July 3, 1962 W. W. H. CLARKE 3,042,916

DIRECTIONAL SYSTEM FOR WAVE PROPAGATED SIGNALS

Filed March 22, 1957 2 Sheets-Sheet 1

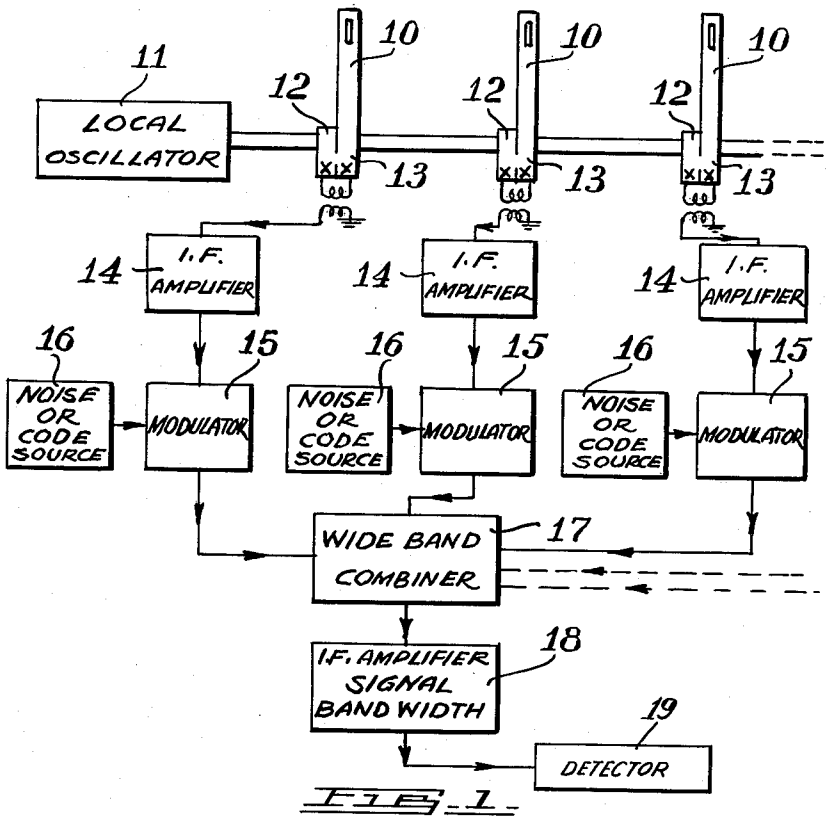


FIG. 1

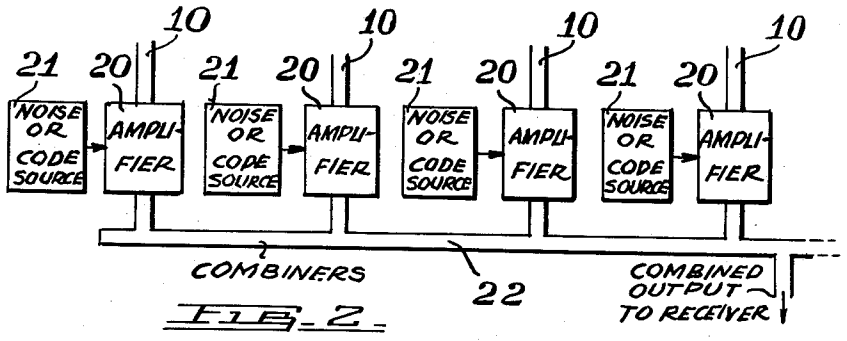


FIG. 2

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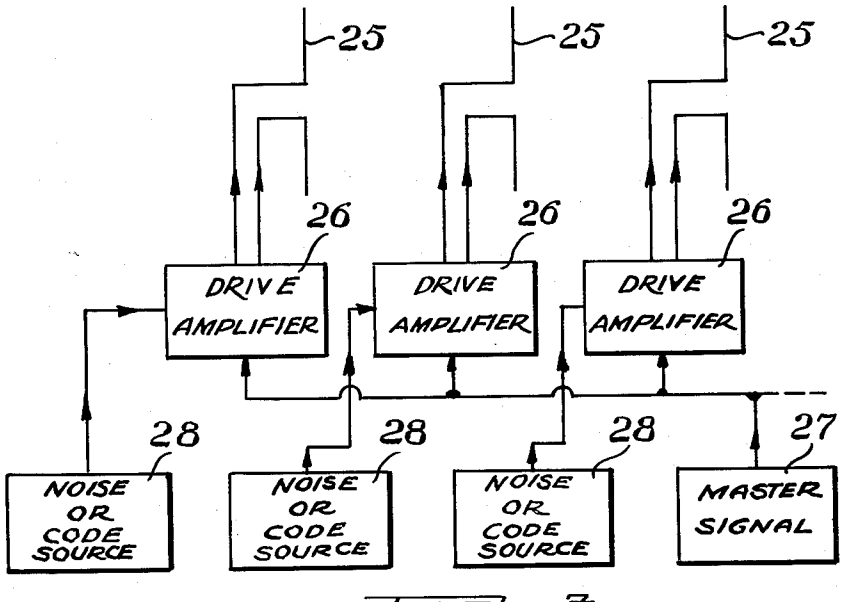


FIG. 3

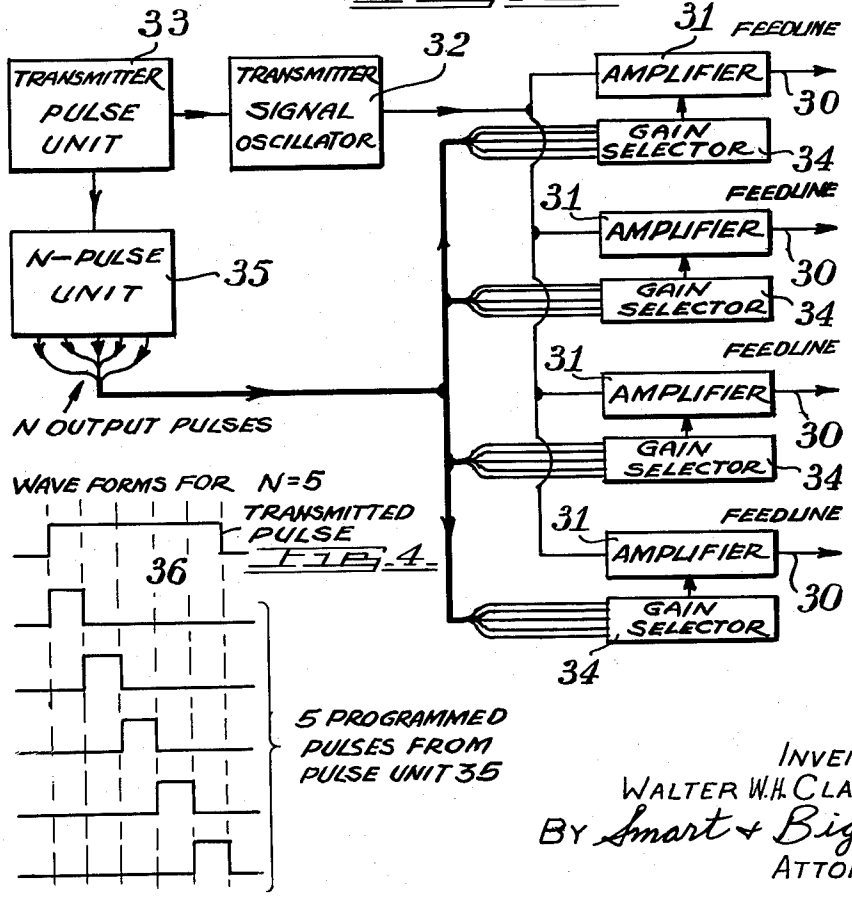


FIG. 4

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DIRECTIONAL SYSTEM FOR WAVE PROPAGATED SIGNALS

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6 Claims. (Cl. 343—100)

This invention relates to apparatus for reducing the effective side lobe level of a multi-element directional system used for wave propagated signals which may be audible or which may be supersonic waves including those of radio frequencies. Although the invention has applications to transducer arrays and hydrophone arrays it will be described in relation to antenna arrays for radio signals.

In the antenna art it is common to use phased poly-fed antenna arrays, that is, antenna arrays in which the phase of the signal to each element of the antenna is preset to provide main lobe reinforcement. The side lobe levels of such antenna arrays are comparable with the performance of paraboloids and other directional antennae. According to current practice with poly-fed antennae arrays an attempt is made to approach the desirable condition of radiating all energy not included in the main beam isotropically but this has been found to involve critical conditions and can be achieved only with great difficulty. Small deviations of mechanical or electrical factors cause the designed performance to be lost. In practical applications it is also found that climatic and other ageing factors will cause long term variations of excitation which will destroy the optimum designed performance. In the present state of the art, side lobes 25 db or more below the main beam are considered very good.

It is known in the antenna art to use a variation of excitations in a controlled related manner according to formulae expressing the formation of a reinforcing plane wave front in a specified direction for the purpose of causing the main lobe to scan (that is to change in direction) in azimuth or elevation, or both. This is done at rates very much lower than the signal bandwidth so that in the radar example several pulses will be radiated in each direction during one sweep of the beam. The sweeping of the beam is accomplished either by frequency or phase adjustment in the controlled related manner.

According to the present invention, apparatus for reducing the effective side lobe level of a multi-element directional system used for wanted wave propagated signals external to the apparatus comprises, a plurality of connections for the corresponding electric signals internal of said apparatus, each connection for the internal electric signals connecting to at least one of the elements, a source of modulating wave of an unique wave form for each connection, each modulating wave having frequency components extending over a bandwidth substantially greater than the bandwidth of the wanted wave propagated signals, and modulating means connected in each connection and adapted to modulate the electric signals being conducted by that connection with the modulating wave for the same connection. The term "unique wavefrom" is to be interpreted as meaning that each modulating wave has a waveform which is different from the waveform of every other modulating wave employed in the system.

According to the invention and in the case of a transmitting antenna a modulation method may be used to reduce the effective side lobe level by removing or spreading most of the side lobe radiated energy to frequencies lying outside the band of the receiver. A similar modulation process may be used at the receiving antenna. Apparatus according to the invention involves independent amplitude or phase modulation by a modulating wave

having an unique wave form such as random noise, containing frequency components covering a much greater bandwidth than the signal radiated or received, of each element or a selected number of elements of the antenna array. With a noise modulation of small modulation index or small degree of modulation (the same order as the side lobe level), the main lobe still contains a major part of the signal which is not noise modulated, whereas in other directions the radiated or received signal will be 100% modulated and thus spread over the noise bandwidth. The noise bandwidth being much greater than the signal bandwidth allows most of the side lobe signals to be rejected by the receiver by virtue of their frequency spread. The term "side-lobe level" is the ratio between the maximum amplitude of the side lobe and the maximum amplitude of the beam or main lobe.

Application of the invention to a transmitter may be by independent amplifiers for each element (or set of elements), the amplifier gain or phase shift being susceptible to modulation of small index or degree by noise signals of selected bandwidth. Application of the invention to a receiver could for example be by independent intermediate frequency amplifiers for each receiving element (or set of elements) these amplifiers being independently noise modulated.

A wide range of parameters exists for optimizing the performance to accord best with the type of signal being used and with the degree of improvement required. The band limits of the noise may be selected over widely varying ranges; the number of elements modulated, the common modulation of certain elements, the type of modulation, the method of modulation may all be varied.

According to the invention instead of the modulating signal being random noise, use may be made of a predetermined sequence of excitation levels or gain levels, the sequence being carried out rapidly so that a number of different side lobe patterns are used during a time interval of the order of the reciprocal of signal bandwidth in use, so that the modulation is substantially wider band then the signal. The predetermined sequence of excitation levels or gain levels may be used repetitively without modification.

It will be of help in understanding the way in which the present invention provides effective reduction of side lobe radiation or reception if consideration is given to the relative magnitudes of side lobes in high gain antennae. An antenna having a gain of 40 db (nominally 10,000 times isotropic radiation) for example, usually may be expected to have an efficiency of about 0.6, which means that 60% of the radiated energy will appear in the main beam whose solid angle is

$$\frac{4\pi}{10{,}000}$$

the residual 40% is then able to generate side lobes in any other direction. Radiated isotropically this residual 40% of the radiated energy would give in any direction an energy density

$$\frac{4}{60{,}000}$$

times that of the main lobe. For arrays or other poly-fed antennae, with which the invention is concerned, it is very difficult to approach this homogeneous radiation of residual power which gives supposedly optimum side lobe levels. However, it is possible to remove any side lobe of say 20 db below the main lobe by adjusting a correctly selected 6% of the radiators some 10% in power by raising or lowering the power; that this procedure would generate other side lobes is axiomatic. This illustrates however that a random variation of the excitation levels of antenna elements will result in a variety of

side lobe patterns and also, in any one direction, in a variety of radiation levels which will mainly be very low and should have an expected average equal to the isotropic radiation case. It may be expected for some antennae that not all directions will approach the same low average and it is likely that the preselected (that is specifically designed) sequence of sets of excitation levels may prove more desirable for such cases. However the degree to which the isotropic radiation (or reception for the receiving antenna case) average may be approached with any given antenna configuration is the same as the degree to which all side lobe directions are equally probable for random small perturbations of the element excitations. There is a further advantage provided by this method. Because the side lobe signals are noise (or code) modulated by a wider band of frequency components than the signal in use, the side lobe energy in any direction is approximately equal to the side lobe isotropic average and occupies a full noise bandwith, and therefore the energy in the signal bandwidth is still less. An example may be used to illustrate this further gain. Consider a matrix antenna (that is, an antenna comprising a plurality of elements spaced out in one, two or even three dimensions) used to transmit (or receive) a carrier at frequency f_0 modulated by a pulse of t seconds' duration. Suppose now that two sets of excitation values for the matrix elements have been determined such that the side lobes (above a chosen value) for one set do not coincide with any of those for the other, and suppose the worst side lobes of either set are 20 db below the main beam. If it is arranged that the feed switch from one set to the other half way through the pulse, then the worst side lobe case is improved from transmitting at 20 db below the main beam to transmitting at that level only for the time $t/2$. In the receiving case the gain levels of the individual receiving elements should be regarded as switching back and forth between the chosen sets of values with square wave periodicity t. Hence the power (in the worst side lobes) is halved and covers twice the bandwidth. Accordingly even this simple example can be expected to give a 6 db improvement. The example becomes more complicated when a number of steps during the pulse are used and it is then that for any one direction a number of excitation levels occur sequentially all of which must be taken into account; in this event it might be thought because the levels average to the isotropic case that this defines the limit, but in fact a further gain due to band spread also occurs. The phase for each successive set of excitation or gain levels is changed at random from the last, hence though the successive amplitudes are likely to be of the same order, band spread occurs and causes a further side lobe effective reduction. It is this aspect of the invention which can offer improvements even in those cases where unfortunate design features cause certain directions to be preferred for side lobes throughout the ranges of excitation perturbations. These perturbations though they may not greatly suppress the side lobes in these directions will cause the side lobes signal phase to change at random, and applied rapidly or in the form of wide band noise will spread the energy outside the signal bandwidth. With this technique according to the invention, it may generally be expected that side lobe levels will average to the isotropic and that signals received or transmitted will, in these side lobe directions, be spread over a band determined by the switching functions or noise and hence the effective side lobe level will be perhaps 10 to 20 db below isotropic. If B_S is the signal bandwidth and B_N is the noise bandwidth, then the theoretical level below isotropic should approach

$$10 \log_{10} \left(\frac{B_N}{B_S} \right) \text{ db}$$

that is 20 db below isotropic can be expected only with noise bandwidths 100 times the signal bandwidth or greater.

The invention will be further described with reference to the accompanying drawings in which:

FIGURE 1 is a block diagram illustrating application of the invention to a receiving antenna array,

FIGURE 2 is a block diagram illustrating a variation in application of the invention to a receiving antenna array,

FIGURE 3 is a block diagram illustrating application of the invention to a transmitting antenna array; and

FIGURE 4 is a block diagram illustrating another application of the invention to a transmitting antenna array.

Design considerations in connection with application of the invention to antenna arrays varies with the bandwidths desired and with the size of antenna and the carrier frequency to be used. It is proposed to discuss first a microwave linear array having individual elements on which signals are independently received, modulated and combined. Referring to FIGURE 1, the array elements **10** shown in the figure are broad face off-centre slots in a set of wave guides. It is desirable at microwave frequencies to use an intermediate change of frequency to a convenient intermediate frequency. This is done as shown in FIGURE 1 by a local oscillator **11** coupled to the array elements **10** through a series of cross-guide couplers **12**. Each cross-guide coupler **12** contains a hybrid mixer crystal unit **13** transformer coupled to an intermediate frequency amplifier **14**. Each intermediate frequency amplifier **14** feeds to a modulator **15** of which the modulating signal is derived from a noise generator or selected coder **16**. The output of each modulator **15** is fed to an input of a wide band combiner **17**, which produces a combined intermediate frequency signal which is fed to a further intermediate frequency amplifier **18**. The remainder of the receiving system may be of conventional design which would include a suitable detector **19**. The design of each of the pieces of apparatus indicated in block form in FIGURE 1 is known to those skilled in the art.

In the embodiment of the invention shown in FIGURE 1 the array elements are broad face off-centre slots in a set of wave guides. There are a wide variety of ways of producing independent reception from such elements. However, it is desirable at microwave frequencies to change frequency to an intermediate frequency by well-known means. The signal from each element is to be shifted to intermediate frequency separately and amplified separately at this frequency; the noise modulations (of small degree) are then applied at intermediate frequency and the separate signals are subsequently combined and used as a composite received signal. By this arrangement it is possible to avoid an undesirable phenomenon of side lobe reception. The modulations remove from the signal band much of a side lobe signal in that band and also moves into the signal band some of a side lobe signal at frequencies outside the signal band. The first intermediate frequency amplifiers may be used to eliminate this side lobe signal if their bandwidth is that of the signals in use. It is to be noted that independent reception from each element, or from several groups of elements, would involve an increase of receiver noise factor by an amount ($10 \log_{10} n$) db where n is the number of seperate receivers. The arrangement described in connection with FIGURE 1 is for example applicable to a multi-element array of wave guide horns, in this case the side lobe averages would approach values for each elevation which are different and are determined by the elevation pattern averaged in azimuth. It is also possible to combine at radio frequency or at intermediate frequency adjacent elements or non-adjacent elements prior to their modulation by noise or the selected coders.

FIGURE 2 of the drawings illustrates how the invention can be applied to a receiver without frequency changing prior to the radio frequency amplifiers. As shown in FIGURE 2 the radio frequency amplifiers **20** are fed with signals from the antennae **10**. The radio frequency amplifiers **20** are gain modulated by noise or code sources

21. Combiner means 22 of conventional design is provided to combine the outputs of the radio frequency amplifiers 20 and the combined output can then be fed into a conventional receiver. The advantages of the narrow band premodulation amplifiers described in connection with FIGURE 1 could also be included in the modification shown in FIGURE 2 by use of signal bandwidth filters connected before the gain-modulated radio frequency amplifiers 20. It is, however, more desirable for some applications where the increase of receiver noise factor is important to gain or phase modulate the signals without electronic devices which generate noise. One method of doing this is by use of ferrite modulators of small modulation index or degree each independently driven by wide band noise or from a code source.

Similar standard circuits may be connected together according to the invention for reception of frequencies at which dipoles and coaxial feeders are more appropriate than waveguides. The transmitting antenna embodiments described below are illustrated by such arrangements which are, however, equally applicable to receivers while the microwave configurations are equally applicable to transmitters.

FIGURE 3 shows in block form application of the invention to a transmitting antenna array comprising dipoles 25 fed by drive amplifiers 26 which in turn obtain the signal to be transmitted from a source of master signal 27. Each drive amplifier 26 is adapted to be modulated by the signal from a noise or code source 28. The remainder of the transmitting system can be of conventional design and the apparatus shown in block form in FIGURE 3 is of well known design.

If desired, groups of elements of a matrix antenna can be driven from a single drive amplifier. For example, an interlace scheme of driving groups of elements of a matrix not all in the same row may be used, or, for example diagonals in the array can be fed in common from noise modulated amplifiers. Also, if desired in the transmitting case using a waveguide, modulators of the ferrite type may be used.

Any antenna having an exciter (or collector) which may be regarded as a distributed feed and divided into poly-feed connections may have the invention applied to it. For example, the invention may be applied to a small horn feeding to a reflecting dish type of antenna. Such a feed normally provides a tapered illumination and if the phase and/or amplitude distribution of this illumination is only very slightly disturbed the resulting side lobe pattern is entirely different. Hence, splitting this feed into several separate sources provides separated channels which may be modulated by dependent noise sources to introduce side lobe suppression. Such splitting of the feed in the H-plane presents no difficulty but there may be some difficulty in splitting the feed in the E-plane for similar proliferation of feed in the other dimension. Thus, when the designed source in a reflector antenna is of dimensions in the H-plane of the order of one-half a wave length, it requires antenna re-design rather than just feed splitting in order to apply the invention in that plane.

FIGURE 4 of the drawings illustrates a split-feed pattern programmed transmitter antenna array. The actual antenna array is not shown in the figure because it may be of conventional design. The antenna array is fed from the feed lines 30 which connect from amplifiers 31. The signal inputs to the amplifiers 31 are obtained from a transmitter signal oscillator 32 which in turn is connected to a transmitter pulse source 33. Each amplifier 31 is modulated by a gain selector 34. Each gain selector 34 has in the particular example illustrated, five input connections to a pulse unit 35 of which the input is connected to the transmitter pulse unit 33. The pulse unit 35 programs the pulses fed to the gain selectors 34 and in the particular example illustrated the gain selectors 34 are designed to preset on five pulse potentials which will select the gains required, or in the case of phase modulation the phase shifts required. A similar arrangement can be used in connection with a receiving antenna. The waveforms for the output pulses of the pulse unit 35 are compared with the waveform of the transmitted pulse in the graph 36 of FIGURE 4.

What I claim as my invention is:

1. Apparatus for reducing the effective side lobe level of a multi-element directional antenna system used for wanted wave propagated signals external to said apparatus comprising, a plurality of amplifier means for the corresponding electric signals internal of said apparatus, each amplifier means for said internal electric signals connecting to a respective one of said antenna elements, said amplifier connections being phased to provide a directional pattern having a main lobe and side lobes, a source of modulating wave for each said amplifier means, each modulating wave having a unique waveform different from the waveform of the other modulating waves, each modulating wave having frequency components extending over a bandwidth substantially greater than the range of frequencies present in the wanted wave propagated signals, and separate modulating means for the respective amplifier means connected to modulate the electric signals being transferred by the respective amplifier means in accordance with the respective modulating waves.

2. Apparatus as claimed in claim 1 comprising, a local oscillator adapted to multiply the signals internal of the apparatus to provide intermediate frequency signals, the modulating means being operative to modulate each of said intermediate frequencies, means for combining the modulated intermediate frequencies into a single output signal, an intermediate frequency amplifier for amplifying said single output signal, and means for detecting the amplified single output signal.

3. Apparatus for reducing the effective side lobe level of a multi-element directional system used for wanted amplitude-modulated wave-propagated signals external to said apparatus, as claimed in claim 1, in which the modulating means is amplitude modulating means.

4. Apparatus as claimed in claim 3 comprising, a local oscillator connected to mix its output signal with the signals internal of the apparatus to provide intermediate frequency signals, the modulating means operating to modulate each of said intermediate frequencies, means for combining the modulated intermediate frequencies into a single output signal, an intermediate frequency amplifier for amplifying said single output signal, and means for detecting the amplified single output signal.

5. Apparatus for reducing the effective side lobe level of a multi-element directional system used for wanted phase-modulated wave-propagated signals external to said apparatus, as claimed in claim 1, in which the modulating means is phase modulating means.

6. Apparatus as claimed in claim 5 comprising, a local oscillator adapted in conjunction with the signals internal of the apparatus to provide intermediate frequency signals, the modulating means being adapted to modulate each of said intermediate frequencies, means for combining the modulated intermediate frequencies into a single output signal, an intermediate frequency amplifier for amplifying said single output signal, and means for detecting the amplified single output signal.

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