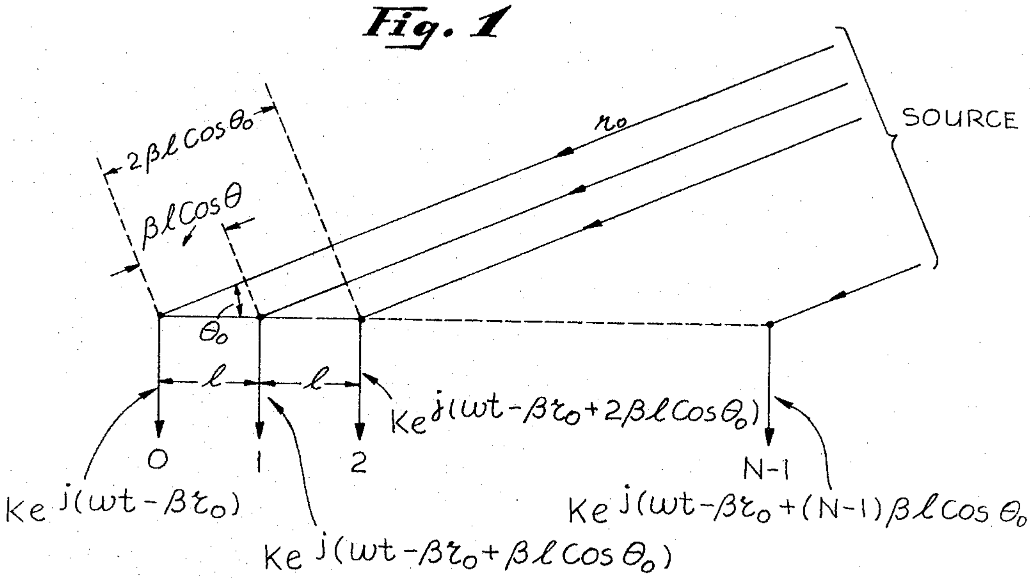
STEERABLE ANTENNA COMMUNICATIONS SYSTEM

Filed July 18, 1961 6 Sheets-Sheet 1

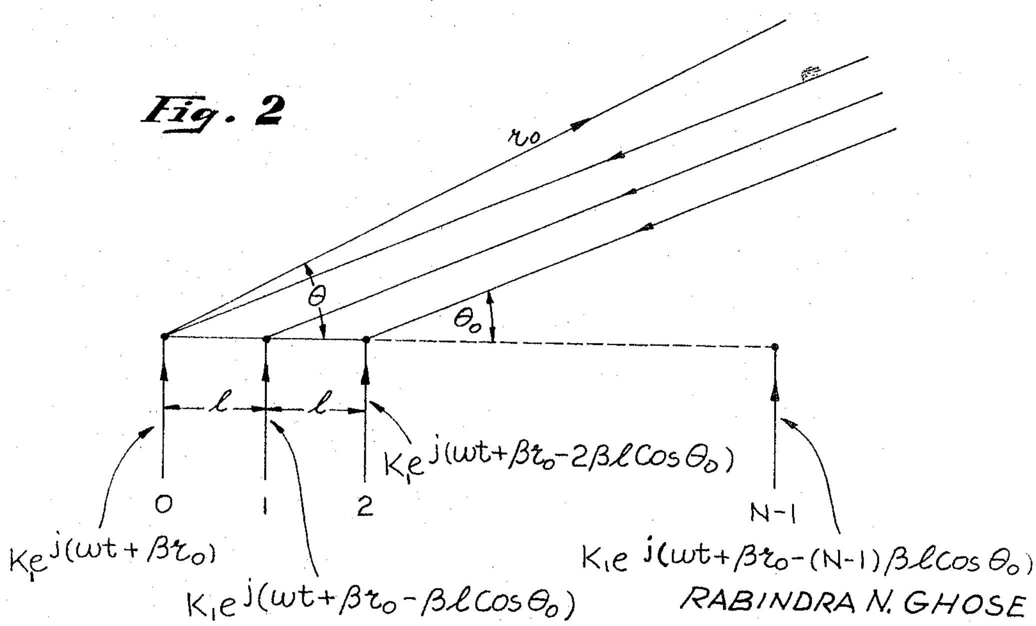
Fig. 1



$\beta = 2\pi/\lambda$

λ = FREE SPACE WAVELENGTH

Fig. 2



$\beta = 2\pi/\lambda$

λ = FREE SPACE WAVELENGTH

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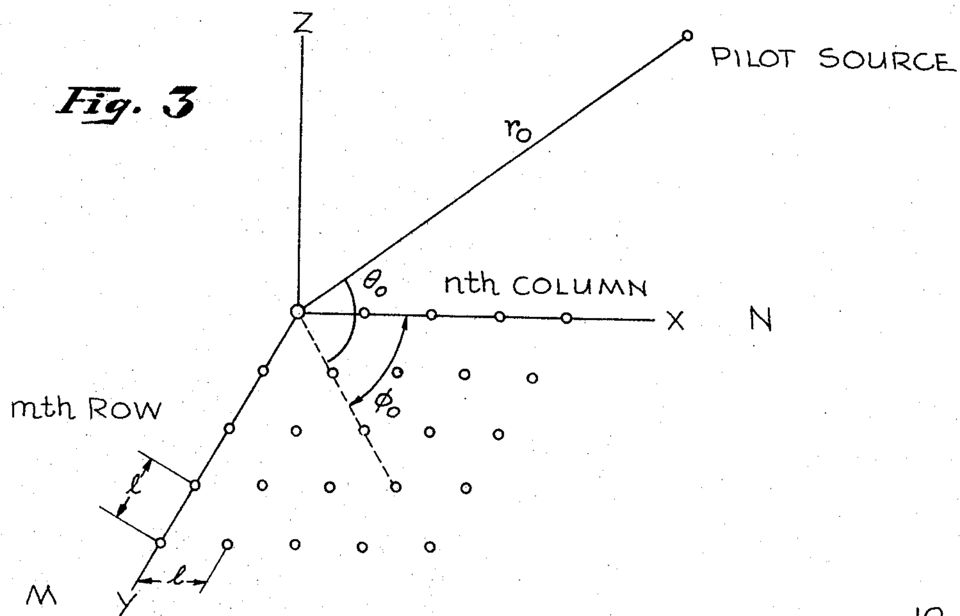
Fig. 3



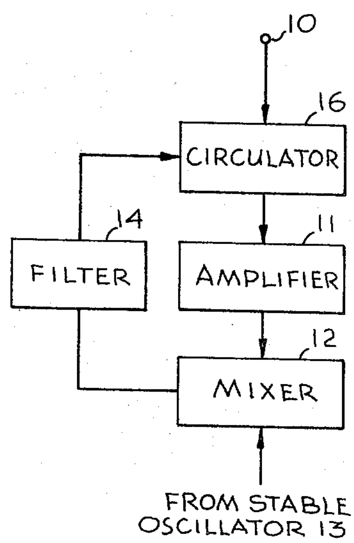


Fig. 4 (a)

Fig 6 (a)

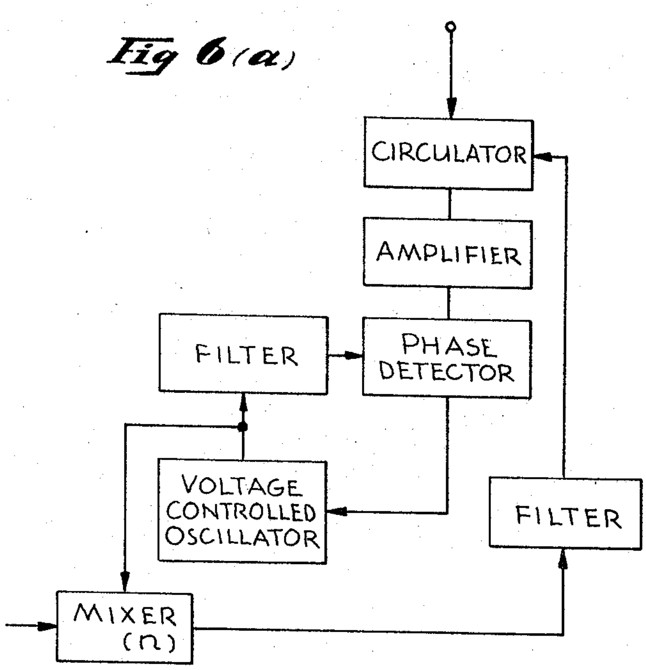


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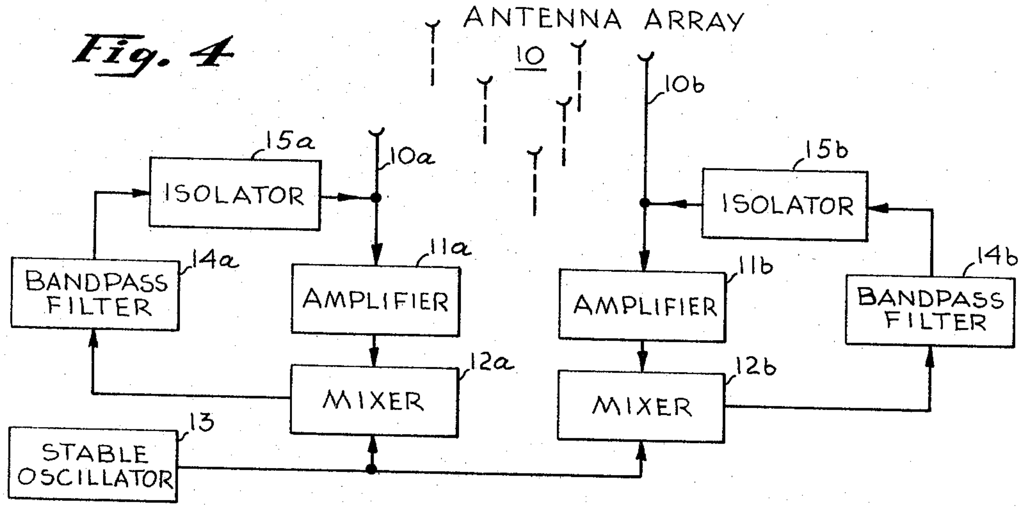
Fig. 4



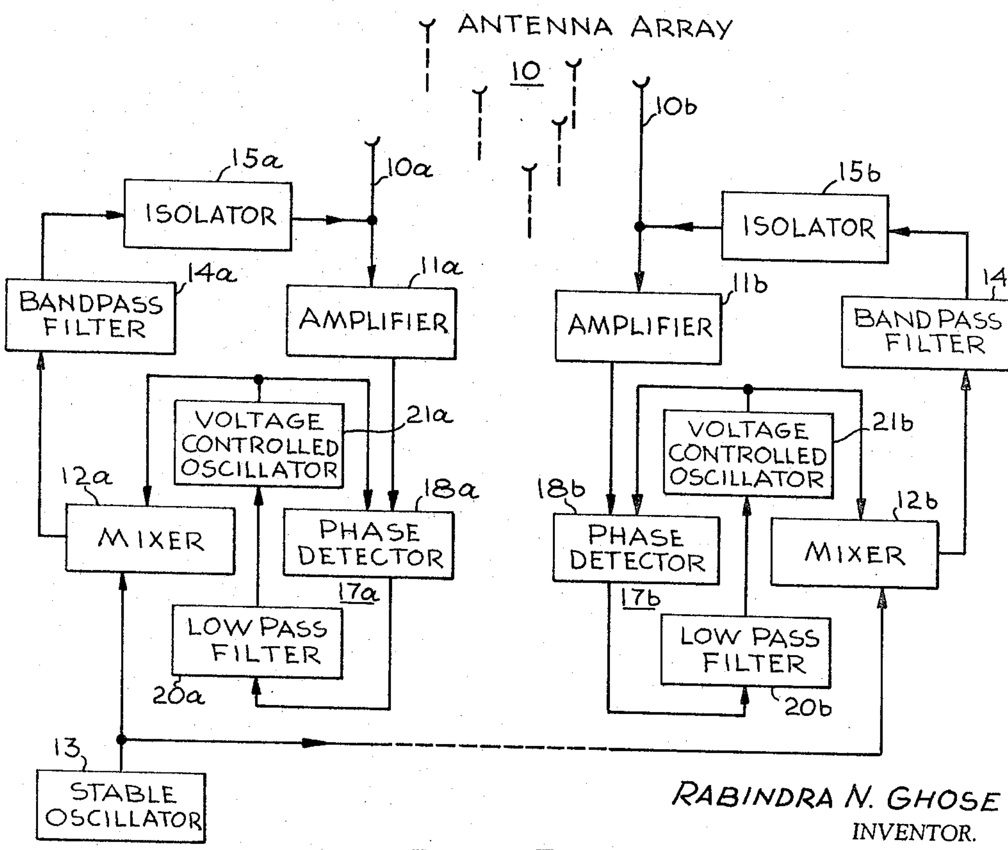


Fig. 5

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STEERABLE ANTENNA COMMUNICATIONS SYSTEM

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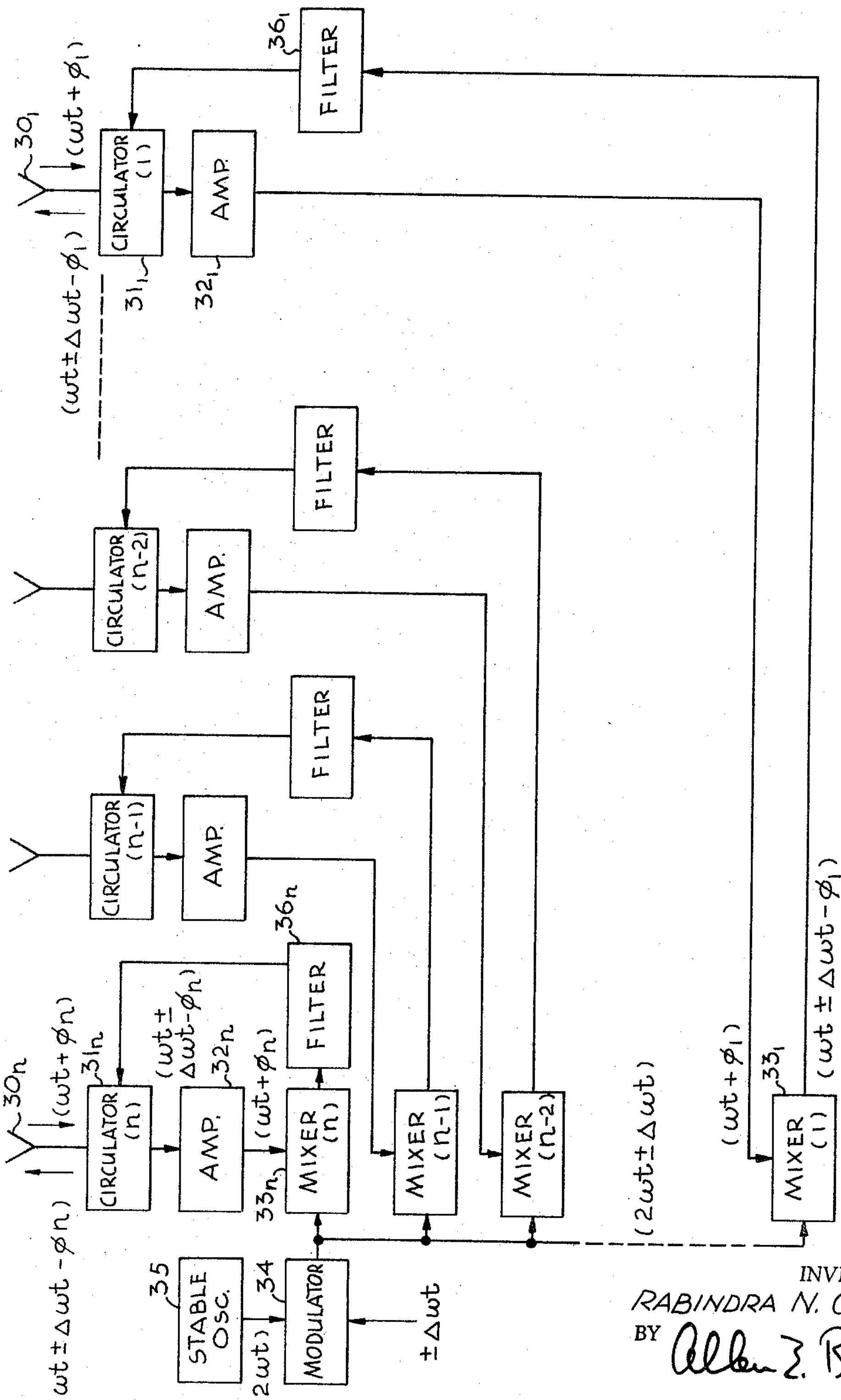

Fig. 6

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STEERABLE ANTENNA COMMUNICATIONS SYSTEM

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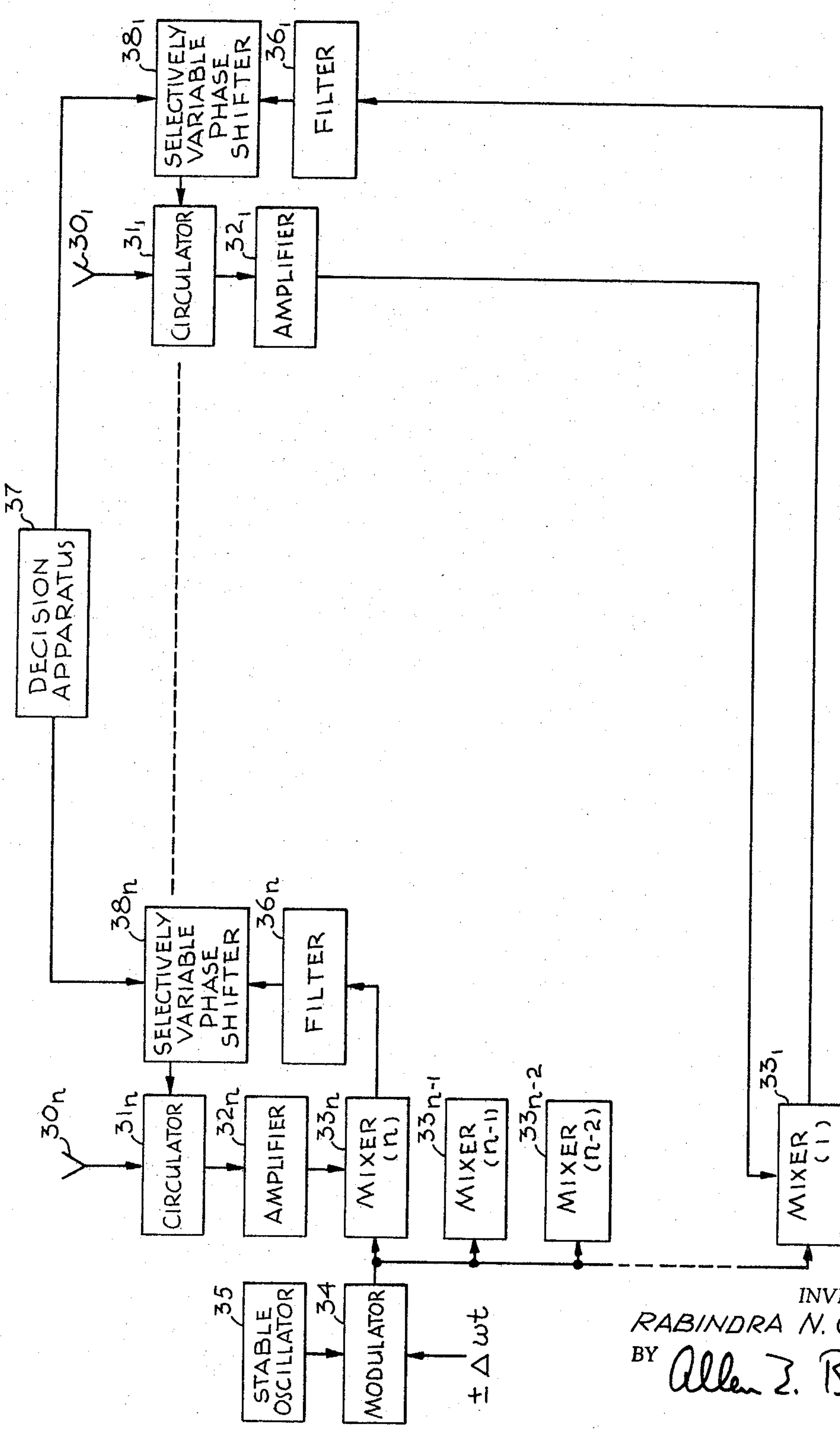

Fig. 7

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STEERABLE ANTENNA COMMUNICATIONS SYSTEM

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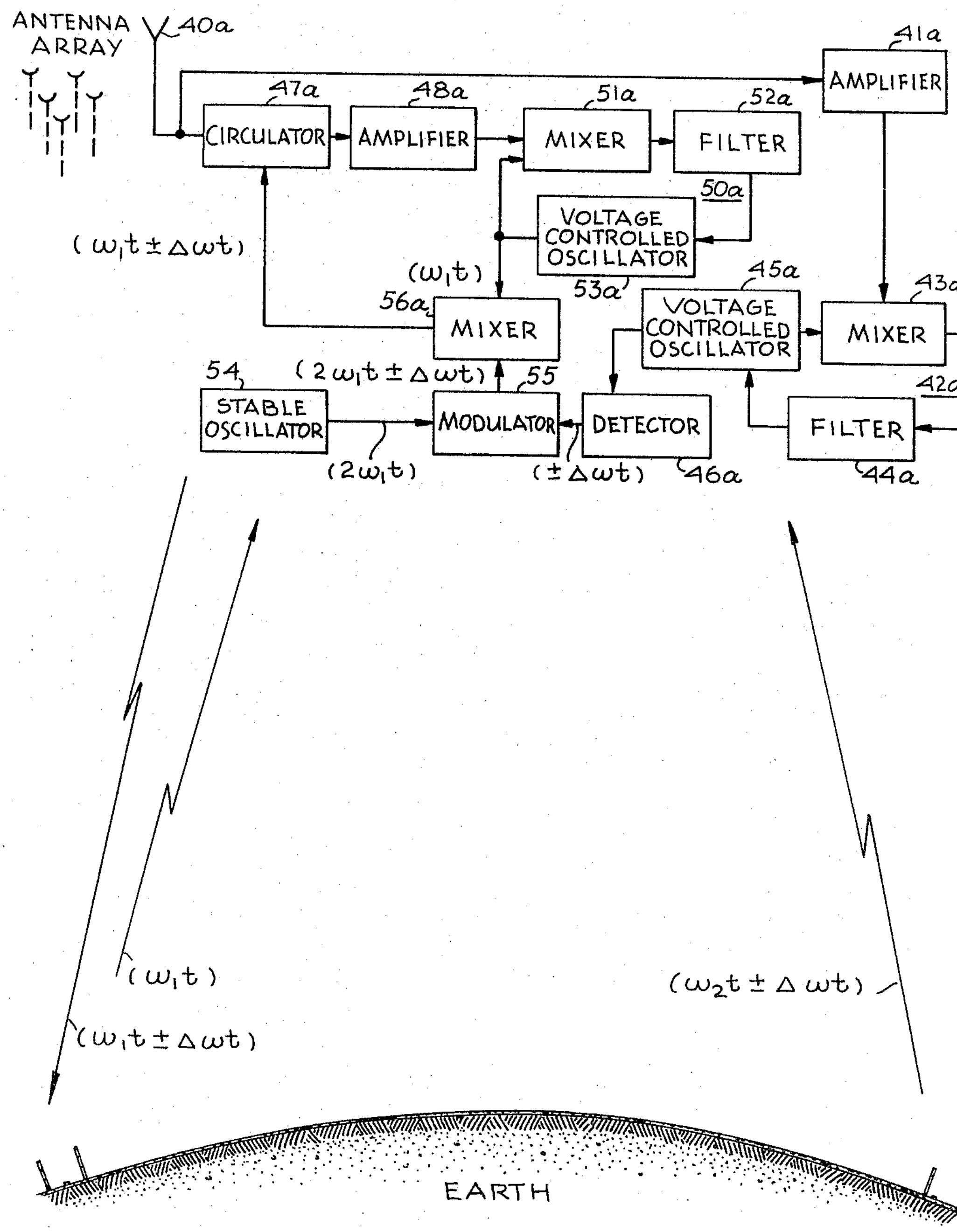

Fig. 8

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STEERABLE ANTENNA COMMUNICATIONS SYSTEM

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Filed July 18, 1961, Ser. No. 124,916
14 Claims. (Cl. 343—100)

The present invention relates in general to the antenna art and more particularly relates to an antenna arrangement that acts like an automatically steerable reflector for an incoming signal from any direction but with the additional capability of amplifying or introducing additional information to the signal before transmitting.

It is axiomatic that point-to-point communication systems can always benefit from transmitting and/or receiving antenna gain. While this is true for ground communication systems, such gain is particularly desirable in satellite and space-vehicle communication systems since relatively large communication distances are involved as well as limited transmitter power at the satellites or space-vehicles. Furthermore, it is ordinarily very difficult to obtain a high antenna-gain for all satellite orientations. More specifically, when a satellite or space-vehicle is not spin-stabilized, or when it tumbles, the field strength at the ground receiving antenna undergoes a wide variation in level. In fact, it can become so vanishingly small that track can be lost. Reliable communications between the ground station and the vehicle is thus seriously jeopardized.

Antenna gain is also desirable in a space-vehicle from the standpoint of power conservation. This is especially true, of course, for deep space probes and/or long-life satellites. Great advantages accrue through increasing the effective radiated power from the satellites in the desired direction while keeping constant the total demand of power demanded from the vehicle's power supply. Demanding larger and larger power supplies in satellites and space probes as a function of their desired longevity has obvious and serious drawbacks in terms of increased payload, weight, size, complexity, etc.

The antenna arrangement of the present invention provides the antenna gain and the power savings spoken of above and is adapted to do so irrespective of the angle of signal arrival. More specifically, when a continuous-wave or coded signal is transmitted with the help of a high-gain antenna from the ground to the satellite or space-vehicle, the antenna arrangement at the satellite "senses" the direction of arrival of this "pilot" signal and orients the satellite transmitter antenna beam to produce maximum radiation in the direction of the ground antenna that is transmitting the pilot signal. This optimum orientation of the beam, it has been discovered, can be achieved by transmitting from the satellite or other vehicle a signal with a phase which is the complex conjugate of the spatial phase of the incident wave. The antenna gain thusly obtained is proportional to the gain of the ground transmitting antenna.

Further benefits may be derived from the present invention in addition to those already mentioned. Thus, by introducing a deliberate and pre-set phase shift so that the signal no longer remains as the complex conjugate of the received signal, the signal transmitted from a space vehicle can be oriented in a given direction that is different from that of the incident signal. Thus, the present invention opens new vistas in the communications art. Moreover, since any antenna arrangement constructed and operated in accordance with the present invention is all-electronic in nature, such an arrangement eliminates the mechanical and other disadvantages associated with present scanning antennas. No requirements for mechanical search-and steering are involved.

It is, therefore, an object of the present invention to provide an antenna system that is able to at all times transmit signals in the same direction as a received signal, and at a higher power level than the received or intercepted power.

It is another object of the present invention to provide an antenna arrangement for automatically and continuously focusing its beam in the direction of a received signal.

It is a further object of the present invention to provide an antenna arrangement for transmitting a signal in any desired direction.

The novel features which are believed to be characteristic of the invention, both as to its organization and method of operation, together with further objects and advantages thereof, will be better understood from the following description considered in connection with the accompanying drawings in which several embodiments of the invention are illustrated by way of example. It is to be expressly understood, however, that the drawings are for the purpose of illustration and description only and are not intended as a definition of the limits of the invention.

FIGS. 1, 2 and 3 are antenna array diagrams useful in explaining the basic principles governing the present invention;

FIGS. 4 and 4*a* are block diagrams of one embodiment of the present invention;

FIG. 5 is a block diagram of a second embodiment of the present invention;

FIGS. 6 and 6*a* are block diagrams of a third embodiment of the present invention;

FIG. 7 is a block diagram of a fourth embodiment of the present invention; and

FIG. 8 is a block diagram of a fifth embodiment of the present invention.

Considering now the drawings, reference is initially made to FIGS. 1 and 2 by means of which the principle of operation basic to the present invention may be illustrated. As shown in the figures, a plurality of N receiving antenna elements are arranged in a linear array, the phase angles between the wavefronts received at the different antennas as well as the signals respectively produced by them in response to the interception of these wavefronts being clearly indicated. Provided identical receiving elements are used in the array, the total radiation pattern of this antenna array will be given approximately by the product of the array-pattern and the individual antenna element pattern. Thus, since there are N elements in the array and each element is separated by a distance "l" from the adjacent one, as shown in the figure, the electric field intensity of the signal received by the array (at a large distance r_0 from the signal source) can be expressed as:

$$Er=\frac{K}{r_0}e^{\frac{j2\pi r_0}{\lambda}}\sum_{n=1}^{N-1}e^{\frac{j2\pi nl\cos\theta_0}{\lambda}} \qquad (1)$$

where

K=some constant depending on the strength of the source
ω=the angular operating frequency of the source
λ=the free space wavelength
θ_0=the elevation angle which the source makes with the line joining the elements constituting the linear array.

A time factor of $e^{j\omega t}$ has been assumed in Equation 1.

Supposing now that by some mechanism the phase angle of the pilot signal at each antenna element is inverted such that if the phase of the received signal at the ith antenna element is $\omega t+\theta_i$, the phase inverter provides a signal with a phase equal to $\omega t-\theta_i$. When this phase-inverted signal is amplified and fed back to the antenna through a transmit-receive switch or circulator, the total signal at a distance r_0 as transmitted from the array can be expressed as:

$$E_t=\frac{K_1}{r_0^2}e^{j\phi_0}\sum_{n=0}^{N-1} e^{\frac{-j2\pi nl}{\lambda}(\cos\theta_0-\cos\theta)} \quad (2)$$

where θ is an arbitrary angle and K_1 is a constant which depends on the power radiated by the transmitting antenna array. From Equation 2, the radiation pattern of the array, when it is transmitting the above signal, can be expressed as:

$$R=\frac{\sin\frac{\pi Nl}{\lambda}[(\cos\theta_0-\cos\theta)]}{\sin\frac{\pi l}{\lambda}\cos\theta_0-\cos\theta} \quad (3)$$

It is thus seen from Equation 3 that when $\theta=\theta_0$, the absolute value of the radiated field becomes maximum, that is, maximum radiation from the antenna array takes place in the direction of the ground transmitting antenna from which the pilot signal is transmitted.

The above explanation was presented in conection with a linear array as illustrated in FIGS. 1 and 2. However, it will be recognized by those skilled in the art that the same explanation is applicable to two or three dimensional arrays. Thus, for example, with respect to a two-dimensional array, when an electromagnetic field is incident on the array from a source at r_0, the electric field intensity received by the array can be expressed as:

$$E_r\simeq\frac{K}{r_0}e^{-j\frac{2\pi r_0}{\lambda}}\sum_{n=0}^{N-1}\sum_{m=0}^{M-1} e^{j\frac{2\pi l}{\lambda}\cos\theta_0(n\cos\phi_0-m\sin\phi_0)} \quad (4)$$

where

K=constant depending on the strength of the source
M and N=number of antenna elements in each column
θ_0=elevation angle
ϕ_0=azimuthal angle

A time factor of $e^{j\omega t}$ has been assumed.

After the signal received by each antenna element is inverted and then transmitted, as previously mentioned, the transmitted field E_t, at a distance r_0 and at elevation and azimuthal angles θ and ϕ, respectively, can be expressed as:

$$E_t=\frac{K_0}{r_0^2}e^{j\phi_0}\sum_{n=0}^{N-1}\sum_{m=0}^{M-1}\exp.\left\{-j\frac{2\pi l}{\lambda}[n\cos\phi_0\cos\theta_0+m\sin\phi_0\cos\theta_0-n\cos\theta\cos\phi-m\sin\phi\cos\theta]\right\} \quad (5)$$

The effective radiation pattern of this two-dimensional antenna array then becomes:

$$R=\left|\frac{\sin\frac{N\pi l}{\lambda}(\cos\theta_0\cos\phi_0-\cos\theta\cos\phi)}{\sin\frac{\pi l}{\lambda}(\cos\theta_0\cos\phi_0-\cos\theta\cos\phi)}\right|\cdot\left|\frac{\sin\frac{M\pi l}{\lambda}(\cos\theta_0\sin\phi_0-\cos\theta\sin\phi)}{\sin\frac{\pi l}{\lambda}(\cos\theta_0\sin\phi_0-\cos\theta\sin\phi)}\right| \quad (6)$$

From Equation 6, it will be evident to those skilled in the art that the maximum radiation from the array takes place when:

$$\theta=\pm\theta_0$$

and

$$\phi=\phi_0$$

Thus, as before, it is seen that the two-dimensional array directs a considerable portion of the transmitted energy in the direction of the ground station from which the pilot signal originated.

Having considered the principles basically underlying the subject invention, reference is now made to FIG. 4 wherein a first embodiment of the present invention is shown. The antenna array therein is generally designated 10 with each antenna in the array being connected to substantially the same circuit arrangement. For this reason, the networks connected to only two of the antennas are shown, namely, the circuits connected to the antennas designated **10***a* and **10***b*. Antenna **10***a* is connected to an amplifier **11***a* which is connected between the antenna and the first input to a mixer circuit **12***a*. A very stable oscillator **13** is connected to the second input to mixer **12***a* whose output end is coupled to a narrow bandpass filter **14***a*. An isolator **15***a* is coupled between filter **14***a* and antenna **10***a*. In a like manner, antenna **10***b* is connected to an amplifier **11***b* which is connected between the antenna and a mixer circuit **12***b*. As before, stable oscillator **13** is connected to the second input to mixer **12***b* whose output is then connected to a filter **14***b*. Finally, an isolator **15***b* is coupled between filter **14***b* and antenna **10***b*.

Considering now the operation of the FIG. 4 embodiment, a signal received either by antenna **10***a* or antenna **10***b*, or by any antenna in the array, is amplified and then mixed with a signal coming from the stable oscillator which operates at substantially twice the frequency as that of the incoming signal. As may be expected, the output of the mixer contains the sum and difference of the phases of the two signals. If now the sum of the phases of the two signals is filtered out and the remaining signal fed back to the antenna through an isolator or circulator, the field radiated from the antenna element will be the complex conjugate of the field received by it. More specifically, if the phase of the signal generated by stable oscillator **13** is $2\omega t$ and the phase of the signal received at antenna **10***a* is ωt plus θ_a, then the phase of the two signals produced by mixer **12***a* are $3\omega t+\theta_a$ and $\omega t-\theta_a$. The signal at the lower of the two frequencies, namely, $\omega t-\theta_a$, is passed through filter **14***a* and isolator **15***a* to antenna **10***a* whereat it is transmitted. It is thus seen that the signal transmitted at antenna **10***a* has a phase which is the complex conjugate of the spatial phase of the signal received by that antenna. In a like manner, the complex conjugate of the spatial phase of the signal received at antenna **10***b* is also transmitted, that is, the signal transmitted is at a phase of $\omega t-\theta_b$. Hence, the phase of the signal transmitted by each antenna in antenna array **10** is the complex conjugate of the spatial phase of the respective signals received by the antenna, with the result that in accordance with the principles previously delineated the maximum value of the radiation pattern for the antenna array is oriented in the direction of the incident electromagnetic wave.

The embodiment of FIG. 4 may be somewhat modified by the substitution of a circulator for isolator **15** in each antenna circuit. The particular manner in which the circulator is connected into the circuit is shown in FIG. 4*a*. As shown, the two inputs to the circulator, which is designated **16**, are respectively coupled to antenna **10** and filter **14**, the output from the circulator being fed to amplifier **11**. The remaining circuitry is interconnected just as it was in FIG. 4 and, therefore, need not be described in detail again. As is well known, the circulator permits signals to be simultaneously passed from antenna **10** to amplifier **11** and from filter **14** to antenna **10** without deleterious effects. Otherwise, the operation is the same as heretofore described.

It may be desirable to introduce a phase-lock loop to receive the continuous-wave pilot signal, especially when the signal-to-noise ratio at the antenna array is expected to be very low. This phase-lock loop simulates a signal having the same phase as that of the incoming signal and, consequently, produces distinct advantages. An antenna circuit that includes a phase-lock arrangement is shown in FIG. 5 to which reference is now made. As shown therein, the phase-lock loop is generally designated **17***a* and includes a phase detector circuit **18***a*, a low pass filter **20***a*, and a voltage-controled oscillator **21***a*, the elements cited being connected in a loop arrangement. More specifically, phase detector **18***a* has two input terminals and produces a variable output voltage whose amplitude and polarity at any time corresponds to the difference in phase between signals applied to its two abovesaid input terminals. Filter **20***a* is coupled between the output end of phase detector **18***a* and the input end of voltage-controlled oscillator **21***a*, the output end of the oscillator being connected, in turn, to the second input terminal to the phase detector. Amplifier **11***a* is connected between antenna **10***a* and the first input terminal to the phase detector. The output from oscillator **21***a* is also fed to one of the two inputs to mixer **12***a*, the other of the mixer circuit inputs receiving the signal generated by stable oscillator **13**. As before, filter **14***a* is connected between mixer **12***a* and isolator **15***a*, the output end of the isolator being coupled to antenna **10***a*.

An identical circuit is shown connected to antenna **10***b*, the elements of this circuit being distinguished by the subscript "*b*." Still others of these same circuits are respectively connected to the other antennas in the array.

In operation, a signal at frequency ω and having a phase angle θ_a is applied to the first input terminal of phase detector **18***a*. Voltage-controlled oscillator **21***a* applies a signal to the second input terminal of the phase detector, the signal thusly applied being generated by the oscillator also at a frequency ω. In response to the two signals applied to it, phase detector **18***a* produces a correcting voltage whose amplitude and polarity corresponds to the relative phase difference between said two signals, as previously mentioned, the correcting voltage thusly produced being smoothed by filter **20***a* and thereafter fed back to voltage-controlled oscillator **21***a*. In response to this correcting voltage, oscillator **21***a* shifts the phase of its signal until the two signals applied to the phase detector are not only at the same frequency but also in phase with each other, at which time the output of the detector is reduced to zero. When this occurs, the signal out of oscillator **21***a* simulates the received signal but is relatively noise-free.

Accordingly, a first signal at a frequency ω and having a phase angle θ_a is applied to the first input to mixer circuit **12***a*. Simultaneously, the signal generated by stable oscillator **13** at frequency 2ω is applied to the second input of mixer **12***a*, with the result, as before, that signals at two different frequencies and phases are produced, namely, a first signal respectively having a frequency and phase of $3\omega-\theta_a$ and a second signal respectively having a frequency and phase of $\omega-\theta_a$. Only the latter signal is permitted to pass through filter **14***a* and isolator **15***a* to antenna **10***a* for transmission so that a relatively noise-free and amplified complex conjugate signal of the received signal is transmitted. At the same time, a relatively noise-free and amplified signal that is the complex conjugate of the signal received by antenna **10***b* is transmitted from that antenna. In general, the signals transmitted from all the antenna elements in the array are respectively the complex conjugates of the signals received by them, with the result that maximum directivity for transmission purposes is achieved in the direction of the incoming signal wavefront.

The embodiments previously described involved transmitting a continuous-wave signal substantially in the same direction as that of an incoming continuous-wave signal. However, it will be recognized that maximum directivity in the direction of a received signal may also be achieved even though the carrier or continuous-wave signal transmitted by the system is modulated by some form of signal information. In other words, although only a pilot or unmodulated continuous-wave signal is received, the received signal may be amplified, then modulated, and retransmitted with maximum directivity. An arrangement for achieving this end is shown in FIG. 6, to which reference is now made.

As shown therein, the antenna array includes "*n*" individual antennas with each antenna being coupled to a circuit loop of the type shown in FIG. 4(*a*), the only exception being that in the FIG. 4(*a*) circuit the second input to the mixer is connected directly to the stable oscillator whereas, in the FIG. 6 arrangement, the second input to the mixer in each antenna circuit is coupled indirectly to the stable oscillator, that is, through a modulator circuit. More specifically, an antenna in the array, designated $\mathbf{30}_n$, is coupled to an input port of a circulator $\mathbf{31}_n$, an output port of the circulator being coupled to an amplifier $\mathbf{32}_n$. A mixer circuit $\mathbf{33}_n$ having two input terminals is respectively connected at these terminals to the amplifier and to a modulation circuit **34**, the modulation circuit itself having two inputs, one such input being connected to a stable oscillator **35** and the other such input being receptive of information signals applied to it for modulation purposes. A bandpass filter $\mathbf{36}_n$ is connected between the output of mixer $\mathbf{33}_n$ and the other input port to circulator $\mathbf{31}_n$, the remaining output port of the circulator being coupled back to antenna $\mathbf{30}_n$. In the same way, each of the other antennas in the array is coupled to an identical circuit, modulator **34** being connected at its output end to the mixer in each of these separate circuits. In other words, modulator **34** and stable oscillator **35** are common to all the antenna circuits included in the system, as shown in the figure.

In operation, a pilot or continuous-wave signal respectively having a frequency and phase of ω and ϕ_n is received at antenna $\mathbf{30}_n$ and, from the antenna, is passed through circulator $\mathbf{31}_n$ to amplifier $\mathbf{32}_n$. After being amplified, the signal at the same frequency and phase is applied to the first input to mixer $\mathbf{33}_n$. Stable oscillator **35**, on the other hand, generates a carrier signal at a frequency of 2ω and this signal is applied to modulator **34** to which signals representing intelligence are also applied, the information signals being designated figuratively by means of the symbols $\pm\Delta\omega t$. The carrier signal out of stable oscillator **35** is modulated by the information signals, with the result that the signals applied to the second input to mixer $\mathbf{33}_n$ may figuratively be said to be $2\omega t\pm\Delta\omega t$. The signals applied to both inputs to the mixer are heterodyned one against the other, the output signals thereby produced being filtered by filter $\mathbf{36}_n$, the bandpass characteristics of the filter being such that signals $\omega t\pm\Delta\omega t-\phi_n$ are applied to circulator $\mathbf{31}_n$. This signal is then passed through the circulator to antenna $\mathbf{30}_n$ whereat it is radiated into space.

In view of the fact that the frequencies of the modulating signals are very much smaller than the frequency of the carrier, it will be recognized by those skilled in the art that the principles previously delineated hold true here notwithstanding the fact that modulation has been superimposed upon the carrier. Consequently, the signal radiated into space at antenna $\mathbf{30}_n$ is basically the complex conjugate of the originally received signal, with the result that here also the beam is directed primarily in the direction of the pilot signal source. For the same reasons, each of the other antennas in the array radiates a signal that is substantially the complex conjugate of the signals respectively received at these antennas. Hence, by means of the embodiment described in connection with FIG. 6, a maximum possible signal can at all times be transmitted from one station to another station or, stated differently, the system of the present invention makes it possible for an antenna array to at all times focus its beam toward a particular point and with maximum possible strength irrespective of the relative positions or orientations of the two stations.

It was previously explained in connection with FIG. 4 (see FIG. 4(*a*)) that a phase-locked loop may be inserted to good advantage in each antenna circuit. The same is true with respect to the embodiment of FIG. 6 and a phase-locked loop is shown included in one of the antenna circuits for this embodiment in FIG. 6(*a*).

In view of the fact that the details of a phase-locked loop as well as the benefits to be derived therefrom have been previously explained and in view of the further fact that the phase-locked loop in FIG. 6(*a*) is identical to that shown in FIG. 4(*a*), a detailed description of the constructional and operational features of such a loop circuit is deemed unnecessary at this point in order to avoid redundancy. Suffice it to say, therefore, that a phase-locked loop may be used in the system of FIG. 6 in the same manner as in the system of FIG. 4.

The embodiments of FIG. 6 and 6(*a*) may be adapted in such a manner that, as and when desired, the transmitted signal can be propagated in a direction that is different from the direction of the received signal. This can be accomplished by introducing a deliberate and preset phase shift in each antenna circuit so that the reflected signal is no longer the complex conjugate of the received signal. The manner in which the referred-to embodiments may be modified for this purpose is shown in FIG. 7 wherein elements similar to or identical with those of FIGS. 6 and 6(*a*) are similarly or identically designated.

As shown in FIG. 7, the adaptation involves adding certain decision apparatus **37** and a plurality of phase-shifter networks 38_1–38_n that are selectively variable, one such phase shifter network for each antenna circuit. Decision apparatus **37** is of the type that acts in response to a predetermined signal, coded or otherwise, to set the various phase shifter networks at desired settings so that each network will produce a predetermined phase shift in the signal applied to it by the associated antenna circuit. More particularly, networks 38_1–38_n are preferably mechanically linked to each other so that the settings for the different phase shifters may be effectively programmed and, furthermore, so that all phase-shifter settings may be attained simultaneously. Moreover, it will be recognized by those skilled in the art that in order to provide optimum directivity in any one of a number of available directions, the phase shifts introduced by phase-shifter networks 38_1–38_n must bear the same relationship to each other as the phase differences resulting from the spacings between the antenna elements in the array. Hence, by means of these different combinations of phase shifts, optimum directivity may be obtained in correspondingly different directions rather than as heretofore only in the direction of the received signal. By this means, information received from one station may be retransmitted with maximum gain to another station in a different direction. Thus, by way of example, a message transmitted from a station at point "A" on the Earth's surface to a satellite overhead can, by means of the FIG. 7 system, be immediately retransmitted to some distant station at a point "B" on the Earth's surface without waiting until the satellite is over the second station and this can be done with maximum gain.

The natural evolution of the system shown in FIG. 7 is the arrangement shown in FIG. 8 by means of which two-way communications is made possible. Again using stations A and B as an example, the embodiment of FIG. 8 permits a message to be sent from station A to station B via some intermediate station, such as a satellite, and also permits a message to be transmitted from station B to station A. Moreover, as will become clearer below, each of the messages may at all times be received and retransmitted with maximum gain. Accordingly, reference is now specifically made to FIG. 8 wherein the circuit connected to one of the antenna elements in the antenna array is shown, the other antenna elements in the array having identical circuits connected to them, a fact that has already been mentioned.

As shown in the figure, the antenna element to which the circuit is connected is designated **40***a*, the circuit itself including an amplifier **41***a* connected between the antenna and a phase-locked loop generally designated **42***a*. Circuit **42***a* is of the type previously described and includes a mixer circuit **43***a*, a bandpass filter **44***a* and a voltage-controlled oscillator **45***a*. Amplifier **41***a* is connected to the first input to mixer **43***a* while oscillator **45***a* is connected to the second input to the mixer, the oscillator also being connected at its output end to a detector **46***a*. Bandpass filter **44***a*, on the other hand, is connected between the mixer output and the input end of the oscillator. The circuit additionally includes a circulator **47***a* which is connected between antenna **40***a* and another amplifier **48***a*, the amplifier, in turn, being coupled to another phase-locked loop generally designated **50***a*. As before, circuit **50***a* includes a mixer **51***a*, a filter **52***a* and a voltage-controlled oscillator **53***a*, these circuit elements being interconnected as heretofore described in connection with phase-locked loop **42***a*. Detector **46***a* and a stable oscillator **54** feed into a modulator **55** whose output, as well as the output from voltage-controlled oscillator **53***a*, is fed into still another mixer circuit **56***a*. Finally, the output of mixer **56***a** is coupled through circulator **47***a* to antenna element **40***a*. With respect to stable oscillator **54** and modulator **55**, it should be mentioned that they are common to all the antenna circuits, that is to say, the output from detector **46** in each antenna circuit in the entire system array is fed to modulator **55**, the output from the modulator likewise being fed to mixer **56** in each and every circuit.

In its operation, a modulated carrier is transmitted from one point on the Earth's surface to a satellite or other vehicle in which the system of FIG. 8 is mounted. Upon receipt, the signal is demodulated, the modulation thereafter being applied to another carrier transmitted to a second point on the Earth's surface. The two carriers are at widely different frequencies and, hence, each may be received or transmitted with maximum directivity. More specifically, if a modulated carrier at frequency ω_2 is received by the antenna array in the FIG. 8 embodiment, the signal thusly received is amplified by amplifier **41***a* and then applied by the amplifier to mixer **43***a* in phase-locked loop **42***a*. In accordance with the principles of operation of phase-locked loops which are now well known in the art and which were described in some detail above, the output obtained from voltage-controlled oscillator **45***a* and applied to detector **46***a* is the received modulated carrier, but relatively noise-free. The signal is demodulated in detector **46***a* and the modulation or message information applied to modulator **55** to which the carrier generated by stable oscillator **54** at frequency $2\omega_1$ is also applied. As a result, the signal out of modulator **55** and applied to one of the inputs to mixer **56***a* is a carrier at frequency $2\omega_1$ that is modulated by the original modulation or signal intelligence.

At the same time that this is going on, an unmodulated carrier at frequency ω_1 is transmitted from a second point on the Earth's surface to the system, this latter carrier being passed from antenna **40***a* through circulator **47***a* to amplifier **48***a*. After amplification, the unmodulated carrier at frequency ω_1 is applied to mixer **51***a* of phase-locked loop **50***a*, the result being that a relatively noise-free carrier signal at frequency ω_1 is applied to the other input to mixer **56***a*. In other words, an unmodulated carrier at frequency ω_1 is applied to one input to mixer **56***a* and a modulated carrier at frequency $2\omega_1$ is applied to the other mixer input, the output thereby obtained being a modulated carrier at frequency ω_1. This final modulated carrier is passed through circulator **47***a* to antenna **40***a* whereat, in accordance with the principles of the present invention previously delineated, it is radiated with maximum gain and directivity toward the second point on the Earth's surface.

Hence, by employing two signals at different frequencies, a system of communications may be established between two distant points on the surface of the Earth, the system at all times operating with maximum gain and directivity. It will be recognized that by using standard multiplexing techniques, more than one message may be communicated at one time in this way.

It should also be mentioned here that any one of a number of different kinds of antennas may be utilized to form an array. Thus, an array may be formed using half-wave dipoles where the circumstances permit. Again, aperture and slotted antenna arrays may be used.

Having thus described the invention, what is claimed as new is:

1. Communications apparatus for automatically retransmitting a carrier signal in the direction from which it is received, said apparatus comprising: an antenna array for intercepting the received signal, the antennas in said array respectively producing output signals that are phased according to the spacings between the antennas and the angle of arrival of the incident wave; networks respectively coupled to the antennas in said array for circulating the output signals therefrom back to their respective antennas for retransmission, said networks respectively including circuits for converting the initial phases of said output signals to their complex conjugates.

2. Communications apparatus for automatically retransmitting a carrier signal in the direction from which it is received, said apparatus comprising: an antenna array for intercepting the received signal, each antenna in said array producing an output signal whose phase due to the spacing of the antennas and the location of the carrier signal source is $-\beta r+\beta l \cos \theta$, where β is $2\pi/\lambda$, λ being the wavelength of the received carrier signal, r is the distance from the carrier signal source to the antenna, l is the spacing between antennas in the array, and θ is the elevation angle which the signal source makes with the line joining the antenna elements constituting the array; and a network coupled to each antenna in said array for converting the phase of the associated output signal to $\beta r-\beta l \cos \theta$, each network being arranged to feed the associated converted output signal to its associated antenna for retransmission.

3. Communications apparatus comprising: an antenna array for intercepting an incoming signal having a first frequency, the antennas in said array respectively producing first signals at said first frequency that are phased according to the spacings between the antennas and the angles of arrival of said incoming signal relative thereto; a stable oscillator for generating a stable second signal at a second frequency; and feedback circuits respectively coupled between said antennas and said stable oscillator, each feedback circuit being operable in response to the first and second signals applied to it to produce a third signal at said first frequency and at a phase that is the complex conjugate of the spatial phase of the associated first signal, said feedback circuits respectively being adapted to feed said third signals to said antennas.

4. The communications apparatus defined in claim 3, said apparatus further including phase-locked circuits respectively coupled between said antennas and said feedback circuits, each phase-locked circuit being operable to reproduce the associated first signal substantially noise-free and to apply said reproduced first signal to the associated feedback circuit.

5. Communications apparatus for automatically transmitting a modulated carrier signal in substantially the same direction from which a similar unmodulated carrier signal is received, said apparatus comprising: a number of antennas for intercepting the received unmodulated carrier signal to respectively produce a corresponding number of unmodulated first carrier signals that are phased according to the spacings between antennas and the angles of arrival of the received unmodulated carrier signal relative thereto; means for producing a modulated second carrier signal; and feedback circuits respectively coupled between said antennas and said means, each feedback circuit being operable in response to the unmodulated first carrier signal and the modulated second carrier signal applied to it to produce a modulated first carrier signal and including means for making the phase of said modulated first carrier signal the complex conjugate of the spatial phase of the associated unmodulated first carrier signal, said feedback circuits respectively being adapted to feed said modulated first carrier signals to said antennas, whereby a modulated carrier signal is transmitted in substantially the same direction as the received unmodulated carrier signal.

6. The communications apparatus defined in claim 5 wherein each of said feedback circuits includes a mixer circuit for heterodyning the unmodulated first and modulated second carrier signals applied to it to produce the associated modulated first carrier signal; and means coupled between said mixer circuit and the associated antenna for simultaneously passing the unmodulated first carrier signal from the antenna to said mixer circuit and the modulated first carrier signal from said mixer circuit to the antenna free from interference one with the other.

7. The communications apparatus defined in claim 6 wherein each of said feedback circuits further includes a phase-locked circuit coupled between said means and said mixer circuit for reproducing the associated modulated first carrier signal substantially noise-free and to apply said reproduced first carrier signal to said mixer circuit.

8. Communications apparatus for selectively transmitting a modulated carrier signal in the same direction from which a similar unmodulated carrier signal is received or in any one of a number of other predetermined directions, said apparatus comprising: a number of antennas for intercepting the received unmodulated carrier signal to respectively produce a corresponding number of unmodulated first carrier signals that are phased according to the spacings between antennas and the angles of arrival of the received unmodulated carrier signal relative thereto; means for producing a modulated second carrier signal; feedback circuits respectively coupled between said antennas and said modulated second carrier signal producing means, each feedback circuit being operable in response to the unmodulated first carrier signal and the modulated second carrier signal applied thereto to produce a modulated carrier signal and including means for making the phase of said modulated first carrier signal the complex conjugate of the spatial phase of the associated unmodulated first carrier signal, said feedback circuits respectively being adapted to feed said modulated first carrier signals to said antennas, whereby a modulated carrier signal is transmitted; and means coupled to said feedback circuits for selectively applying additional phase shifts to the modulated first carrier signals respectively associated therewith, said means including apparatus for making said additional phase shifts bear the same relationship to each other as the phase shifts introduced in the unmodulated first carrier signals by the spacings between the antennas and the angles of arrival of the received unmodulated carrier signal.

9. The communications apparatus defined in claim 8 wherein said means includes a phase shifter mechanism in each of said feedback circuits capable of phase shfiting the associated modulated first carrier signal by different amounts; and apparatus coupled to said phase shifter mechanisms for simultaneously adjusting them to produce the additional phase shifts of said modulated first carrier signals.

10. Communications apparatus for selectively retransmitting a carrier signal in the direction from which it is received or in any one of a number of other predetermined directions, said apparatus comprising: an antenna array for intercepting the received signal, the antennas in said array respectively producing output signals that are phased according to the spacings between the antennas and the angle of arrival of the incident wave; networks respectively coupled to the antennas in said array for circulating the output signals therefrom back to the antennas for retransmission, said networks respectively including circuits for converting the initial phases of said output signals to their

complex conjugates and respectively including mechanisms capable of additionally phase shifting said output signals by selected amounts; and means coupled to said phase-shifting mechanisms for simultaneously adjusting them to produce the additional phase shifts respectively selected for said output signals.

11. A system for transferring information between two distant stations, the transmission to the second station automatically being accomplished with optimum directivity, said system comprising: a number of antennas for intercepting a modulated first carrier signal received from the first station and an unmodulated second carrier signal received from the second station, said antennas, in response to the latter signal, respectively producing a corresponding number of unmodulated second carrier signals that are phased according to the spacings between said antennas and the angles of arrival of the received unmodulated second carrier signal relative thereto; a number of networks arranged to respectively feed said second carrier signals back to said antennas, said networks respectively including circuits for changing the phases of said second carrier signals to the complex conjugates of said spatial phases; and a number of additional circuits respectively coupled between said antennas and said networks for transferring to said second carrier signals the modulation contained in said first carrier signals.

12. The system defined in claim **11** wherein each of said networks includes means for isolating the output of the associated antenna from its input, a phase-locked circuit coupled to the output end of said means for reproducing substantially free of noise the second carrier signal intercepted by the associated antenna; an oscillator for generating a third carrier signal; a modulator circuit coupled between said oscillator and the associated additional circuit for reproducing said third carrier signal modulated with the modulation transferred from the associated first carrier signal; and a mixer circuit coupled between said modulator circuit and said phase-locked circuit and to said means, said mixer circuit being operable in response to said reproduced second and third carrier signals to apply said first carrier signal to said means modulated in the same manner as said first carrier signal.

13. An antenna system comprising a plurality of independent networks and a single local source of signals to be used in common by all of said networks, said networks each comprising an antenna element, means for abstracting electromagnetic signals impinging upon said antenna element, means for beating at least a portion of said abstracted signals with the output from said local source, the frequency of operation of said source being higher than the frequency of said abstracted signals, means for separating the difference frequency modulation sideband produced by said beating means, means for processing said difference frequency sideband for transmission, and means for applying said processed signal to said antenna element for transmission.

14. An antenna system as defined in claim **13** in which the frequency of the output from said local source is equal to approximately twice the frequency of said abstracted signals.

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