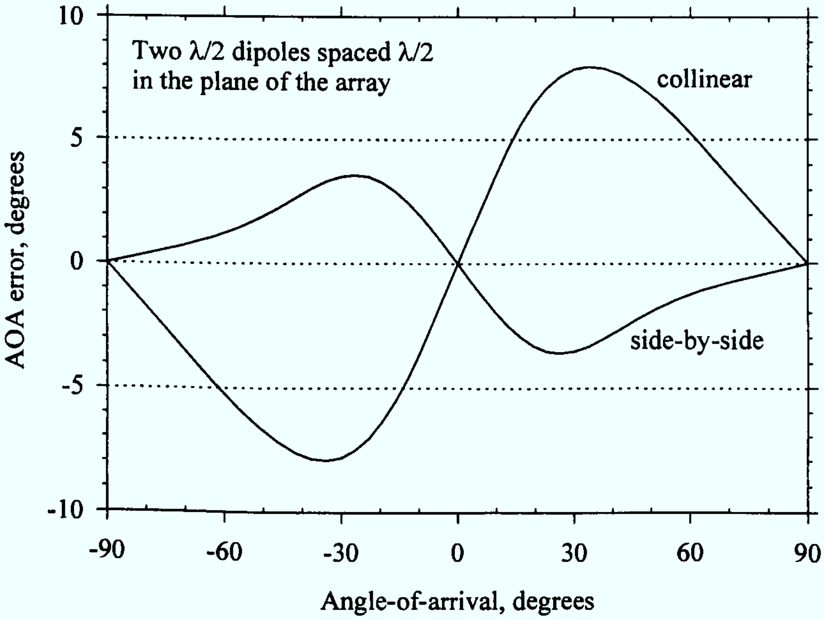

Fig.3.2 The error in AOA induced by mutual coupling, for two dipoles spaced l/2.

3.2 A 3-Element Interferometer Array.

3.2.1 *The Basic Principle*

In order to circumvent some of the problems outlined above, a simple 3-element system has been developed [Webster and Jones, 15] and applied to the measurement of angle-of-arrival of return echoes in a meteor radar [16]. The basic principle is illustrated in fig.2.3 in which the 3 antenna elements are well spaced but, crucially, the difference in separation is set equal

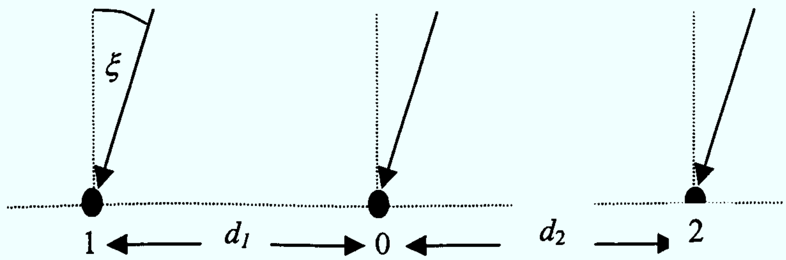

Fig. 3.3 A linear 3-element array with spacings differing by $\lambda/2$. The centre element is used as a phase reference.

to $\lambda/2$. As a result, two estimates of ξ are available from,

$$\sin\xi = -\frac{\lambda}{2\pi}\frac{(\phi_{10}-\phi_{20})}{(d_1+d_2)} = -\frac{\lambda}{2\pi}\frac{(\phi_{10}+\phi_{20})}{(d_1-d_2)} \tag{3.1}$$

The first, involving the full aperture, gives an accurate but many-valued estimate of ξ, while the second (with d_1-d_2 = $\lambda/2$) removes this uncertainty; the sense of the phases should be noted.

A pictorial representation of the approach is given in fig. 3.4. Essentially, the angle-of arrival value from the full aperture that is closest to that indicated by the equivalent 0.5λ array, is taken as the required answer. It might be expected that the wider the total aperture, the greater the accuracy in the final result (the error bands become narrower). While this is true in principle, the number of possible solutions also increases proportionately. Noise then places limits on the overall aperture size since the possibility of multiple values falling within the unambiguous range should be avoided. In the planning process, therefore, account must be taken of this in selecting the element spacing. Separations of 2.0λ and 2.5λ have been used [15] with some success to determine the angle-of-arrival of forward-scatter meteor radar echoes, this being taken as a reasonable compromise between the need for accuracy and the reality of a noisy environment. If the signal to noise ratio is expected to be sufficient, then increased aperture systems can be deployed and, in fact, a separate additional "out-rigger" element at a further spacing of 4.5λ has been tried with some success in the above mentioned system.

3.2.2 *System Performance*

From fig.3.4, it is apparent that the wide aperture gives a good estimate of the angle-of-arrival. The error ($\Delta\xi$) in ξ is related to the total error ($\Delta\phi$) in the measured phases at the outer antennas by:

$$\Delta\xi \approx \frac{1}{\cos\xi}\cdot\frac{\Delta\phi}{(d_1+d_2)} \tag{3.2}$$

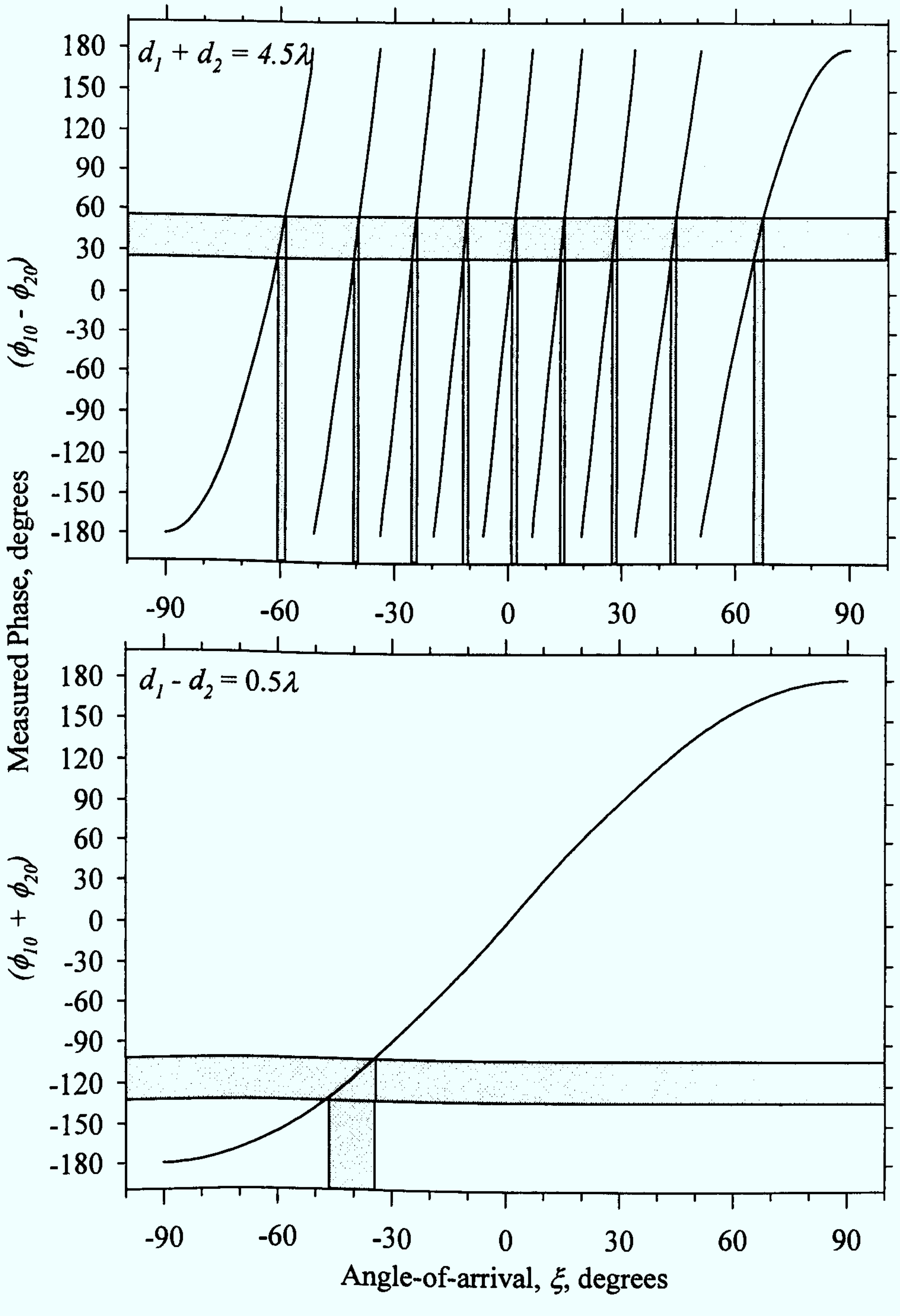

Fig 3.4 The relationship between the measured phase angles and the derived angle-of-arrival for the three element array. An actual value of AOA of 40^0 and phase uncertainty of $\pm 15^0$ are assumed for illustrative purposes. A value in the range $40^0 \pm 0.5^0$ would be inferred.

Fig.3.5 shows a representative display of 500 samples of measured phases at the two outer antennas in which, for convenience, the actual phase difference is assigned to be 90^0 with an SNR of 10dB. The estimated value of ϕ is 90.1^0 with a standard deviation, σ_ϕ, of 12.4^0 and a standard error in the mean of 0.55^0. For an AOA, $\xi \sim 0^0$, and $(d_1 + d_2) = 4.5\lambda$, this in turn leads to a standard deviation in ξ of $\sigma_\xi \approx 0.44^0$ and standard error in the mean of 0.02^0. These

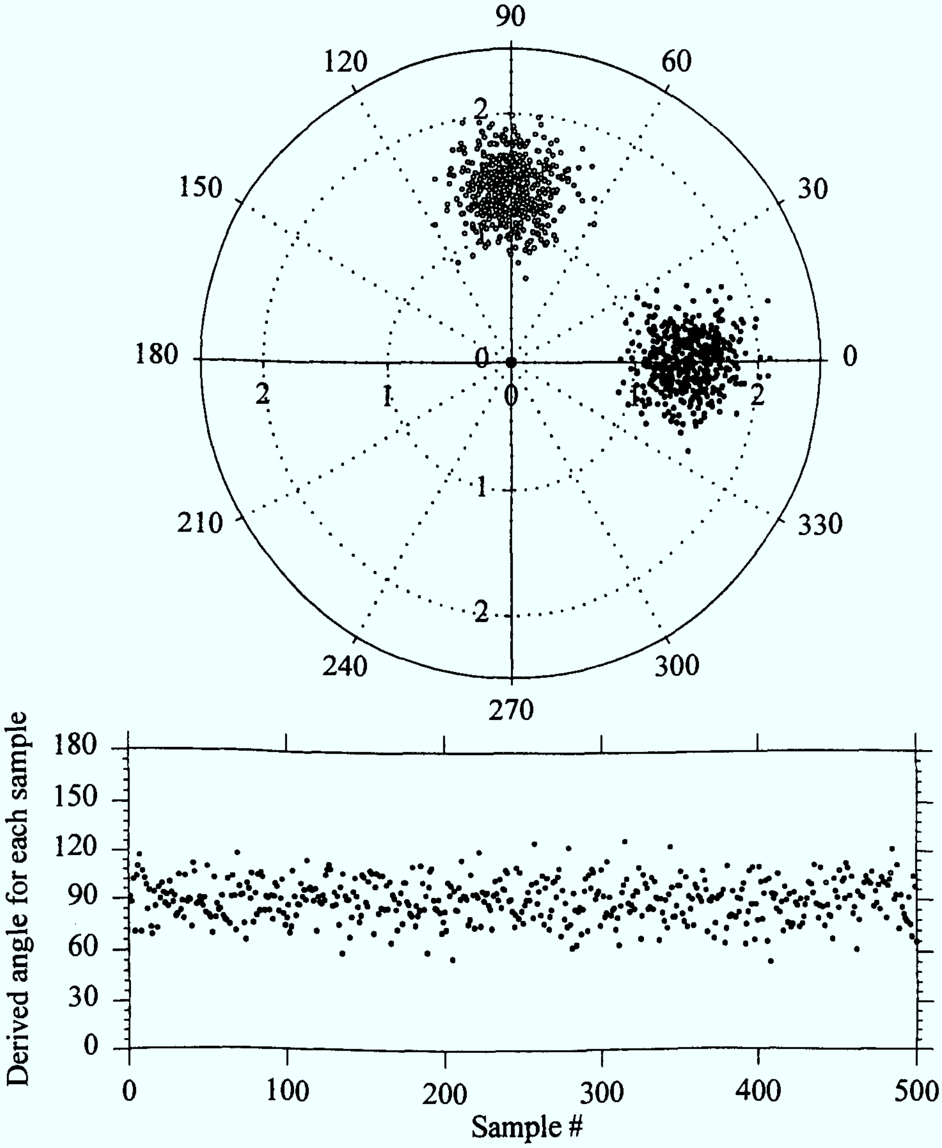

Fig. 3.5 A phasor plot (upper) of the signals received on the two outer antennas for an assigned phase difference of 90^0 and SNR of 10dB; 500 samples taken. A scatter plot of the individual samples (lower).

values are dependent on the signal-to-noise ratio (SNR) and the aoa, ξ, as shown in fig. 3.6. Since n estimates from a population with standard deviation, σ, result in a standard error in the mean of $\sigma/\sqrt{n}$, it is clear that very accurate estimates of AOA are possible in principle provided that sufficient time is available to make many measurements.

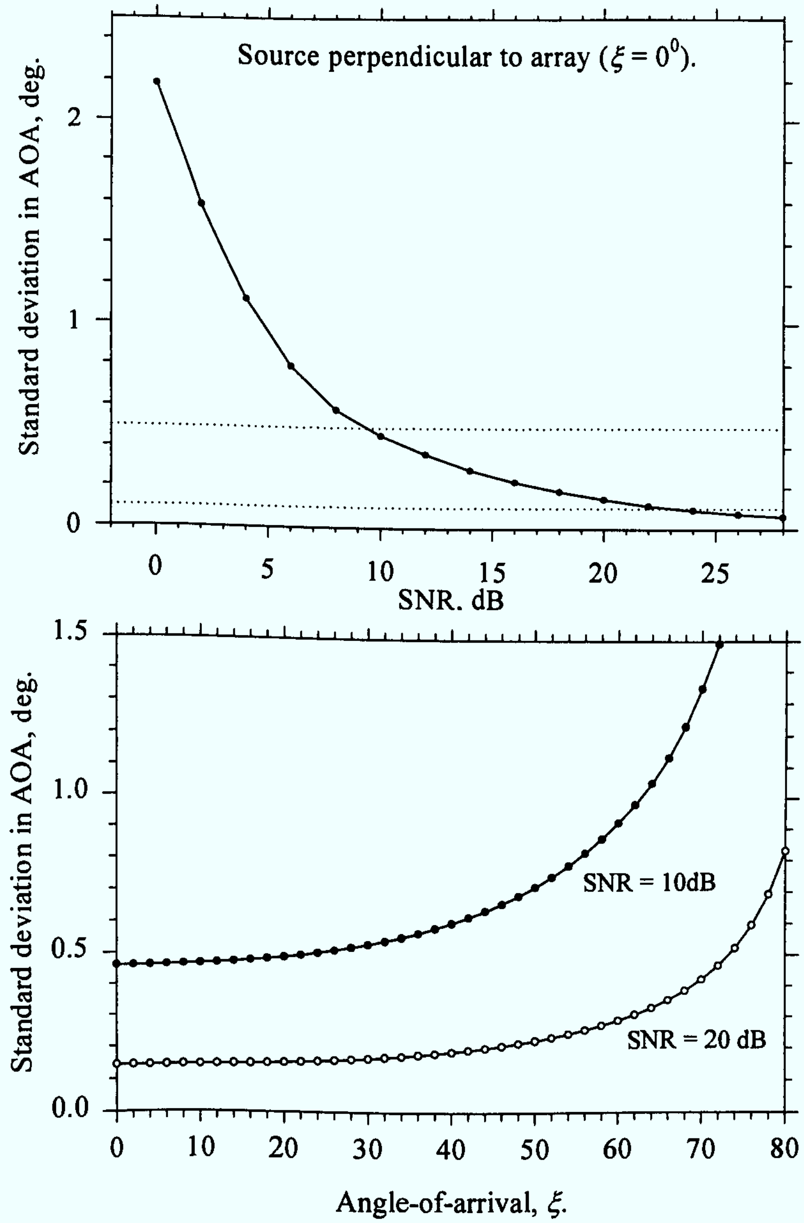

Fig. 3.6 Variation of the standard deviation σ in the angle-of-arrival (ξ) with signal-to-noise ratio (SNR) and with ξ for the 3-element array (2.0λ and 2.5λ).

4. The Long Baseline System.

4.1 *Interferometer measurements.*

To place the numbers in perspective, if an accuracy of $\pm 0.1^0$, say, in angle-of-arrival is attainable from each of the receiver locations, then this translates into about ± 10m in lateral position at a distance of 5km. The suggestion is that once this kind of resolution is attained, then the long baseline shown in fig.1.1 should allow even greater precision. Measurement of the phase difference between the signals at the two receivers, gives the potential location of the source lying on a hyperbola with major axis aligned with the "array" axis; representative curves are shown in fig. 4.1. The intersection of hyperbolae from the three different baselines then gives the location of the source as shown in fig.4.2.

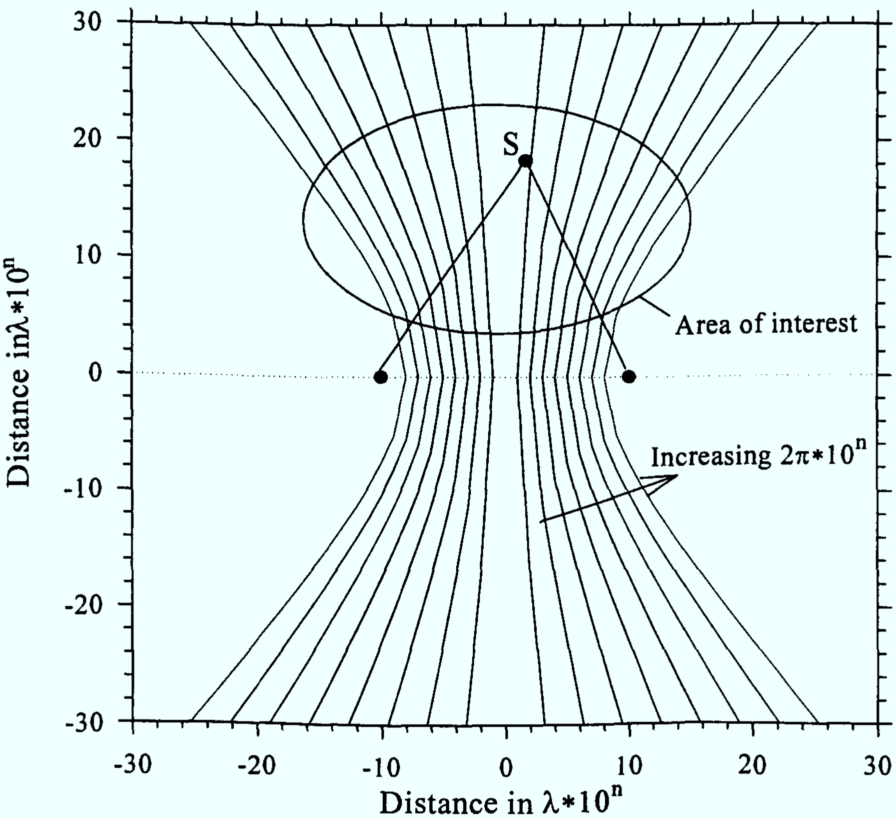

Fig. 4.1 Representative hyperbolae associated with fixed difference in distance from the source to each of two receivers.

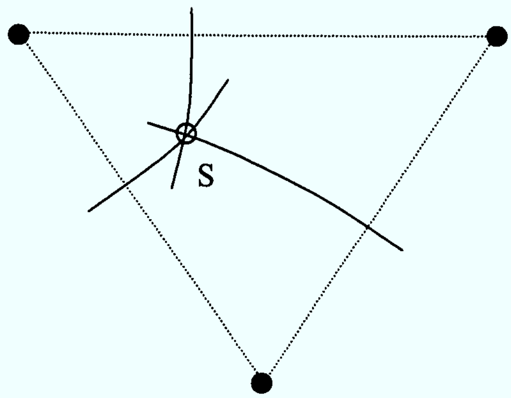

Fig. 4.2 Location of the source, S, at the intersection of the hyperbolae from the respective baselines.

In the absence of any other reference, the familiar phase ambiguity of 2π radians arises as the difference in distance between any two of the receivers changes by one wavelength (λ). With the proposed geometry, this means that the lateral distance between adjacent possible hyperbolae is in the order of one wavelength (see fig.4.1). Since we are considering a range in λ from a maximum of 2m, down to about 0.3m, much smaller than the initial accuracy from the three individual sites, it is clear that multiple possibilities will result, the resolution of which may prove difficult if not intractable.

4.2 *Time-Difference-of-Arrival (TDOA)*

Given the above problem, a look was taken at the possibility of using differences in the time-difference-of-arrival (TDOA) of the signal at the three receivers. For this, a reasonable modulation of the signal is needed, and while this is in general unlikely to be optimized for this purpose, it may be possible to establish the source location with some accuracy. The geometry, hyperbolae and all, is the same as for the interferometer, but this time the sampled time series of the modulating signal is used. The relative delay between the signal received on two of the receivers establishes the difference in distance (i.e., the relevant hyperbola) from source to receivers. Cross correlation between the two samples of the modulating signal facilitates this process, an example of which is shown in fig.4.3. In order to establish the location of the source with an accuracy in the order of ±10m. or better, a resolution in time delay of ±30ns or better is needed which may be a tall order given the range of modulation schemes which may be encountered. It might be noted in passing that the LORAN position fixing system operates essentially as the inverse of our problem and claims a resolution in the order of ±200m. In fig. 4.3, the demodulated signal was simulated using the sum of several

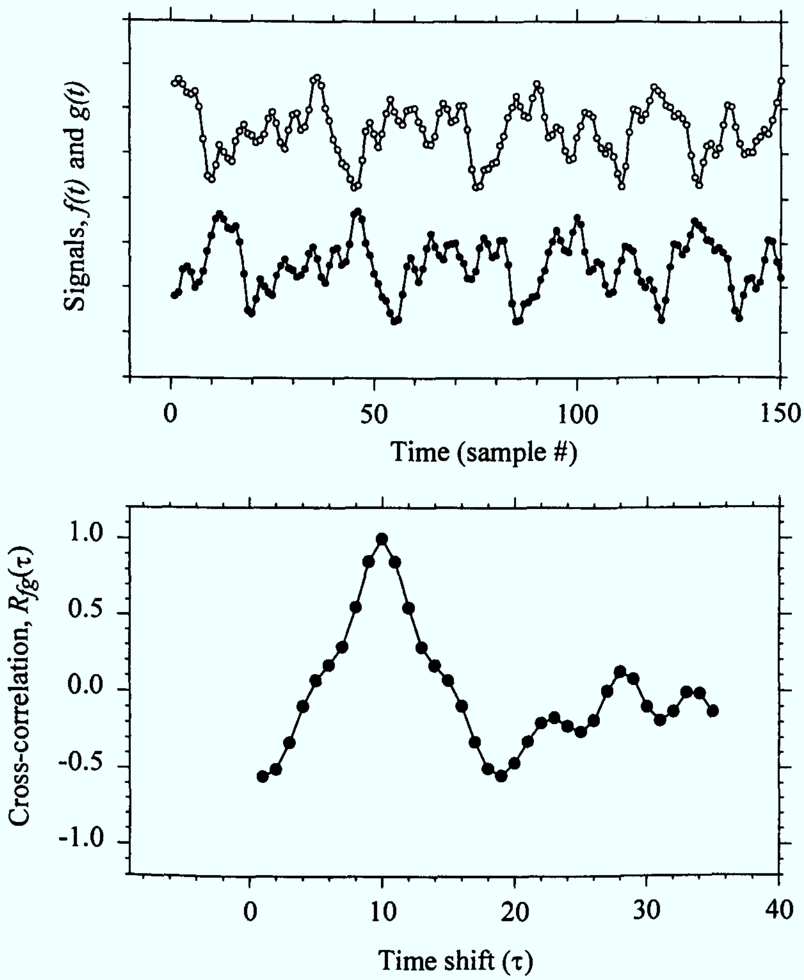

Fig. 4.3 Modulation at two receivers with a delay equal to 10 sampling intervals. The cross-correlation process gives an accurate estimate of this delay.

sinusoids, unrelated in frequency with the sampling rate set at twice the highest frequency component; no extra noise was introduced. The signal *g(t)* is a replica of *f(t)* time shifted by 10 sampling intervals. The cross correlation process accurately measures this shift and the location of a peak occurring between points can be established by curve-fitting the points around the peak. The effect of poor signal to noise is shown in fig. 4.4, which is identical to fig.4.3 except for the introduction of noise for a signal-to-noise ratio of just 3dB. In both cases, 1000 sampling points were used in evaluating the cross correlation and the effectiveness of long integration times in extracting the signal from noise is well illustrated by fig.4.4.

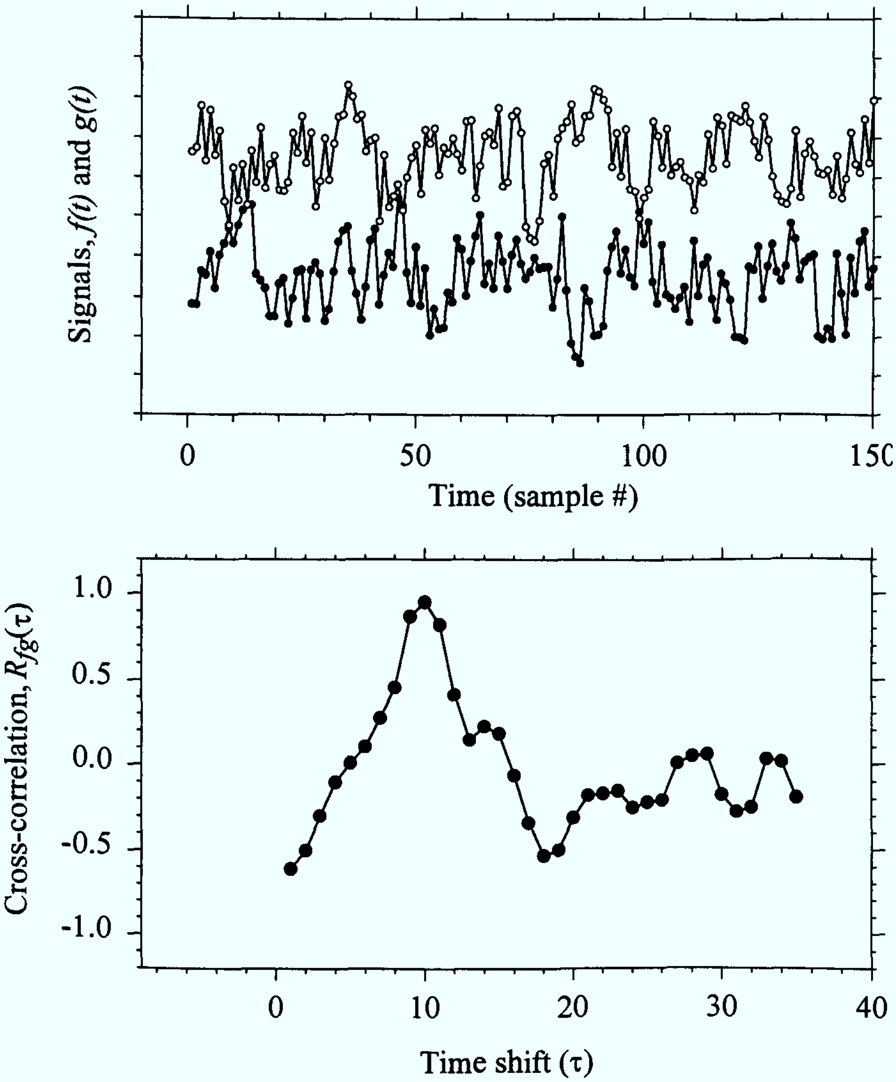

Fig. 4.4 Similar to fig. 4.3, with the addition of noise for a 3dB SNR. Note the slight shift in the estimate of the delay. Further measurements would produce estimates centred around the true time shift.

As for the accuracy of the technique, modulation of some sort is needed and the end result depends on the character of the modulation. Allowing an estimate accuracy of one tenth of the separation between time shifts for a reasonable SNR and sampling at the Nyquist frequency (twice the highest signal frequency), a bandwidth of 100kHz would result in a time delay accuracy of 0.1*5μs or about 150m. in distance.

5. Discussion.

The arguments presented so far have been based on the ideal situation where there is a clear line-of sight path from transmitter to receiver and no other paths due to reflections etc. This is unlikely to be the case in practice other than, perhaps, in a maritime or a rural situation but even then, reflections from the surrounding terrain (or water) may cause some uncertainty in the measurements and need to be considered. In deploying any system to measure directions and locations, it is reasonable to assume that every effort would be made to avoid reflected signals from nearby buildings by suitable choice of site. Further, the locations would be chosen to provide as commanding a view as possible of the area of interest. Given that, allowance then has to be made for the surroundings of the transmitter.

5.1 Transmitter in an Urban Environment.

If the transmitter cannot be "seen" by the receivers, then this has two negative effects on the determination of the origin of the received signal. First, the most direct signal must find its way out of the source region either by transmission through obstructions, or around them (diffraction), or both. This may result in a considerable attenuation of the received signal compared to the numbers quoted in Section 1. Second, any additional reflected signals will arrive with a different angle-of-arrival from, and be delayed relative to, the most direct. This latter point is likely to be the more serious from the point of view of source location.

For a significant reflection to occur from a neighboring building, several criteria have to be met. First, the building must have a relatively smooth surface (in relation to the signal wavelength); it is assumed to have a moderate to high reflection coefficient (0.5 to ~1.0 depending on the material and the angle-of-incidence). Second, the building surface must be suitably oriented to produce a reflection in the direction of the receiver(s). Third, and perhaps most important, the building must present an area which is comparable to the dimensions of the first Fresnel zone at that point. The geometry is illustrated in fig. 5.1 which shows the general shape of the first Fresnel zone and is the area needed to provide a strong reflected signal at the receiver; a lesser area will result in a proportionately weaker signal. The dimensions increase with distance from the source and the variation in the longer dimension for a source along the direction perpendicular to the transmitter-receiver axis is illustrated in fig. 5.2.

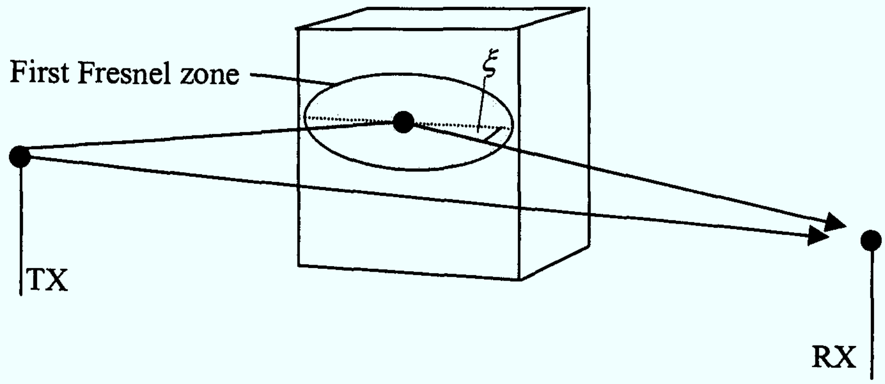

Fig. 5.1 The geometry of reflection from a building. The size of the first Fresnel zone is dependent on the distance from source to reflection point and the angle-of-incidence (ξ).

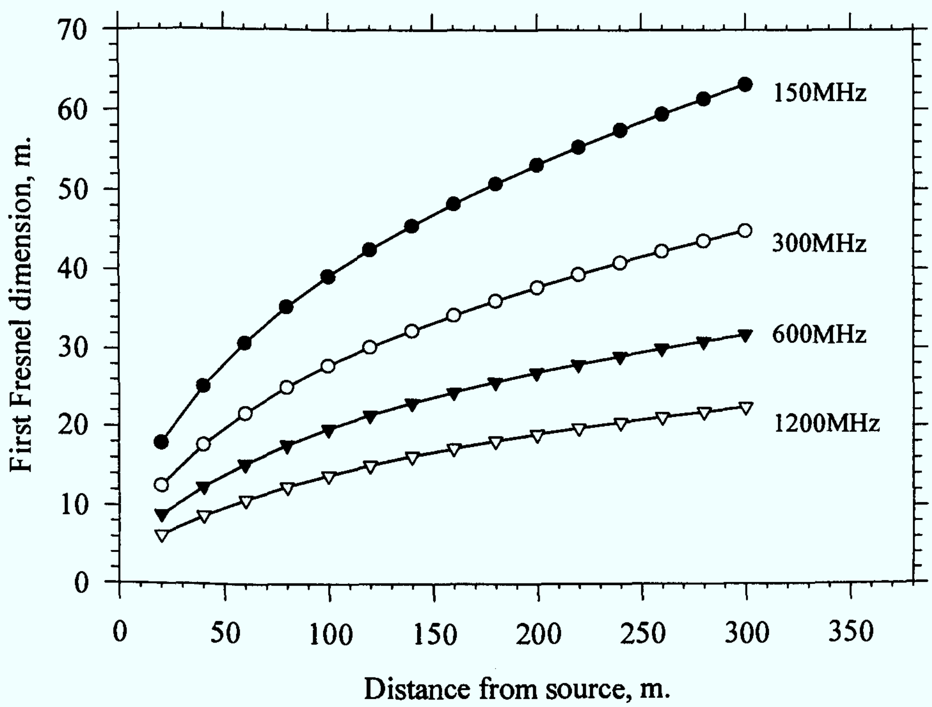

Fig. 5.2 First Fresnel zone longer dimension versus distance from source in a direction perpendicular to transmitter-receiver axis; transmitter to receiver distance of 3km.

From all of these considerations, it seems likely that rays from any building reflections in the transverse direction will be limited to about 100m. or so at a distance of 3km., at least for frequencies at the lower end of the range. This results in angular and time delay differences relative to the direct ray in the order of 2^0 and 0.33μs respectively. The effect of this scenario on the performance of the 3-element array, for example, is to produce an uncertainty in the measured AOA, the simulated standard deviation in this particular example being in the order of 2^0 for signals of similar strength.

Having said that, it is clear that if the transmitter and receiver are close together, ≤1km. say, and both well "buried" in the urban environment, then reflected rays from a much wider range are to be expected [7, 8, 10]. Any such multipath is likely to cause signal fading and hence degraded SNR, which in turn affects the performance of the measuring system, be it AOA or TDOA. For our purposes here, it is assumed that the source is stationary. A mobile source would be expected to produce a signal varying widely in amplitude and in number and direction of the multiple paths. In any case, the 3-element array is not expected to be able to resolve several paths with widely differing AOAs.

5.2 Signal Processing Algorithms for AOA Estimation.

In recent times, much effort has been put into the development of algorithms to enable the resolution of separate rays arriving from different directions. Usually, these are applied to systems that are all round looking and often employ uniform circular arrays [9, 10]. The resolution of rays closely spaced in AOA, using data from an array, can be accomplished using a Maximum Likelihood algorithm as used in [17]. Another popular high-resolution algorithm is multiple signal classification, MUSIC, (Schmidt [18]), and extensions [19, 20, 21]. Estimation of signal parameters via rotational invariance techniques (ESPRIT, [22]) also finds favour as a computationally efficient and robust approach to AOA estimation. An excellent review of these, and other, techniques may be found in [23]. These techniques are computationally intensive and well suited to the establishing of a data base for modelling activities. They are, perhaps, less suited to a routine role in the location of radio sources, although with computing developments proceeding apace, this may be a fruitful area to explore.

6. Summary and Recommendations.

It seems that the layout suggested in fig.1.1 has some merit in that angle-of-arrival measurements at the three receiving locations are potentially able to provide very accurate position location under ideal conditions. However, it also seems unlikely that this could be improved upon by using long base-line interferometry due to the inherent problem of phase ambiguity. Time-difference-of-arrival (TDOA) may be an option depending on the type of signal transmitted from the source. An additional complication with well-separated receiving sites is the need for some form of synchronization depending on the scheme used.

The "ideal conditions" mentioned above specifically excludes the situation where multiple reflections of significant amplitude result in many paths arriving at the receiver from as many different directions. In any case, under such circumstances it would be difficult to decide on the true direction of the source unless simultaneous AOA and TDOA information were available.

A simple 3-element array has been described which is capable of providing very accurate angular data provided that there is only a single path to the receiving site. A small angular spread in azimuth for several paths might be tolerable, but we would not expect that widely spaced paths would be resolvable due to the limited amount of phase information available. The array might be useful in a maritime or rural environment provided that the receiving site is well removed from any potential strong reflection source. Similarly, a two-axis version would be capable of position determination in azimuth and elevation in an aeronautical situation; this is akin to the excellent performance experienced in meteor radar observations. A test of the effectiveness of the system under several different conditions might prove to be of interest.

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