March 16, 1965 P. J. SFERRAZZA ETAL 3,174,150

SELF-FOCUSING ANTENNA SYSTEM

Filed June 29, 1962 5 Sheets-Sheet 1

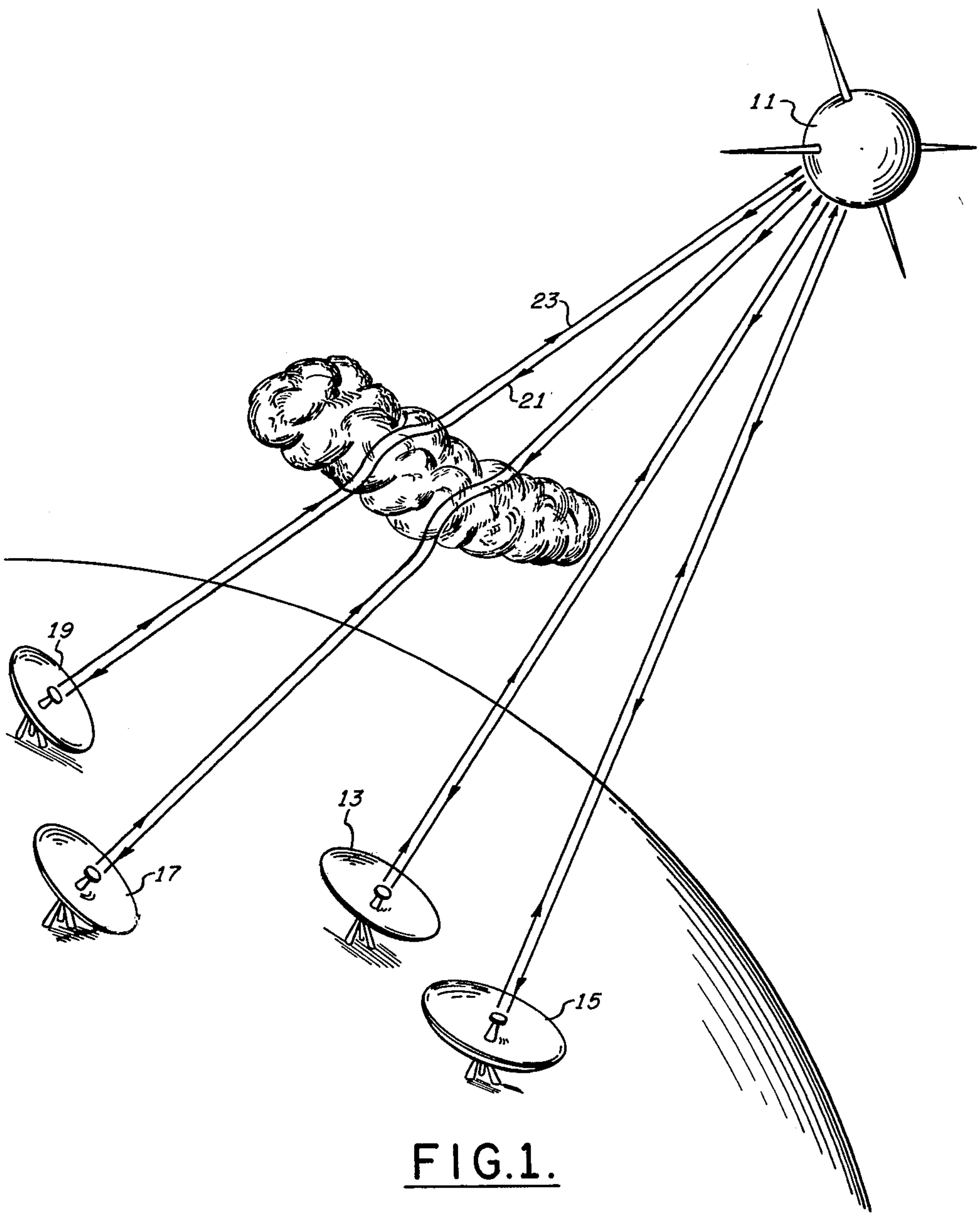

FIG.1.

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SELF-FOCUSING ANTENNA SYSTEM

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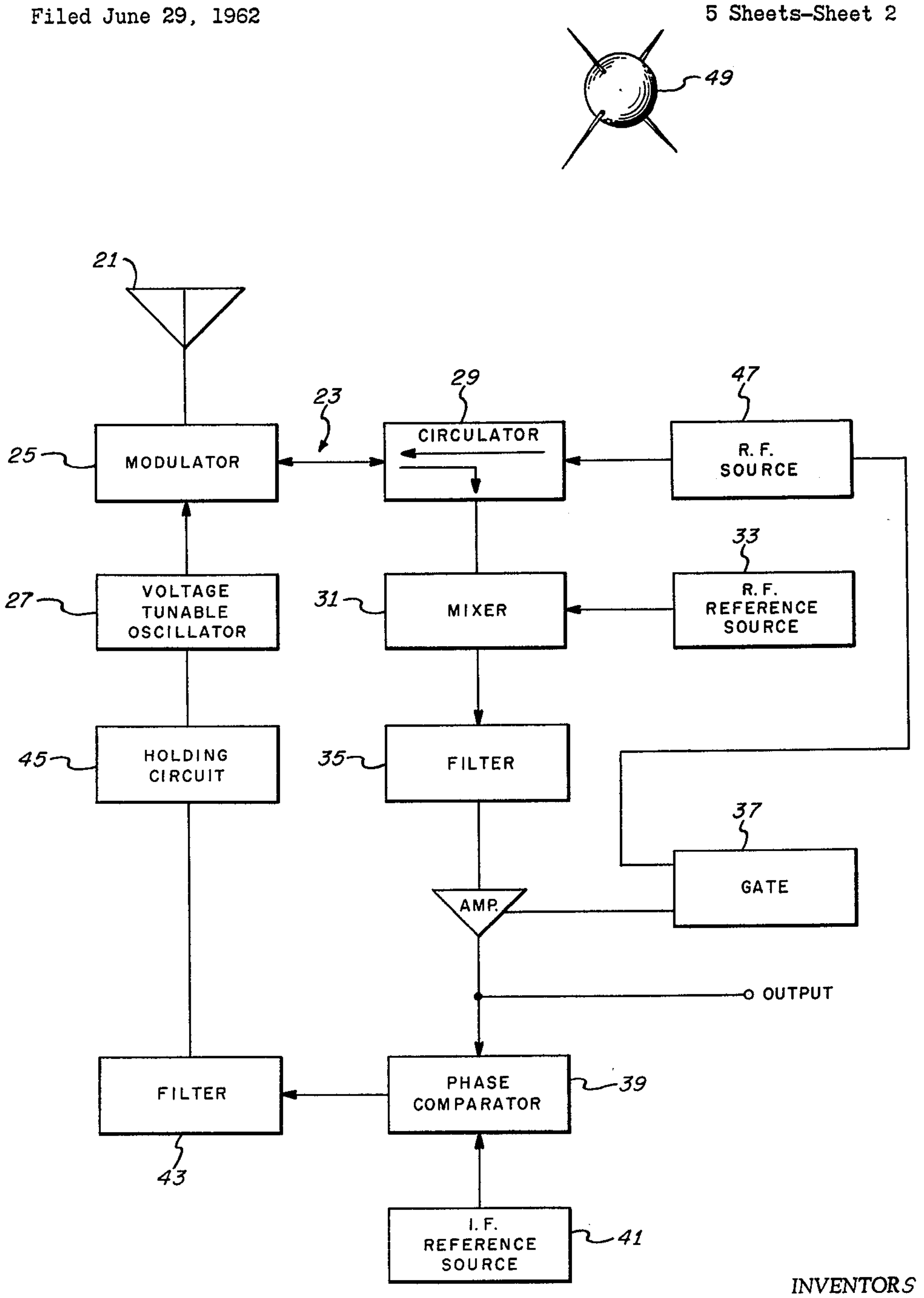

FIG. 2.

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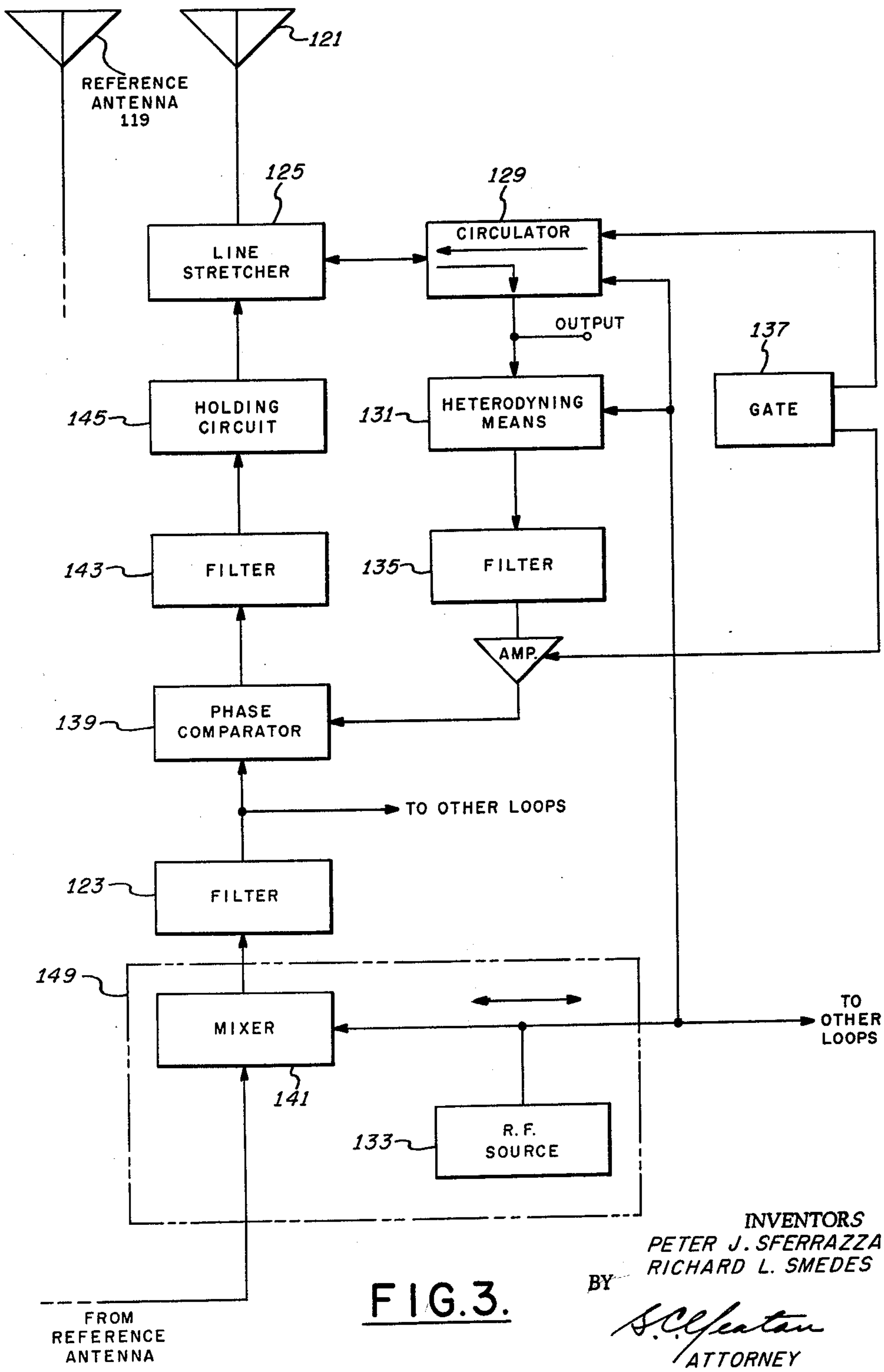

FIG. 3.

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SELF-FOCUSING ANTENNA SYSTEM

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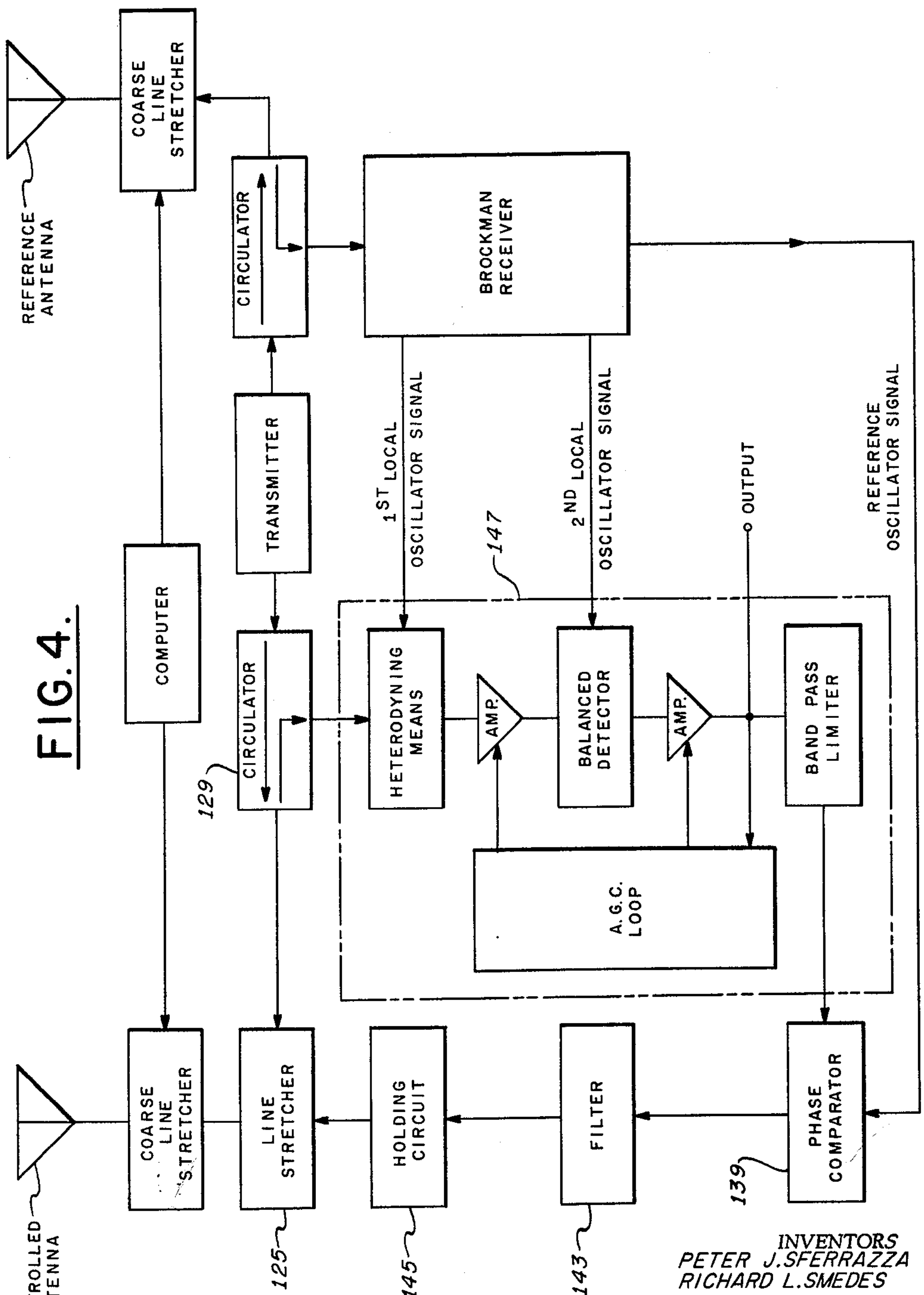
FIG. 4.



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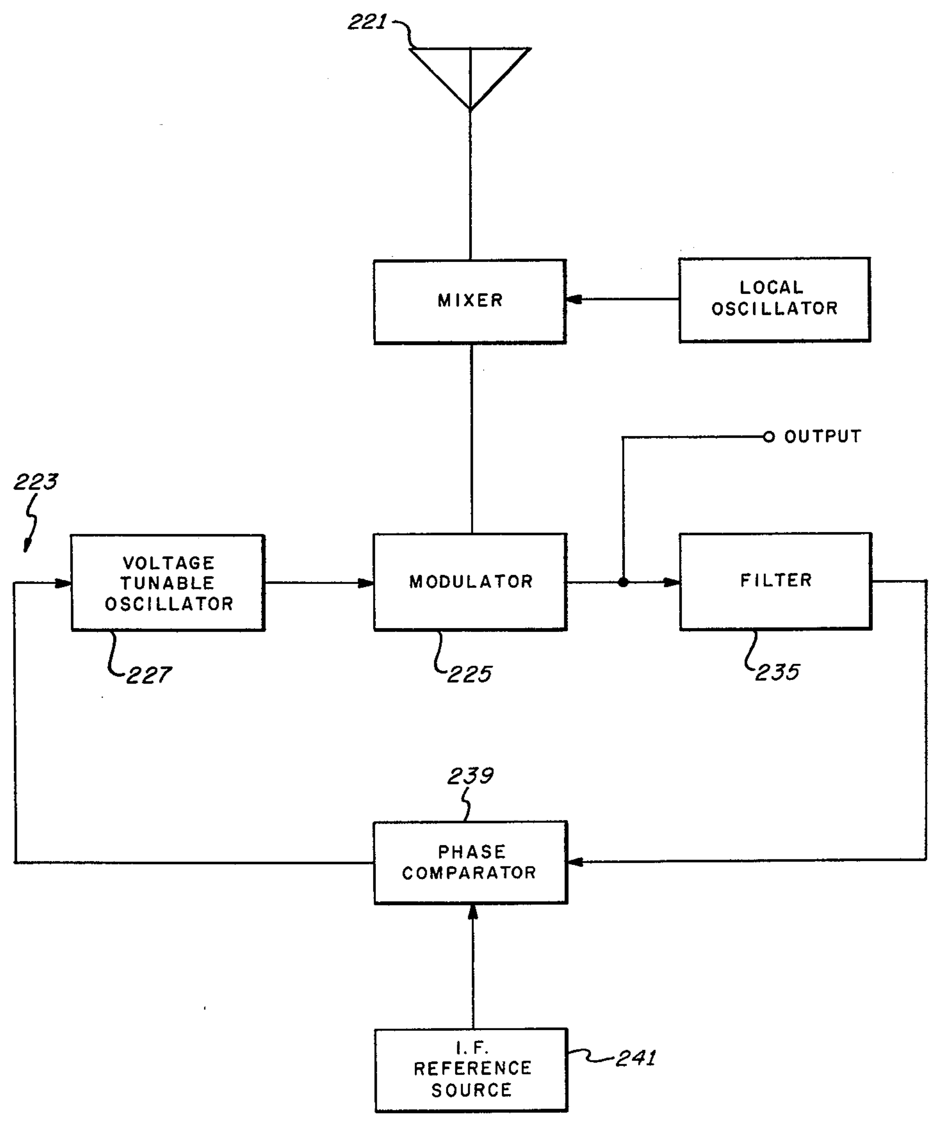

FIG. 5.

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3,174,150
SELF-FOCUSING ANTENNA SYSTEM

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Filed June 29, 1962, Ser. No. 206,225
11 Claims. (Cl. 343—100)

This invention concerns an improved antenna system, and more specifically concerns a self-focusing antenna system.

High gain antennas usually depend upon large parabolic reflectors to concentrate the electromagnetic energy into a collimated beam. The amount of gain that can be achieved by increasing the diameter of the reflector is limited, however, since extremely large reflectors require mechanical tolerances that are impractical to attain at a reasonable cost. Even though it might be possible to achieve a very high gain antenna by precise control of the surface contour, atmospheric disturbances across the surface of such a large reflector would be sufficient to introduce variable phase decorrelations. Since both of these limitations result in phase errors, automatic phase control techniques can eliminate them.

Systems have been devised for steering a beam of electromagnetic energy radiated from an antenna array, in which the various antenna elements are phased by means of computers so as to provide a coherent signal in a given direction. Although these prior art systems are intended to provide high gain by summing the contributions of many individual antenna elements, the open loop control of the phase of the received or radiated electromagnetic energy leads to the same problem encountered with large parabolic reflectors. Although the computers adjust the phase of the individual antenna elements for the theoretical optimum performance in a given direction, atmospheric disturbances and the like can cause the theoretical adjustments to be in error.

Prior art phased array systems are also inadequate when the target is moving so that the received signal includes a Doppler component. The frequency as well as the phase of the signal at each element of the array must be corrected under these conditions. Since a continual phase change is equivalent to a frequency change, the necessary frequency correction can be made by phase adjustment alone. This, however, requires such rapid phase adjustments that the computer methods become impractical.

Furthermore, the prior art systems are not applicable in communications systems wherein it is desirable to transmit and receive simultaneously. Such simultaneous transmission and reception requires the use of separate frequencies. Since prior art systems correct for phase only, a steering error will occur in that the angle of radiation from phased arrays is a function of frequency as well as phase. This steering error also precludes the use of such prior art devices in communications systems since such systems require a considerable bandwidth. If the array is adjusted to receive the carrier frequency properly, it will not be adjusted for optimum reception of the sideband frequencies.

The present invention overcomes the difficulties experienced in prior art devices by compensating for frequency as well as phase variations on a closed loop basis.

It is therefore an object of the present invention to provide an antenna array system capable of focusing on rapidly moving targets.

Another object of the present invention is to provide an extremely high gain receiving or transmitting antenna at a reasonable cost.

A further object of the present invention is to provide

a self-focusing antenna system capable of focusing on targets in the near-field as well as in the far field.

Still another object of the present invention is to provide a self-focusing antenna array system capable of receiving and transmitting on different frequencies without steering error.

Yet another object of the present invention is to provide a broadband antenna array system that is capable of locking on a narrow band carrier signal yet receiving all sidebands coherently.

The individual features which are believed to be characteristic of this invention, together with further objects, 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.

FIG. 1 is a perspective view illustrating a typical environment in which the invention is to be used,

FIG. 2 is a schematic block diagram of one form of the invention,

FIG. 3 is a schematic block diagram of another form of the invention,

FIG. 4 is a schematic block diagram of a form of the invention for use under severe operating conditions, and

FIG. 5 is a schematic block diagram of still another form of the invention to be used for reception only.

Referring now to the drawings, FIG. 1 illustrates a situation in which a stationary target **11** contains a radio frequency signal source. Rays of electromagnetic energy originating at this source traverse different paths in reaching the individual antenna array elements. The rays reach antenna elements **13** and **15** by a reasonably direct route, however those reaching elements **17** and **19** must pass through a region of atmospheric disturbance. The phase of the signals intercepted by an individual antenna element thus depends upon the physical path length and the propagation anomalies encountered by the ray in reaching that antenna element.

The phase delay in these paths is reciprocal so that a signal traversing a path **21** in the receive direction will experience the same phase shift as a signal traversing the corresponding path **23** in the transmit direction.

If, now, the phase delay of the signals received at each element is determined with respect to a common reference, the succeeding wave may be re-transmitted with an initial phase displacement that is the complex conjugate of the phase of the received wave. The phase delay experienced by the re-transmitted waves will just counteract the initial phase displacement given each wave and the energy from the various antenna elements will reach the target coherently.

If target **11** were moving, the received signals would contain a Doppler shift in frequency that might be different at each antenna element. This situation requires complete synchronization: the frequency as well as the phase of the re-transmitted wave must be corrected in each antenna element and its associated circuits in order to provide signal coherence at the target.

FIG. 2 depicts, in schematic form, one type of phase locked loop embodying the principles of the present invention. This circuit can correct for Doppler frequency shifts as well as phase shifts.

An antenna element **21** is coupled to a phase locked loop **23** through a reciprocal single sideband suppressed carrier modulator **25**. Any suitable modulator of this type may be used for this purpose, such as the frequency converter described by P. J. Sferrazza, one of the present applicants, in U.S. Patent 2,745,060. Such modulators are capable of producing an output voltage equivalent to the frequency and phase difference between the received signal and the oscillator signal.

A voltage tunable oscillator **27** supplies a modulating signal to the modulator 25. The difference signal from the modulator 25 is fed through a circulator 29 to a mixer 31 where it is subtracted from the output of the radio frequency reference voltage source 33. The reference source 33 generates voltages at a frequency equal to that which finally reaches the target, as will be demonstrated later. A low pass filter 35 is coupled to the output of the mixer 31 to assure that only the lower sideband or difference frequency obtained from the mixer 31 is passed. A gate 37 switches the circuit alternately between the transmit and receive conditions. During the receive portion of the cycle, the gate 37 permits signals to be passed to a conventional phase comparator 39. During the transmit portion of the cycle, the gate 37 permits energy from a radio frequency source 47 to be passed to the circulator 29. The phase comparator receives the loop signal as well as a signal from the intermediate frequency reference source 41. The phase of the output signal from the source 41 determines the phase of the signal reaching the target. The comparator 39 produces an output voltage whenever the frequency or phase of the signal from the loop departs from the signal from the reference 41. Any output from the phase comparator 39 is smoothed by a filter 43 and passed to a conventional pulse stretcher or holding circuit 45. The voltage tunable oscillator 27 produces a modulating voltage whose frequency and phase are determined by the voltage applied to its input terminals. A variety of types of oscillators are available for this purpose. Typical of these are the oscillators described in the article: "Reactance Tube Modulation of Phase Shift Oscillators" by Dennis and Felch, pp. 601–7 of the Bell System Technical Journal for October 1949.

The radio frequency source 47 provides energy for transmission. The frequency of this source is made to be numerically equal to the sum of the frequencies of the outputs of the source 33 and the source 41. The source 47 is coupled to the antenna 21 through the circulator 29 and the modulator 25.

The entire antenna array system typically comprises several antenna elements 21 coupled to their respective loops 23. Each loop is fed by the common reference sources 33 and 41 and by the common transmitter source 47.

To better understand the operation of this embodiment of the invention, assume that the first signal has just been returned from the target. Assume further that the phase of this signal is retarded and the Doppler frequency shift is such that the received frequency is lower than the frequency reflected from the target.

The output of the modulator will be equal to the received signal minus some initial modulating signal supplied by the oscillator. This output signal of the modulator may be considered as being composed of a known component plus an unknown component. The known component is equal in frequency to that of the signal actually reflected at the target and therefore equal to the signal at reference source 33. The unknown component includes the Doppler frequency and the phase delay of the received wave plus the frequency and phase characteristics of whatever modulating signal is supplied by the oscillator. The modulator output signal, in passing through mixer 31 and filter 35, is subtracted from the reference voltage from source 33. Since the signal from source 33 is equal to the known component of the modulator output voltage, only the unknown component is passed on to phase comparator 39. This unknown component will initially differ from the intermediate frequency reference voltage from source 41 and thus produce an error voltage tending to change the frequency and phase of oscillator 27. This transitory situation will exist until the oscillator produces a modulating voltage such that no signal appears at the output of the phase comparator. When this balanced condition exists, the unknown component being supplied to the phase comparator from filter 35 is equal to the intermediate frequency reference source 41. Therefore, the frequency of the signal from source 41 is equal to the sum of the Doppler and the modulating frequencies. Or stated as a corollary, the modulating frequency at balance is equal to the difference of a frequency from source 41 and the Doppler frequency.

Similarly, under these conditions, the phase angle of the modulating signal will be equal to the difference between the phase of the signal from source 41 and the phase delay of the received signal.

The oscillator will be maintained at this setting by holding circuit 45 during the succeeding transmit period.

The signal from source 47 has a frequency equal to the sum of the frequencies of source 33 and source 41. In passing through the modulator, the modulating frequency will be subtracted from this transmitter frequency. Since the modulating frequency is equal to the difference between the frequency of source 41 and the Doppler frequency, the frequency radiated from antenna element 21 will be equal to the frequency of source 33 plus the Doppler frequency. The phase of the radiated signal will be advanced from the phase of the signal from reference source 41 by an amount equal to the phase delay of the received signal.

In travelling to the target, the signal will experience a phase delay and frequency shift just sufficient to counteract the initial displacement from the references given to the radiated signal. The portions of the composite signal from the individual antenna elements of the array will arrive at the target coherently.

The foregoing explanation assumed a Doppler shift such that the received signal was lower in frequency than the signal reflected from the target. If a Doppler shift is encountered in which the received wave has a higher frequency than the signal reflected from the target, the opposite correction will take place in the loop so that transmitted signal coherence at the target will still be obtained.

A somewhat similar embodiment of the invention may be used when the target position is restricted to the far field of the antenna array. Under these conditions, the Doppler frequency shift to each antenna element or focusing loop is identical since rays of energy to the various antenna elements are substantially parallel.

This embodiment of the invention comprises a reference antenna element and one or more controlled antenna elements. Each controlled element is coupled to an individual phase locked loop.

FIG. 3 illustrates a controlled antenna element and a typical circuit that may be associated with it in using this embodiment of the invention.

The reference antenna element 119 communicates with a mixer 141. Energy received by the reference antenna element causes a signal to enter the mixer 141 where it is mixed with a signal from a radio frequency source 133 to provide an intermediate frequency reference signal.

Portions of this reference signal as well as portions of the radio frequency source energy are coupled to each loop in the overall system.

An error signal controlled TEM mode line stretcher 125 in the phase locked loop communicates with the associated antenna element 121. The line stretcher 125 may be constructed conveniently from conventional coaxial or planar transmission line operating in the TEM mode. The velocity of propagation associated with this mode is substantially independent of frequency and substantially equal to the free space velocity of electromagnetic energy. Because of this feature, beam steering errors inherent in ordinary phase shifters can be eliminated and high gains over broad bandwidths can be realized. Line stretchers of this type require a simple rotational or translational movement for their adjustment. Servomechanisms for converting an error signal into these types of mechanical movement are well known in the art.

The line stretcher 125 is coupled through the circulator 129 to a heterodyning means 131. The heterodyning means 131 is also coupled to the radio frequency source 133. Filter 135 and filter 123 preferably are designed to pass only the Doppler frequency component of the incoming signal. This provides the advantage of narrow band operation of the closed loop components without sacrificing wideband signal reception as will be demonstrated.

A gate 137 switches the circuit alternately between the transmit and receive conditions. During the receive portion of the cycle, the gate 137 permits signals to be passed to the conventional phase comparator 139. During the transmit portion of the cycle, the gate 137 permits energy from the radio frequency source 133 to be coupled to the circulator 129. A similar gate circuit and circulator may be employed in the reference antenna circuit for transmit and receive applications.

For applications in which this embodiment of the invention is to be used for reception only, it is sometimes more convenient to replace the line stretcher with a variable delay line operating in the TEM mode. Such a delay line can be placed between the heterodyning means and the phase comparator so as to operate on the intermediate frequency energy.

The comparator 139 is also coupled to receive an intermediate frequency reference signal from mixer 141. Any output from comparator 139 is smoothed by low pass filter 143 and passed to holding circuit 145. Holding circuit 145 conveniently may comprise a conventional pulse stretcher or "box car" circuit. Holding circuit 145 is coupled to the conventional mechanical servo control means in controlled line stretcher 125.

Radio frequency source 133 is coupled to a circulator 129 in each loop so that a portion of its output may be supplied to the various antenna elements during periods of transmission.

To better understand the operation of this embodiment of the invention, assume that a signal containing an unknown Doppler shift and phase shift with respect to source 133 reaches the antenna element 121. Another portion of the same wave front impinges on the reference antenna element 119, causing a signal to enter the mixer 141. The mixer 141 passes the difference frequency between the signal from the reference antenna element 119 and the signal from source 133. Since the received signal comprises a frequency component equal to the transmitted frequency from the source 133 plus a Doppler frequency component, mixer 141 passes only this Doppler component. The mixer 141 and the source 133 constitute a reference source 149 from which the Doppler frequency output may be used as a reference signal for the various phase comparators in the system. The phase of this reference voltage is the same as the phase of the signal eventually reaching the target, as will be demonstrated.

Another portion of this received signal passes directly from the antenna 121 to the line stretcher 125 where it experiences a phase shift depending upon the initial adjustment of this member. The shifted signal passes through circulator 129 to the heterodyning means 131. This heterodyning means cooperating with low pass filter 135, provides a signal whose frequency is the difference between that of the received signal and the signal from source 133. The frequency of this difference signal, however, is the Doppler frequency of the received signal. The phase of this signal with respect to source 133 is equal to the phase delay of the received signal plus whatever phase displacement was provided to the signal in passing through line stretcher 125. This signal is coupled to phase comparator 139. Since the frequency of this signal and that of the reference are both equal to the Doppler frequency, the Doppler frequency variations in the received signal are automatically neutralized. Because of the original phase differential, however, a

voltage output will be obtained from comparator 139. This voltage is coupled to the controlling elements in line stretcher 125 so that this member is adjusted until the phase of the signal reaching phase comparator 139 equals the phase of the reference signal from mixer 141. When this condition of balance has been attained, substantially no voltage will appear at the output terminals of the phase comparator 139 and the setting of the line stretcher 125 will remain fixed until a subsequent change in the received signal requires that a readjustment be made.

At balance, the phase change imparted to the received signal must be sufficient not only to overcome the phase delay of this signal with respect to the output of source 133, but also to shift the phase by an additional amount necessary to overcome the phase discrepancy between the outputs of the mixer 141 and the source 133. Or stated as a corollary, the line stretcher advances the phase of the received signal by an amount equal to the phase angle of the received signal with respect to the output of source 133 plus the phase angle of the output of the mixer 141 with respect to the output of the source 133.

The succeeding pulse of transmitter energy passes through the line stretcher and receives the same phase displacement as that experienced by the previous pulse of received energy. This transmitted signal, in travelling between the antenna and target, is delayed in phase by the same amount as that experienced by the previously received signal. Thus, the phase delay experienced by the transmitted signal in travelling from the antenna element to the target just counteracts that portion of the phase shift imparted by the line stretcher 125 that was used to overcome the delay in the received signal. The signal thus reaches the target with a phase angle just equal to that of the reference signal from the mixer 141. Since the portions of the signal from the individual antenna elements each arrive at the target with a phase angle equal to that of the reference, these signals are coherent. The frequency of the signal reaching the target will be different from the source 133 because of the Doppler shift, but since the Doppler shift in the case of a target in the far field is the same for each antenna element, the frequency of the signals from each antenna element will be identical.

Since the Doppler frequency shift of the received signals for a reflecting target, is the sum of the shifts experienced by the wave travelling to the target and back again, it can be of considerable magnitude. Thus, the frequency of the received wave can depart significantly from the frequency of the transmitted wave, and phase shifters used in the prior art devices are not applicable under these conditions. The angle of radiation from arrays using ordinary phase shifters is a function of frequency. By using TEM mode line stretchers however, the control is exercised by actually changing the electrical length of the loop.

It has been convenient to consider the action of the line stretcher 125 in terms of the phase shift produced by this member in describing the operation of the phase locked loop. However, the overall operation of the array when subjected to various frequencies can best be understood in terms of variations in loop path length.

A wave front of electromagnetic energy arriving at an angle to the plane of the array reaches the various antenna elements at successively different times. The physical lengths of the various loops are automatically adjusted so that the earlier received portions of this wave front pass through longer loop paths and all portions of the wave front arrive at the respective phase comparators simultaneously. The portions of the succeeding transmitter signal experience the same variations in loop path lengths and emanate from the various antenna elements in reverse succession to that of the received waves. The radiated energy thus forms a wave front that propagates back in the direction of the target.

Since the electrical length of TEM mode line stretchers is substantially the same as the free space wavelength for all frequencies in the range of interest, the received and transmitted waves have identical radiation directions regardless of the departure in frequency of the received wave from the frequency of the transmitted wave.

Although the circuit of FIG. 3 has been described for time-sharing operation in which periods of reception are alternated with periods of transmission, it will be appreciated that this basic circuit can be readily adapted for duplex communication use in which signals are transmitted to the target at the same time that signals of a different frequency are received from a transmitter in the target. This requires only that the circulator be in the form of a diplexer so that the receiver may be isolated from the reflections of the antenna circuit. Holding circuit **145** can be adjusted for minimum pulse stretching in this application and gate **137** can be set to close both circuits. The frequency departure of the received signal from the transmitted signal is again neutralized in the phase comparator since the reference signal itself is a function of the frequency of the received signal.

The line stretchers **125** are again automatically adjusted in response to the received wave. The direction of propagation of the simultaneously transmitted wave is determined by this adjustment.

It will be further appreciated that this circuit is useful in high gain communication systems since the system can operate on a narrow bandwidth so as to adjust automatically to the phase and frequency of the carrier, yet operate as a wide band system adjusted to transmit and receive all sidebands coherently.

Consider an array of antenna elements in which the individual elements are adjusted in phase by ordinary phase shifters. A wave front of electromagnetic energy consisting of a single frequency carrier arriving at an angle to the plane of the array, will reach the individual antenna elements at successively different times. These delays in arrival time are equivalent to specific phase delays at the carrier frequency. The phase shifters can be adjusted to compensate for these resulting phase delays and to bring the individual signals into coherence at some point in the circuit. If now, the carrier is modulated, sideband frequencies will appear in addition to the carrier frequencies. The delay in arrival time of the wave front at the various antenna elements represents a different phase shift for each of these individual frequencies. The phase shift that was used to bring the portions of the carrier signal into coherence will not serve to bring the sideband frequencies into coherence.

Consider, however, the case of a system such as that depicted in FIG. 3 in which a TEM mode line stretcher is used to bring the various portions of the signal into coherence. Variations in times of arrival at the various antenna elements are compensated by adjusting the path lengths of the various loops. The adjutsed loop lengths are the same for the sideband frequencies as for the carrier frequency. The signals are coherent regardless of frequency. In this way, maximum gain for a wideband communication system is automatically achieved by using just the carrier frequency for adjustment. The loop can employ narrow band filters **123** and **135** that pass only the modulation product that corresponds to the difference between the carrier frequency of the received wave and the frequency of the source **133**. This provides efficient noise elimination and rapid loop response without sacrificing the necessary bandwidth for the intelligence-carrying sideband frequencies.

Although the circuit of FIG. 3 will adjust properly when the signals reaching the various antenna elements are within a wavelength, a certain amount of ambiguity results from the fact that the individual loops can lock on a succeeding wavefront and cause the system to operate at less than optimum efficiency. This ambiguity problem can be overcome by providing auxiliary means for obtaining a preliminary coarse adjustment. This can be accomplished conveniently by inserting additional coarse

line stretchers in each antenna lead. These coarse line stretchers can then be adjusted manually or by means of computers, after which time the closed loop line stretchers **125** can be adjusted precisely by the loop components. The coarse line stretchers may conveniently employ TEM mode coaxial or planar transmisison line devices. In situations involving widely spaced antenna elements, known variable delay lines employing magnetic recording techniques may be used if desired.

In situations, for instance, in which a system is alternately switched between the transmitting and receiving functions, the coarse line stretchers can be adjusted by a computer during the transmit portion of the cycle. During the next receive portion of the cycle, the system can be again self-adjusted by means of the closed loop so as to remove any accumulated errors.

Although the basic circuit of FIG. 3 is adequate for many applications in which the target remains in the far field, it will be appreciated that refinements of this basic circuit may be used when more elaborate transmission systems are involved.

Radio links with artificial satellites, for instance, might involve numerous telemetry channels. For such applications, the basic circuit of FIG. 3 may be modified for use with a more complex receiver.

FIG. 4 depicts such a modified circuit used in conjunction with a particular radio tracking and communication receiver described by M. H. Brockman et al. on pages 643–654 of the Proc. of the I.R.E. for April 1960. The Brockman receiver employs a phase-coherent, double conversion superheterodyne system that may be used in the reference antenna circuit to provide first and second local oscillator signals as well as a reference oscillator signal to the various phase lock loops.

The double conversion means and A.G.C. loop **147** of the Brockman receiver may be further used in each phase lock loop in place of the corresponding heterodyning means **131** of the basic circuit.

The circuit of FIG. 4 also may incorporate a computer-tuned coarse line stretcher in each antenna lead.

Each of the previously described loops can be used as self-locking loops operating on received signals only. Coherent signals can be taken from appropriate points such as the loop input to the comparators. However, in applications in which it is desired to use the antenna system only for reception, the circuit can be simplified by eliminating the circulator.

A simplified circuit for this type of service is illustrated in FIG. 5. In this circuit, electromagnetic energy is received by an antenna array element **221**, converted to a convenient intermediate frequency, and coupled to a phase-locked loop **223**. This incoming signal is mixed in modulator **225** with the output of voltage tunable oscillator **227**. The output of modulator **225** is passed through an intermediate frequency tuned filter **235** to phase comparator **239**. Intermediate frequency reference **241** is coupled to each phase comparator in the system. The output of the phase comparator is used to adjust the frequency output of oscillator **227** as explained with reference to oscillator **27** of FIG. 2. A coherent signal may be taken from each loop at the output of modulator **225**.

The operation of this circuit can be better understood by considering the initial signal reaching antenna **221**. Assume that this signal contains a Doppler frequency component and has been retarded in phase. This signal is converted to an intermediate frequency and mixed with some initial modulating signal supplied by oscillator **227** in modulator **225**. The output of this modulator is passed through filter **235** so that only the desired modulation product is passed on to the phase comparator.

Under the assumed conditions, the output of the filter, will in general, differ in phase and frequency from the output of standard reference **241** so that an error voltage will appear at the output of phase comparator **239**. This error voltage will tend to change the frequency and phase of oscillator 227 so as to reduce the error voltage. This transistory situation will exist until the oscillator produces such a modulating voltage that substantially no signal appears at the output of the phase comparator. When this balanced condition is attained, the oscillator 227 will be providing a signal of such frequency and phase that when it is effectively subtracted from the incoming signal in modulator 225, a signal equal in phase and frequency to the intermediate frequency standard reference will be coupled to the phase comparator. Since the intermediate frequency reference is common to all the loops, the loop signal being supplied to the phase comparators at balance is coherent in each loop.

In essence then, this circuit compares the carrier component of the received signal to the standard reference frequency, and then the action of the feedback loop forces the phase of the signal to be locked to that of the standard. Since the circuits are all phase locked to the same standard, the sidebands may be added coherently. Thus the signal-to-noise ratio of the array is equal to the number of individual antenna elements multiplied by the signal-to-noise ratio of one of these elements. The information-carrying sideband is prevented from affecting the loop by a narrow band filter 235. At balance, each loop in the system will produce a sideband with essentially the same phase. For this reason the signals may be added coherently.

Although several embodiments of the invention have been shown and described, it is understood that numerous and varied other arrangements can readily be devised in accordance with these principles by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. A high gain antenna system comprising a source of independently generated intermediate frequency reference voltage; a plurality of controlled antenna elements; a phase locked loop coupled to each controlled antenna element; each phase locked loop including correction means for adjusting the phase of a signal flowing in said loop, said correction means being connected to receive a signal directly from the associated antenna element, heterodyning means connected to receive a signal from said correction means for converting the signal in a portion of the loop to a signal having a frequency equal to that of the reference voltage, a phase comparison means for producing an error voltage whenever the phase of the loop signal differs from the phase of the reference voltage, said correction means being responsive to the output of said comparison means so as to adjust the phase of the loop signal until the error voltage disappears; and output means for extracting a coherent signal from each loop upon the reception of an electromagnetic wave by said antenna element.

2. A high gain antenna system comprising a source of independently generated intermediate frequency reference voltage, a plurality of controlled antenna elements, a phase locked loop coupled to each controlled antenna element, said loops each containing synchronizing means connected to receive a signal directly from the associated antenna element, heterodyning means connected to receive a signal from said synchronizing means for producing a signal in a portion of said loop with a frequency equal to that of said reference voltage, comparison means coupled to said source of reference voltage for producing an error voltage whenever the signal in said loop departs from synchronism with said reference voltage, control means coupled to receive the output of said comparison means, said synchronizing means being coupled to said control means for correcting the signal in said loop whenever such signal departs from the reference, and signal output means for extracting a coherent signal from each loop upon the reception of an electromagnetic wave by said antenna elements.

3. A high gain antenna system for alternately transmitting and receiving electromagnetic energy comprising an intermediate frequency reference source; a radio frequency reference source; a radio frequency power source providing energy at a frequency equal to the sum of the frequencies provided by the two reference sources; a plurality of antenna elements; an individual phase locked loop coupled to each antenna element; said phase locked loops each including a modulator coupling the loop to the respective antenna element, frequency mixing means to produce a signal having a frequency equal to the difference in frequencies of the signal from said radio frequency reference source and a signal from said modulator, means for comparing the incoming mixing means output signal in that loop to the intermediate frequency reference, means for compensating for the departure in phase and frequency of the received signal from the radio frequency reference, means for subtracting the amount of this departure from a subsequently transmitted signal, output means for coupling a coherent signal to external utilization means upon the reception of an electromagnetic wave; and switching means for periodically coupling the source of radio frequency power to the antenna elements through the individual compensating means.

4. A self-focusing antenna system for alternately transmitting and receiving electromagnetic energy comprising a source of radio frequency energy, a reference source of intermediate frequency voltage, a plurality of antenna elements, an individual phase locked loop coupled to each antenna element, said phase locked loops each including a reciprocal single side band suppressed carrier modulator coupled to the associated antenna element for shifting the phase and frequency of the incoming signals, a phase comparator coupled to said modulator and to said reference source for obtaining an output voltage representative of the phase and frequency difference between the shifted incoming signal and the reference signal, a voltage tunable oscillator coupled to the output of said phase comparator and to said modulator so that the modulation frequency supplied to the modulator is changed until the output from said phase comparator reaches a predetermined minimum value, holding means for maintaining the desired modulation frequency throughout a transmitting cycle, and coupling means for connecting said radio frequency source to each antenna through the respective modulators so that the phase of the transmitted signal is shifted by the same amount as the preceding received signal.

5. A high gain antenna system responsive to signals containing a Doppler component comprising a reference source of intermediate frequency energy; a reference source of radio frequency energy; and a transmitter source of radio frequency energy having a frequency numerically equal to the sum of the frequencies of said intermediate frequency reference and said radio frequency reference; a plurality of antenna elements; individual phase locked loops coupled to each antenna element; said phase locked loops each including a voltage tunable oscillator, a reciprocal single sideband suppressed carrier modulator coupled to said voltage tunable oscillator and to the associated antenna element so as to provide an output equal in frequency and phase to the difference between the received signal and the voltage tunable oscillator signal, a mixer coupled to the output of said modulator and to said radio frequency reference source, comparison means coupled to said mixer and said intermediate frequency source so that an error signal is produced whenever the phase or frequency of the signal from said mixer departs from said intermediate frequency reference, conducting means interconnecting said phase comparator and said voltage tunable oscillator so that the frequency of the voltage tunable oscillator is adjusted upon reception of an electromagnetic wave until substantially no error signal appears at the output of the phase comparator, output means for extracting a coherent signal

upon the reception of an electromagnetic wave, and holding means for maintaining the frequency of the oscillator substantially constant for a predetermined time; coupling means interconnecting said transmitter source and said modulator so that signals to be transmitted are coupled to the antenna elements through the modulator.

6. A duplex antenna system comprising a reference antenna; a source of radio frequency energy; an intermediate frequency reference source, said intermediate frequency reference source including a mixer connected to receive a signal directly from said reference antenna and a signal directly from said source of radio frequency energy; a plurality of controlled antenna elements; a phase locked loop coupled to each controlled antenna element; each phase locked loop including controlled means for adjusting the electrical length of the loop, heterodyning means connected to receive a signal from said controlled means and a signal from said source of radio frequency energy, comparison means coupled to said reference source and to said heterodyning means for providing a voltage whenever the phase of the loop signal differs from that of the reference signal, coupling means connecting the output of said comparison means to said controlled means for adjusting the controlled means whenever the phase of the loop signal departs from the phase of the reference signal, and output means for extracting a coherent signal upon reception of an electromagnetic wave; coupling means interconnecting said source of radio frequency energy and each controlled means whereby the signal to be transmitted passes through the same adjustable length portion of the loop as the concurrently received signal.

7. A duplex antenna system comprising a reference antenna, a source of radio frequency energy, a reference voltage source connected to receive signals from said reference antenna and from said source of radio frequency energy so as to provide an output signal equal to the difference in these signals, a plurality of controlled antenna elements, a phase locked loop coupled to each controlled antenna element, each phase locked loop including error voltage controlled means for adjusting the physical length of the loop, heterodyning means connected to produce a loop signal equal to the difference of the output signals from said controlled means and from said source of radio frequency energy, comparison means coupled to said reference source for providing an error voltage whenever the loop signal departs from synchronism with the reference signal, coupling means connecting the output of said comparison means to said controlled means for adjusting the physical length of the loop until the error voltage substantially disappears, output means for extracting a coherent signal from the loop whenever electromagnetic waves are received by the associated antenna element, coupling means interconnecting said source of radio frequency energy and each controlled means whereby the signal to be transmitted is subjected to the same variations in path length as the concurrently received signal.

8. A high gain antenna system comprising:

(*a*) a transmitter source of radio frequency energy,
(*b*) a reference antenna,
(*c*) a superheterodyne receiver coupled to the reference antenna,
(*d*) a source of reference signals in said receiver,
(*e*) a plurality of controlled antenna elements,
(*f*) a phase locked loop coupled to each controlled antenna element,
(*g*) each phase locked loop including a controllable TEM mode line stretcher coupled to the associated antenna element, heterodyning means to produce an intermediate frequency signal in a portion of the loop, a phase comparator coupled to receive the intermediate frequency signal and a signal from said reference source, means interconnecting the phase comparator and the line stretcher whereby the line stretcher is adjusted upon the reception of electromagnetic energy until the output of the phase comparator becomes essentially zero, and output means for extracting a coherent signal from the loop, and
(*h*) a coarse line stretcher coupled to each antenna to provide preliminary adjustment of the antenna system.

9. A self-focusing antenna array system for alternately transmitting and receiving electromagnetic waves without steering error comprising a source of radio frequency energy, a source of reference voltage, a plurality of controlled antenna elements, an individual phase locked loop coupled to each controlled antenna element, said loops each containing a controllable TEM mode line stretcher coupled to the associated antenna element, heterodyning means coupled to said line stretcher for passing only the Doppler component of the received signal, phase comparison means for detecting the departure of the Doppler component from the reference voltage, controlling means interconnecting said phase comparison means and said line stretcher whereby said line stretcher is adjusted upon the reception of electromagnetic energy until the output of said phase comparator becomes essentially zero, holding means for maintaining the setting of the line stretcher substantially constant throughout the succeeding transmit period, output means for extracting a coherent signal from the loop, and switching means for periodically coupling the source of radio frequency energy to the antenna elements through the associated line stretchers.

10. A duplex antenna system comprising a source of radio frequency energy; a reference voltage source; a plurality of controlled antenna elements; a phase locked loop coupled to each controlled antenna element; each phase locked loop including a controlled TEM mode line stretcher for adjusting the physical length of the loop, heterodyning means to provide a loop signal corresponding to the Doppler frequency of the received wave, comparison means coupled to receive signals from said heterodyning means and from said reference source for providing an error voltage whenever the loop signal departs from synchronism with the reference signal, coupling means connecting the output of said comparison means to said controlled means for adjusting the physical length of the loop until the error voltage substantially disappears, output means for extracting a wide band coherent signal from the loop whenever electromagnetic waves are received by the associated antenna element; and coupling means interconnecting said source of radio frequency energy and each controlled means whereby the signal to be transmitted is subjected to the same variations in path length as the concurrently received signal.

11. A broad band antenna system comprising a reference antenna; a reference voltage source coupled to said reference antenna; a plurality of controlled antenna elements; a phase locked loop coupled to each controlled antenna element; each phase locked loop containing output means for extracting a broad band signal from said loop, filter means for passing essentially only the Doppler frequency of the received wave to a portion of the loop, comparison means coupled to said reference source for providing a voltage whenever the phase of the Doppler signal in said loop differs from the phase of the signal from said reference source, and controlled means responsive to the output of said comparison means for adjusting the electrical length of the loop until the Doppler signal in said loop is in phase with the signal from said reference source whereupon coherent carrier and sideband signals can be derived from each of said output means.

References Cited in the file of this patent

UNITED STATES PATENTS

3,036,210 Lehan et al. ____________ May 22, 1962