Adaptive Array for Elimination of Multipath Interference at HF

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Abstract—**A four element adaptive array using a modulated pilot signal added to the communication signal at the transmitter has been constructed and tested at high frequency (HF). The pilot signal modulation was designed to discriminate against undesired HF multipath. The array reduces the strength of undesired modes by spatial nulling, while maintaining response in the direction of the desired mode. The array was used to receive signals that propagated via a 150-mi over-ocean path. The antenna configuration and frequency selection were such that the ground wave and ionospheric modes of propagation were approximately equal. The pilot signal, used as a reference for the adaptive array, consisted of a single tone, phased reversed by a pseudorandom sequence. The bandwidth of the pilot signal was selectable at either 3 kHz or 6 kHz. A pulse sounder was used to measure the response of the array system to the arriving modes. During the test the ground wave $1E$, $1F_1$, and $1F_2$ modes were observed, occasionally simultaneously. The array reference signal could be locked to any arriving mode and the array processor was able to discriminate against all other modes by directing spatial nulls. The reduction in strength of the undesired modes measured during the test was greater than 15 dB.**

INTRODUCTION

THE adaptive array concept is to adaptively control the amplitude and phase of the signal from each array element in order to null interfering signals, while maintaining response in the direction of the desired signal. Widrow has developed an algorithm for doing this based on minimizing the mean-square difference between the array output and a reference signal [1] (least-mean-square (LMS) algorithm). The reference signal is a coherent estimate of the desired signal.

Widrow suggests the use of a pilot signal transmitted locally from the same direction as the desired signal or injected into the array elements phased to correspond to the direction of arrival (DOA) of the desired signal. The locally generated pilot signal is also used for the adaptive array reference signal. In both cases the DOA of the desired signal must be known.

Compton [2] has demonstrated a laboratory version of an adaptive array based on the LMS algorithm using a sample of the transmitted signal as the adaptive array reference. Of course for the communication problem if one had a sample of the desired signal then the adaptive array for interference nulling would be unnecessary.

For the radar problem a local reference signal can be generated by using knowledge of the time and DOA of the desired signal. This concept has been found to work well on high frequency (HF) radar signals [3], [4].

For the general communication problem where the time and the DOA of the desired signal are unknown the generation of a reference signal for the adaptive array poses some problems. Riegler and Compton [5] have discussed the application of the adaptive array concept to amplitude modulated communications signals, whereby the adaptive array output would be processed to generate a representation of the transmitted carrier for use as the reference signal. This approach does not require knowledge of the desired signal DOA.

For spread spectrum signals the adaptive array output can be processed using knowledge of the redundancy of the spreading technique to generate a reference signal [6]. This approach also does not require the adaptive array to have knowledge of the desired signal's DOA.

Previously we demonstrated the concept of adding a pilot signal to the transmitted communications signal. This approach also eliminates the need for local knowledge of the desired signal's DOA and will work for any communication modulation format. However, for LMS processors about half of the transmitted power must be put into the pilot signal [7], [8]. Our previous array used a single tone pilot signal and both single sideband (SSB) voice and multiple tone quadrature phase-shift keyed (QPSK) tones for information transmission.

The single tone pilot is not practical for use in scenarios where deliberate interference is encountered since interfering signals can easily be generated to contain the same pilot tone. To counter this problem the pilot signal can be modulated by a signal known only to the transmitter and desired receivers such as a pseudonoise sequence [9]. Computer simulations using such a pilot signal have shown that an additional advantage to the communicator can occur in that when the pilot signal has sufficient bandwidth to resolve the multipath components the array will recognize multipath modes outside of the correlation window as undesired signals and eliminate or reduce them by nulling [7], [8].

The adaptive array described in this paper uses the concept of a modulated pilot signal added to the communications signal at the transmitter. This array was used in an on-the-air HF test and the array's ability to cancel multipath interference was demonstrated.

HARDWARE DESCRIPTION

A block diagram of the four-channel receiving adaptive array is given in Fig. 1. The antenna used consisted of 11-m whips. A broad-band preamplifier preceded the down converter. The down converter filters were especially matched to maintain a minimum null depth of at least 42 dB over the center 10 KHz of the passband. An external synthesizer and multicoupler were used to provide a coherent local oscillator to each of the four down converters.

The adaptive array processor was constructed using analog circuitry following the LMS algorithm. The complex weights for each channel were obtained by amplitude weighting quadrature components obtained by use of a quadrature hybrid. The processor was provided with a mode allowing the freezing of the weights ("hold" mode) for test purposes. In the hold mode, the weights were very stable with 20 dB nulls observed for periods exceeding 20 min.

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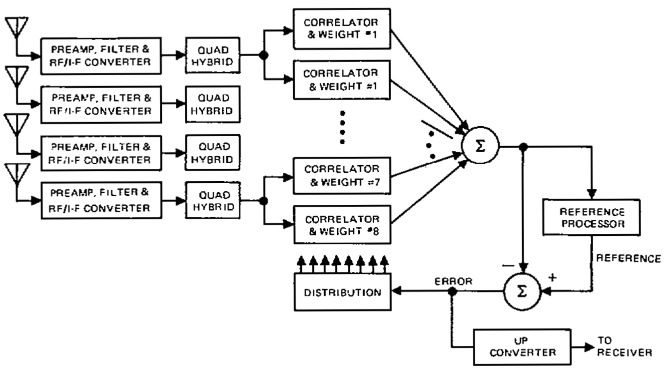

Fig. 1. Adaptive array block diagram.

The time constant of an LMS processor depends upon the feedback loop gain of the processor and the number of array elements involved as well as the power and direction of arrival of the signals to be nulled. For the system used, the down converter automatic gain controls fix the level of the signals to the processor. The total array time constant observed for a single null was about 0.15 s. A more complete description of the adaptive array processor is given in [10].

The error signal provided to the correlators is developed by subtracting the array output from an estimate of the desired signal (reference signal). This estimate of the desired signal is actually an estimate of only the pilot portion of the transmitted signal. The reference is obtained by passing the array output through the reference signal processor.

The pilot signal used was a single tone phase reversed by a repeating pseudorandom sequence. The two chip rates available for this sequence were 3 kHz and 6 kHz; for both rates the sequence was restarted at approximately a 10-Hz rate.

A block diagram of the transmitting equipment is given in Fig. 2. A standard AN/URT-23 transmitter was used consisting of a T-827 exciter and an AM-3924 1 kW amplifier. The T-827 exciter is an up converter capable of generating SSB and suppressed carrier double sideband at frequencies between 2 and 30 MHz. The AM-3924 is a wide-band linear amplifier capable of 1 kW peak power over the HF band. The transmitting antenna was an 11-m whip similar to that used for receiving; a base tuner was used to provide impedance matching.

The output of the pilot modulator consisted of a 500-kHz sine wave, phase reversed according to the repeating pseudorandom sequence. In addition a "sounder" mode which transmitted only the first chip of the repeating sequence provided a means of determining the various propagation modes received, as well as enabling personnel at the receive site to manually synchronize the array reference to the time of arrival of any particular propagation mode.

In the exciter the intermediate frequency (IF) signal from the pilot generation hardware and the information portion of the signal from the exciter are added together in the exciter IF stages. The exciter then translates the combined signal to the desired radio frequency and the output is amplified for transmission.

The information portion of the signal could be upper sideband (USB) or lower sideband (LSB) or both, and consist of voice or data. The center frequency of the pilot signal could be changed to correspond to the carrier frequency or the center of the upper or lower sideband. This flexibility allowed testing of three candidate modes of operation.

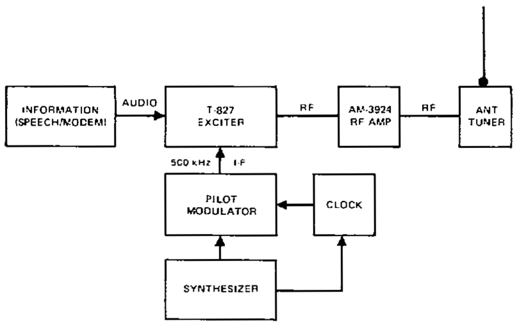

Fig. 2. Transmitting equipment for adaptive array sky wave test.

Mode 1 consisted of transmitting the narrow-band (3 kHz) pilot signal in one sideband while the information portion of the signal was transmitted in the other sideband. The frequency spectrum transmitted by this mode is illustrated in Fig. 3(a). A disadvantage of the approach is that 6-kHz bandwidth is required.

Mode 2 is illustrated in Fig. 3(b). The narrow-band pilot and information signals are transmitted on the same sideband; therefore taking only the standard 3-kHz frequency allocation. The pilot and information signal occupy the same bandwidth and, therefore, interfere with each other. The reference processor output signal has a fixed level for stability and the array output is subtracted from it in order to form the error signal. For a desired signal consisting of both pilot and information as defined by ρ, the ratio of pilot/information signal power, it can be shown that after adaptation (steady state) the error signal value of (reference–pilot)/information signal power ρ_ϵ is the inverse of the transmitted value of ρ:

$$\rho_\epsilon = \frac{1}{\rho}.$$

The reason for this is illustrated in Fig. 4. For steady state the average output of each weight multiplier must be zero. Thus at each weight multiplier output the term resulting from the correlation of the uncancelled information signal must be cancelled by the pilot/reference signal term.

For the array to satisfy this condition it must adjust itself so that the amplitude of the desired signal pilot, at the array output, is smaller than the fixed level reference processor output by the amount required. In other words, the array weights scale to meet this requirement as a function of the fixed level output of the reference processor. Therefore, care must be taken in the selection of this level. If it is too large, the signals from the array cannot cancel it and the null will be destroyed; if it is too low, the array weights will operate near their zero level at the expense of null depth and dynamic range.

The only time the error signal does not contain a mix of pilot and information signals is when $\rho \to \infty$ (desired signal nearly 100 percent reference). For this case $\rho_\epsilon \to 0$ and the information signal dominates the error signal output. This is the case when transmitting analog voice information because the voice duty cycle is very low. In this case the error signal has the pilot signal stripped off and, therefore, can be sent directly to the receiver (Fig. 1).

For analog voice transmission, the above approach of eliminating pilot/information interference by using the error signal for reception is viable and was demonstrated during the test. However, for continuous data signals, the value of ρ would be one, and therefore, pilot and information are equally

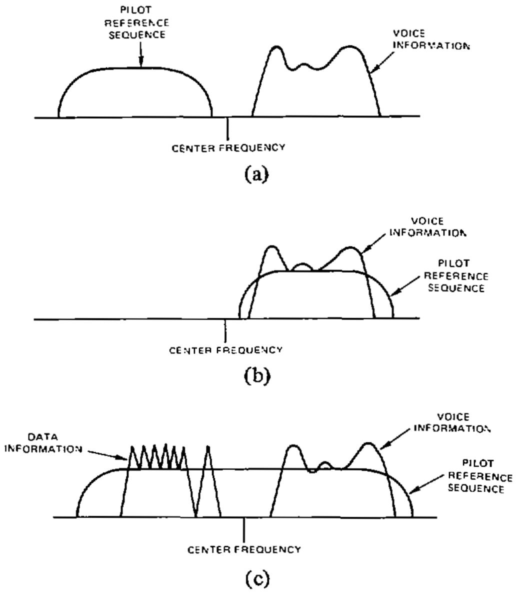

Fig. 3. Spectrums of three modes of combining the information and pilot signal. (a) Mode 1: 3 kHz reference in LSB, 3 kHz information in USB. (b) Mode 2: 3 kHz reference and information in USB. (c) Mode 3: Wide-band reference with 3 kHz voice in USB and 3 kHz data in LSB.

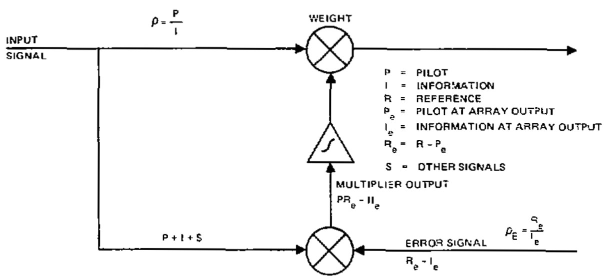

Fig. 4. Correlator weight detail with steady-state value. For steady-state multiplier, output is zero and $RR_e = -II_e$ which is satisfied if $\rho_E = 1/\rho$.

mixed in both the array output and the error signals (i.e., $\rho = \rho_\epsilon = 1$). For this case a separate adaptive loop is required to eliminate the pilot from the array output. One possible configuration for such a loop is given in Fig. 5.

This configuration was not tested; however, it could be used when the pilot and information signal share the same bandwidth to strip off the pilot signal allowing the information signal to be recovered. A potential disadvantage of this approach is that only stations equipped with adaptive processors would be able to receive the information.

Mode 3 illustrated in Fig. 3(c) used the wide-band 6 kHz pilot signal; information can be transmitted on one or both sidebands. The advantage of this mode is that the wide-band pilot can discriminate between multiple propagation modes that have smaller time delay differences. The disadvantage is the 6-kHz frequency allocation required. Since information and pilot share the same bandwidth an adaptive processor with reference is required to recover the information.

Fig. 6 gives a detailed block diagram of the reference processor which correlates the array output with the pilot sequence transmitted. Correlation is done by use of a balanced modulator driven by the baseband sequence. The output of the balanced modulator is filtered by a phase-locked loop (PLL)

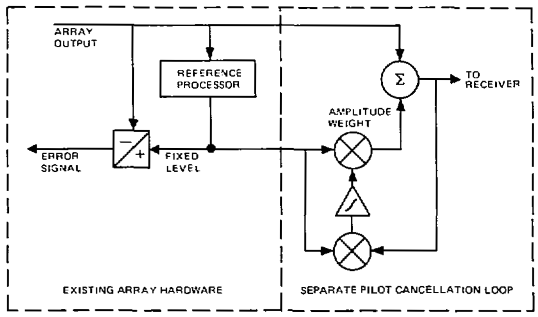

Fig. 5. Separate pilot cancellation loop.

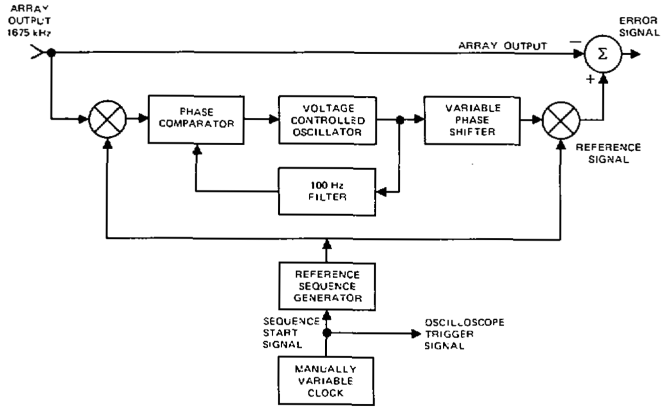

Fig. 6. Adaptive array reference processor system.

having an effective bandwidth of 100 Hz. The PLL was followed by a variable phase shifter which eliminated the 90° PLL phase shift and any other phase difference between the array output and reference processor. The PLL output is an IF sinusoid corresponding to the pilot carrier. The signal is then remodulated by the reference sequence to form the desired signal estimate (reference signal).

A manually variable clock was used to start the sequence generator and a scope trigger signal was generated at the same time. The method of synchronizing the receiving sequence generator to a particular mode consisted of transmitting the sounder signal and examining the array output with an oscilloscope triggered by the variable clock signal. Synchronization to a particular mode was done by adjusting the manually variable clock until the received sounder pulse from that mode appeared at the left side of the scope display.

For a real communication system manual synchronization would be unsatisfactory. Automatic synchronization can be done by sweeping the reference sequence generator clock over the time uncertainty and looking for a peak of the correlator output [9]. During the test this synchronization concept was demonstrated by sweeping the manually variable clock until the PLL lock indicator light went on. However, when using this technique the mode the array reference is synchronized to its unknown. Another technique we found useful was to listen to the audio output of the receiver connected to the reference signal and sweep the clock until the characteristic sound of the sequence was minimum.

SKY WAVE TEST

Geometry

For the sky wave test, a 234-km over-ocean path along the Southern California coast between San Diego (Pt. Loma) and

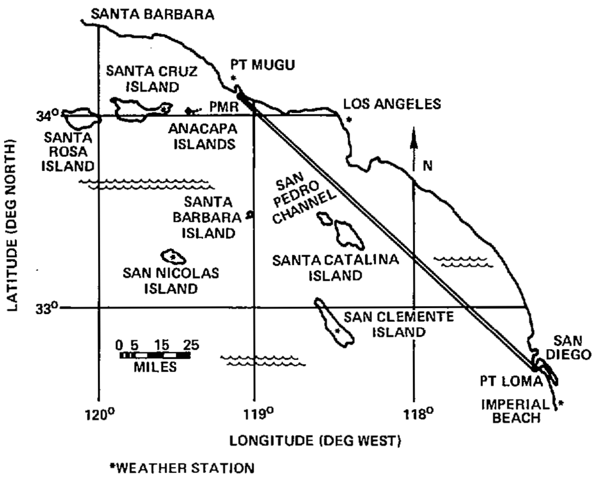

Fig. 7. Sky wave test path.

Pt. Mugu was chosen and is shown in Fig. 7. The transmitter was located on the beach at Pt. Mugu and the receiver was located at the Naval Ocean Systems Center (NOSC) site on Pt. Loma.

An HF ionospheric path prediction program was used to predict the various ionospheric modes that could occur on this path during the test. The available frequencies for testing were 3.4, 4.5, 5.9, 6.8, and 9.3 MHz.

The two modes which the computer program indicates can exist over this path are one-hop E layer reflection ($1E$) and one-hop F layer reflection ($1F$), with the $1F$ predominant most of the time. The $1F$ mode arrives at an elevation angle of about 70° while the $1E$ mode arrives at about 40°. The prediction calculations were done using quarter-wave vertical monopoles. Comparison with previous measurements on this path [11] indicates that the ground wave mode would be nearly equal to the ionospheric modes—depending on the mode, frequency, time of day, etc. The location of the receiving antennas used at the Pt. Loma site are shown in Fig. 8.

PROCEDURE AND RESULTS

Multipath Interference Elimination

The primary purpose of the test was to demonstrate the ability of the adaptive array to eliminate multipath interference. For this reason the test procedure was started by using the sounder mode on each of the assigned frequencies in order to determine the existing propagation conditions. During transmission of the sounder mode, reception was done using only a single element of the array so that the array pattern would not affect the relative strength of the various modes.

The frequency having the most interesting multipath structure would be chosen for further testing. An example of a typical evening sounder scope trace on 4.5 MHz is given in Fig. 9(a). Note that the ground wave and $1F$ mode are present and approximately equal in strength.

Using the sounder trace the receiver reference clock was manually synchronized to the desired receive mode. The transmitter was then switched to the reference mode chosen for testing. For this example the wide-band reference signal was used and the resulting waveform received on a single channel is shown in Fig. 9(b). Note that strong multipath interference present is indicated by the variation in the envelope of the received signal. All four channels of the array were then activated and the array allowed to adapt. The resulting waveform is given in Fig. 9(d); the relatively constant envelope of the received signal indicates that much of the multipath interference has been eliminated by the array. After adaptation, the array pattern was fixed by holding the array weights and the receiver automatic gain control (AGC) voltages. The transmitter was then switched to the sounder mode. The resulting display on the oscilloscope (Fig. 9(c)) indicates the effect of the array on the received multipath structure.

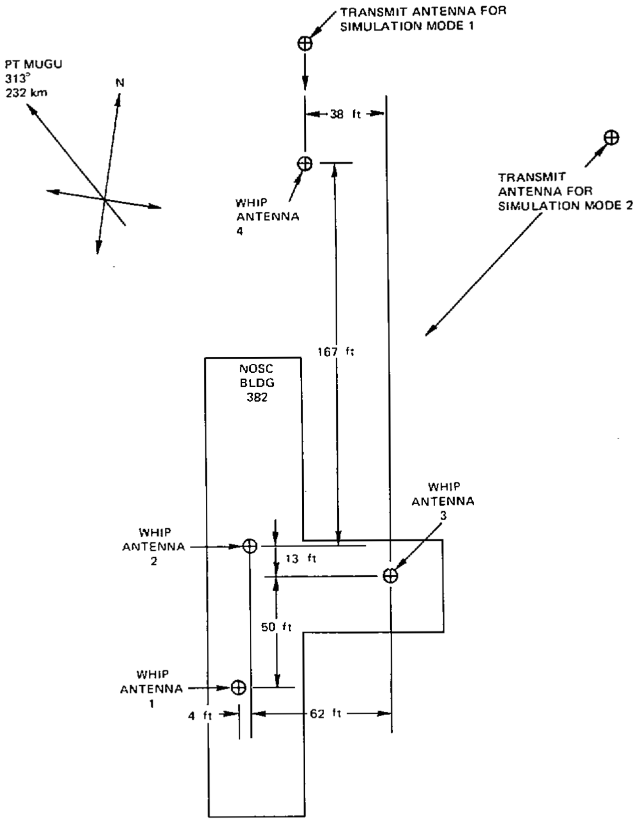

Fig. 8. Adaptive array antenna layout test geometry for adaptive array tests.

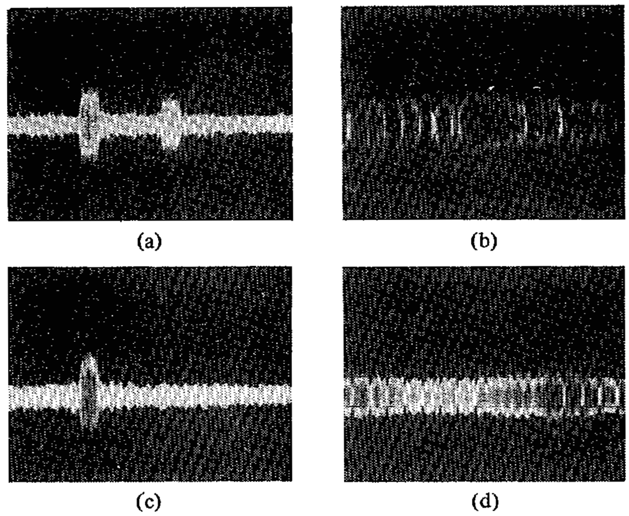

Fig. 9. Oscilloscope display of received signals for July 25, 1977. 2046 PDT–4.5 MHz–500 μs/cm. (a) Sounder–single channel. (b) Wide-band (WB) pilot–single channel. (c) Sounder–fixed after adaptation. (d) WB pilot–adapt.

The signal strength of the ionospherically propagated modes varies with time (fades). Over the near term the fading of an individual mode is primarily due to polarization rotation. The received polarization is a function of position as well as time and, therefore, is slightly different at each of the receiving antenna elements. The net result is that the relationship between the amplitude and phase of the signals received by each of the antennas for a mode varies cyclicly at a rate corresponding to the polarization rotation rate of the mode. Typically the period is several seconds long and can be much longer. Thus if the array is nulling an ionospherically propagated mode in real time, the weights will track these changes in the amplitude and phase of the signal received from that mode and adjust themselves in order to maintain the null. However when the array pattern is frozen the null remains but only for the polarization existing at the time the pattern was fixed. After freezing the weights as the polarization of the mode rotates, the received mode originally nulled can be observed varying up and down and going through a deep null when the polarization of the mode rotates back to the attitude it was in when the array pattern was frozen.

In order to document the effect of the array on the received multipath structure, the operator photographed the oscilloscope trace of the received sounder signal when the mode was in the null condition. Fig. 9(c) was generated in this manner and it shows that the multipath ratio was enhanced by more than 15 dB. However, due to the inability to measure the array's effect on the received modes in real time, no quantitative measurement of performance was accomplished.

A second example of array performance is given in Fig. 10. Fig. 10(a) shows the received sounder signal from a single antenna. The first arriving mode is the ground wave followed by an F layer mode that appears to have two components. The resultant received wide-band reference showing the result of multipath is given in Fig. 10(b). Initially the ground wave mode was chosen for synchronization and the array allowed to adapt. The resulting reference signal received by the array appears in Fig. 10(d) and shows that the multipath interference has been nearly eliminated. The array pattern was then fixed and the sounder mode transmitted (Fig. 10(c)). Note again that apparently two F layer modes are present. Figs. 10(e) and 10(f) show the results of synchronization to the second arriving ionospheric mode. The received pilot shows the slight effect of mode interference. The reason for this is that the two arriving F region modes are not separated enough in time (i.e., one-half chip width) for the array to totally discriminate between them. However the sounder trace indicates that some discrimination against the first arriving mode was present. Note the excellent null on the ground wave which does not fade and, therefore, remains when the array pattern is fixed.

The third example using the wide-band reference is given in Fig. 11. Taken on 5.9 MHz, the example shows a ground wave mode, a strong $1E$ mode, and a weak $1F$ mode. The array was synchronized to the ground wave mode and the results are shown in Figs. 11(c) and 11(d). The sounder trace indicates that the two sky wave modes were nulled but not totally. This is because when two sky wave modes are nulled, their polarization rotates independently and it is unlikely that this polarization would return to the same condition which existed at the time the array pattern was frozen. Hence, the actual null depths obtained were very likely much greater than those observed using this technique. It is also interesting to note in this example that an interfering signal on this frequency was nulled as can be seen by comparing the noise level of the two sounder traces.

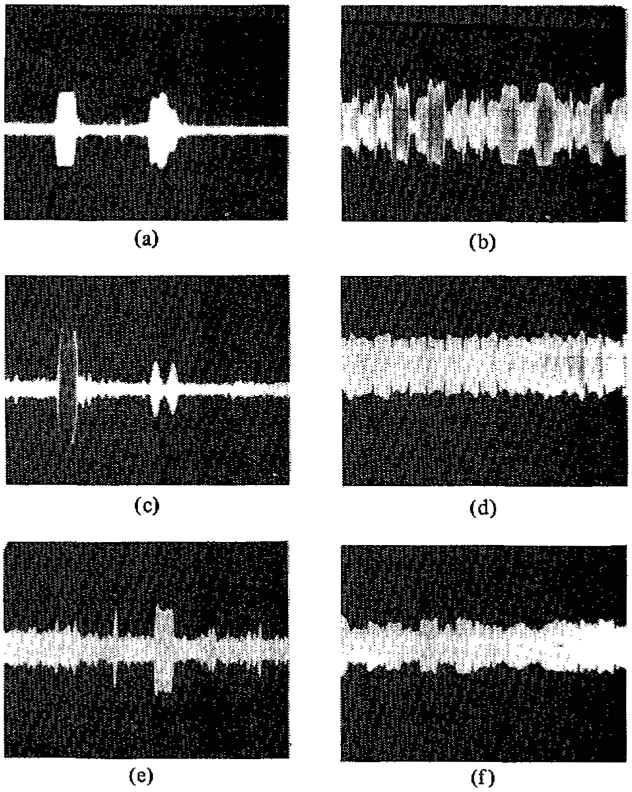

Fig. 10. Oscilloscope display of received signals for July 26, 1977. 0935 PDT-6.8 MHz-500 μs/cm. (a) Sounder–single channel. (b) WB pilot–single channel. (c) Sounder–fixed after adapt (sync to ground wave). (d) WB pilot–adapt (sync to ground wave). (e) Sounder–fixed after adapt (sync to $1-F_2$). (f) WB pilot–adapt (sync to $1-F_2$).

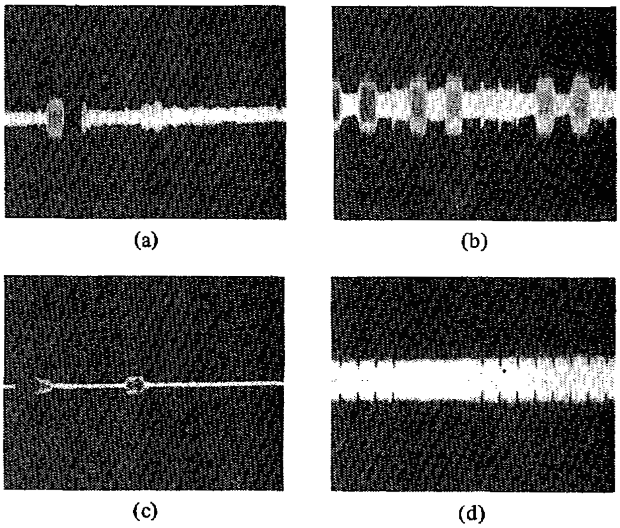

Fig. 11. Oscilloscope display of received signals for July 25, 1977. 2130 PDT-5.9 MHz-500 μs/cm. (a) Sounder–single channel. (b) WB pilot–single channel. (c) Sounder–fixed after adapt. (d) WB pilot–adapt.

All of the examples given above are for the wide-band pilot signal. The narrow-band pilot signal was used during the test and found to perform equally well as long as only ground wave and F modes were present. However it did not work as well in the case where just the ground wave and E mode were present because it did not have enough bandwidth to discriminate between the modes. The chip time of the narrow-band sequence is 600 μs and the differential delay between the ground wave and E mode was about 300 μs. Some discrimination was observed but no quantitative data could be obtained with the existing equipment.

Performance Using Single Sideband Voice

During the test period single sideband voice was transmitted using both the narrow-band and wide-band reference signal in modes 1, 2, and 3. The pilot suppression in the error signal proved to be adequate for analog voice signals due to the low duty cycle of voice and the relatively long time constants of the array and reference systems. It is especially interesting to note that the mode using the narrow-band reference in the same sideband as the voice information worked very well. In this mode a small amount of reference signal comes through the receiver but not enough to disturb the voice communications.

Excellent copy through interference was obtained for all three modes of operation. This experiment demonstrates the feasibility of using a modulated reference signal within the same bandwidth as the information signal. Tests were not done for digital data as no modems were available and, as previously mentioned, a separate reference cancellation loop would be required.

CONCLUSION

The use of a modulated pilot signal added to a communications signal to generate the reference signal required by an adaptive array receiving system has been demonstrated at HF. It has been shown that, given appropriate values of reference bandwidth and array aperture, discrimination against multipath propagation can be obtained by spatial nulling, while at the same time nulling unwanted interfering signals. The reduction to unwanted modes was found to be greater than 15 dB when using the wide-band (6 kHz) reference. However there were times that the narrow-band reference (3 kHz) was not able to provide the required discrimination. For longer paths than the one used for this test the delay difference between modes will be less and, hence, even more bandwidth may be required for these cases.

The modulated reference signal can share the same bandwidth as the information signal if adaptive techniques are used to separate reference and information at the receiver. During the tests this technique was partially demonstrated using single sideband voice information.

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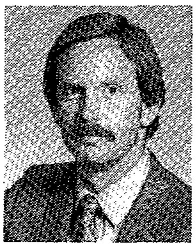
Dr. Hansen was chairman of the San Diego Chapter of the Antennas and Propagation Society in 1978. He is a member of Sigma Xi and URSI.



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During 1971–1973, he was a Research Engineer at DARE Technology. While there, he investigated the feasibility of using scaled millimeter waves for macroscope model imaging of radar targets for cross-section analysis. In 1973 he transferred to the Naval Ocean Systems Center (NOSC) in San Diego to join the High Frequency Special Communications Group. His initial two years' work at the Center was devoted to designing microprocessor based instrument and conducting field tests in the HF communication environment. From 1975 to the present, he has used his background in microprocessors and HF propagation phenomena to explore communications enhancement through adaptive array techniques.