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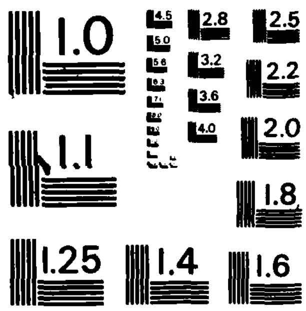


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# ON THE USE OF NULL-STEERING ARRAYS TO ENHANCE THE QUALITY OF HF SKYWAVE COMMUNICATIONS

R.H. CLARKE





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# ON THE USE OF NULL-STEERING ARRAYS TO ENHANCE THE QUALITY OF HF SKYWAVE COMMUNICATIONS

R.H. Clarke

## S U M M A R Y

The quality of HF skywave transmissions is degraded by the presence of multiple propagation paths between transmitter and receiver. Multipath signals are characterised by amplitude fading and associated phase variations as well as a spread in the propagation times and arrival angles of the skywave components. The use of null-steering array techniques (either manual or adaptive) to attenuate all but the dominant component of a multicomponent wavefield is discussed. Propagation measurements are presented which give an insight into the type of ionospheric conditions required for null-steering arrays to lead to a significant enhancement in the quality of skywave transmissions.

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# 1. INTRODUCTION

An aspect of HF skywave communications which is attracting increased attention is the transmission of medium-speed (typically 2400 bits/s) digital data at error rates of less than one error per thousand bits (ie $10^{-3}$). In both Europe and North America, the congested HF spectrum is an important limitation to acceptable data transmission since signal-to-noise ratios of about 15 dB or greater (depending on the type of modulation) are required to achieve the above performance. It follows from the lower channel-occupancy levels in the Australian region that propagation effects may be of major importance here in limiting the performance of skywave data transmission systems.

In this paper (presented originally to the Radio Research Board Seminar on Array Beamforming and Steering in Adelaide during March 1981), some relevant characteristics of HF skywave transmissions are reviewed. An Australian experiment to investigate the quality of digital data skywave transmissions is then discussed. The most important error mechanism is associated with deep amplitude fading caused by the interference of multipath components which are of comparable magnitude. The use of adaptive arrays and null-steering arrays is examined as these offer the possibility of reducing the amplitudes of some of the arrival components, thereby reducing the depth of fading and enhancing data quality.

# 2. CHARACTERISTICS OF HF SKYWAVE TRANSMISSIONS

In general, a skywave signal will comprise multiple components which propagate through different regions of the ionosphere and consequently have differing angles-of-arrival at the receiver. Angular spread alone will not cause a degradation in the performance of many types of skywave systems, but multipath signals are characterised by an additional spread in either or both of the following:

(a) Doppler frequency shift caused by ionospheric movements;

(b) Propagation time through the ionosphere.

## 2.1 Time delay and frequency spread

A spread in the Doppler frequency shift gives rise to a resultant signal whose amplitude varies with time, ie amplitude fading. The fading rate is directly dependent on the spread in Doppler frequencies whilst the fading depth depends on the relative magnitudes of the various spectral components. Doppler measurements of multipath components have been made by various workers. Shepherd and Lomax(ref.1 ), for example, have shown that where two or more modes are present, these normally have different Doppler frequencies and that individual modes have components (eg O and X rays) which can often be resolved in the frequency domain.

Time-delay spread is primarily the result of propagation via two or more ionospheric modes. It is almost invariably accompanied by frequency spread but the converse is not necessarily true - ie frequency spread can exist in the absence of significant time-delay spread (Clarke and Tibble, reference 2). Intersymbol interference arises when the spread in time delays of the arrival modes is comparable with the data-frame period (ie the duration of individual data bits). This is a major error source in single-tone modems and led to the development of multi-tone modems. In these, data is carried on several tones, leading to longer data-frame periods. For example, the Kineplex PSK modem(ref.3) transmits 2400 bit/s data over 16 tones with a data-frame period of 13.3 ms.

## 2.2 Angular Dispersion

Relatively few measurements of the angles of arrival of obliquely-propagated multicomponent skywaves have been reported in the literature. Sweeney(ref.4) utilized a 256-element 2.5-km broadside array to observe the structure of skywave signals propagating over a 2600-km path. Daytime studies indicated that single-hop propagation modes typically possess a discrete azimuth and time delay, the system resolution being approximately 1° and 8 μs respectively. Multiple-hop echoes on the other hand are generally spread in both azimuth and time delay.

Rice(ref.5) observed FMCW transmissions over a 900-km path using a 32-element 1.2-km broadside array. Time-delay resolution of 20 μs was available, allowing azimuthal measurements of individual modes. Typically, each mode comprised multiple components which were separated by less than the 20 μs time-delay resolution. The azimuthal separation of these components was not measured but it should be comparable (or less than) the standard deviation which Rice(ref.5) found for the dominant component, viz 1.2° for the 1-hop F2 mode, 0.8° for 1-hop $E_s$ and 0.4° for 1-hop E modes.

Although neither experiment made direct measurements of the azimuths of components of one-hop modes, they suggest an azimuthal spread of about one degree or less. Whilst this result is almost certainly not representative of all conditions, it implies a relatively small azimuthal dispersion for single-hop modes.

Elevation angles of arrival of CW transmissions propagating over an 800-km path were measured by Clarke and Tibble(ref.2) using an eight-element vertical array of 74-m aperture. Oblique ionograms recorded over the same path indicated the corresponding mode structure. The complex amplitudes of signals received in each of the eight aerials (this corresponded to one data frame) were measured at a rate of typically ten frames per second. Both single-frame techniques (called wavefront analysis) and multi-frame methods (based on cross-spectral analysis) for deducing the amplitudes and elevation angles-of-arrival of the multicomponent wavefield were evaluated. Wavefront analysis is the term given to techniques which involve the off-line combination of complex amplitudes in a hypothetical beamforming network (b.f.n.). The parameters of the b.f.n are adjusted to give minimum output, which is equivalent to steering nulls in the reception pattern. On the assumption that the incoming wavefield comprises discrete components arriving from well-defined directions, plus noise, the ensuing nulls in the reception patterns of the b.f.n. should coincide with the arrival angles of the discrete components. Three results of this investigation are relevant here:

(a) Single-frame techniques generally performed poorly, the one exception being occasions when the incoming signal amplitude was relatively steady, indicating one dominant arrival component. When irregular fading was observed (indicating the arrival of three or more components), wavefront analysis gave rise to unrealistic solutions in which the elevation angles and amplitudes of the arrival components varied markedly with time. Regular fading indicates the arrival of two main components which may belong to the same mode or to separate modes (eg E and F). In the former case, wavefront analysis was not able to resolve the components (due to their similar elevations) but in the latter case, resolution was generally possible except in the antiphase case when the phase paths differed by $(2n + 1)\lambda/2$. Here, n is an integer and λ the radiowave length.

(b) Spectral analysis techniques rely on the assumption that the Doppler frequency shifts of multipath components differ, due to the differing propagation paths through the ionosphere. A measure of the success of these methods is that the temporal variations of the calculated arrival angles and amplitudes are generally smooth. The most notable exceptions are when the number of spectral components is greater than about 4 or when multiple $E_s$ components are present. In the latter case, the differential Doppler shift is typically less than 0.02 Hz and quite long time series must be available to ensure resolution of the components.

(c) Spectral analysis techniques showed that individual modes (1 hop $E_s$, 1 hop F and more complex modes) frequently comprise two or more components whose angular separation in the vertical plane is typically in the 2° to 5° range.

2.3 Factors which influence the quality of skywaves carrying digital data

The Kineplex technique for transmitting digital data at up to 2400 bits/s rates (Section 2.1) utilizes a CW tone 605 Hz from the carrier frequency. In an experiment to investigate digital data transmissions over a skywave path between Townsville and Sydney, amplitude and Doppler frequency spread measurements were made on this tone. Oblique ionograms recorded on the same path indicated the mode structure.

The effect of signal fading on the error rate is illustrated in *figure 1(a)*. It is apparent immediately that errors are associated with deep amplitude fades. Moreover, a 15-dB reduction in the transmitter power at 1941 hours appears to have little effect on the overall error rate, indicating that the error mechanism is not, in this case, the result of an inadequate signal-to-noise ratio during a fade. This point is reinforced when the number of errors observed in each fade (normalised by multiplying by the fading period) is plotted against the fading depth (figure 1(b)). A threshold fading depth of 20 dB exists (for both full and reduced transmitter power levels) below which fades tend to be error-free and above which error bursts occur.

Single-moded sporadic-E propagation (at frequencies above the one-hop F-mode maximum observed frequency) is a common feature during the summer months and this resulted in high-quality data transmissions. Reducing the operating frequency so that propagation was multimoded typically caused a degradation in the error rate of typically one or two orders of magnitude. However, on combining all data recorded in the equinoxial and winter months - *via single* (1-*hop* F but not 1-hop $E_s$) or multiple (1- and 2-hop F and $E_s$) modes - data quality was found to be essentially unaffected by the number of propagation modes or the degree of time-delay spread, provided the latter did not exceed about 1 ms(ref.6).

Instrumentation to measure Doppler frequency spread was unavailable for the summer trials, but in the equinoxial and winter months, data quality experienced a steady degradation as the Doppler frequency spread increased.

A detailed discussion of the error mechanism is beyond the scope of this paper, but the following points are believed to be key features:

(a) Errors in the PSK system are associated with the rapid change in phase during amplitude fades. Both the time rate of change of phase and the fading depth increase in a two-component fade as the relative amplitudes of the components approaches unity (assuming a constant fading period).

(b) An increasing Doppler frequency spread results in a greater number of fades per unit time and therefore a higher error probability.

(c) The frequency spectra associated with $E_s$ modes are typically less than 0.1 Hz wide(ref.7), accounting for the low error rate for $E_s$-mode transmissions (typically less than $10^{-4}$). However, the Doppler spread of F-mode transmissions has been observed to vary from less than 0.1 Hz to greater than 1 Hz(ref.1) with corresponding error rates of $10^{-4}$ or less to greater than $10^{-2}$.

(d) Apart from occasions at night and during thunderstorm periods, an inadequate signal-to-noise ratio is not an important source of errors in the Australian region. This may not be the case in North America and Europe.

### 2.4 Summary

Transmission of digital data over HF skywave circuits is best accomplished at the frequency which results in minimum fading depths and Doppler frequency spread. While this can generally be achieved by frequency management, unacceptably high error rates can still occur. Further improvement might be obtained by reducing the number of multipath components collected by the receiving system. Observations to date indicate that multipath components are poorly resolved in azimuth of arrival and, in the case of F-mode transmissions, time delay. The most promising means of resolving multipath components would appear to be in the elevation-angle and Doppler-frequency domains.

## 3. NULL STEERING IN THE VERTICAL PLANE

### 3.1 Non-adaptive techniques

Off-line null-steering networks based on the Cawsey(ref.8) method of wavefront analysis have been evaluated using data recorded in the vertical-array experiment which is outlined in Section 2.2. The signal processing involved in this procedure is shown in figure 2(a) and examples of the ensuing polar patterns appear in figure 2(b). These correspond to a radiowave frequency of 8.06 MHz and involve the combination of aerial outputs from levels 3 and 6 (ie an aerial spacing of 27.6 m). The primary nulls appear at (i) 25.5° (broken-line curve) and (ii) 13.5° elevation (full-line curve).

The time series shown in figure 3(a) is the aerial-2 voltage obtained at a frequency of 8.06 MHz on 22 April 1975, the transmissions having propagated over an 800 km path and involved two modes, viz sporadic-E and F. The aerial-2 output itself corresponds to a null-steering network with a primary null at 90° elevation. Fading depths which range from 5.5 to 27 dB are evident. Spectral analysis of the vertical tower data indicated the reception of two main components at elevations 13.5° and 25.5°. Application of the null-steering networks whose polar patterns are plotted in figure 2(b), resulted in the outputs shown in figure 3(b); (i) corresponds to a null at 25.5° elevation and therefore represents the $E_s$-mode transmission while (ii) corresponds to a 13.5° null, representing the F-mode. The latter now shows only three fading cycles with depths ranging from 7 dB to 23 dB and which is apparently caused by interference between unresolved F-mode components. The increased fading period and the small reduction in the fading depth should give rise to a significant improvement in data quality. The output of network (i) with a null at 25.5° represents a considerably greater enhancement, with the most severe fade now being less than 3 dB deep. It is an excellent example of the high quality of sporadic-E modes.

Further analysis of multimoded transmissions containing sporadic E and higher angle modes should be undertaken to determine whether the above improvement in signal quality is typical of that to be expected in an operational situation. Single-mode transmissions have also been analysed and although a reduction in fading depth of 5 to 10 dB is usually observed there is a need for more refined null-steering networks with sharper nulls than those resulting from the Cawsey theory.

### 3.2 Adaptive techniques

Whereas the non-adaptive method of null steering involves the separate operations of angle measurement (using single or multi-frame methods) and subsequent adjustment of antenna weights, these operations are combined in adaptive arrays. The antenna weights are adjusted automatically to optimise, for example, the output signal-to-noise ratio (SNR). There is a marked similarity between this technique and that of wavefront analysis and the problems encountered in the latter (Section 2.2) may resurface when adaptive techniques are applied to HF skywave data. In particular, their ability to cope with a signal experiencing a deep fade (the result of destructive inteference between multipath components) should be examined.

To date, adaptive techniques have been applied primarily to situations where a wanted signal often with known characteristics arrives from a known azimuth and is accompanied by interfering signals arriving from unknown (but different) arrival directions. Adaptive algorithms for reducing multipath effects in skywave communications might be based on the following schemes:

(a) Maximising the SNR of a pilot tone. Although data quality is not usually limited by an inadequate SNR, maximising this parameter during a deep fade would be achieved by nulling all but the major arrival component. Problems may arise with high SNR or when time-delay spread is evident leading to frequency-selective fading.

(b) Minimising the received power subject to the constraint of a main beam steered in a particular direction. It could find application when an E or $E_s$ mode accompanies higher angle modes. The elevation angle of the former could be calculated with sufficient accuracy, and the main beam formed in this direction. Minimising the output power would be achieved by nulling higher angle modes.

Given the importance which is being attached to the transmission of digital data, there is a definite need to continue the development of adaptive techniques with particular emphasis on suitable algorithms for multipath skywaves.

## 4. CONCLUSION

The interference of multipath signals is the major factor in limiting the quality of digital data skywave transmissions in Australia. The multipath signals often have similar azimuths of arrival and propagation delay but can be most easily resolved in the vertical angle and Doppler frequency domains.

In cases where E and F modes are present together, null steering in the vertical plane can lead to dramatic improvements in signal quality by nulling all but the E mode. Adaptive null steering has potential also and there is a definite need to investigate these techniques further. Any improvement in signal quality should be compared with that obtained by the proven technique of site-diversity reception.

## 5. ACKNOWLEDGEMENTS

The author thanks staff, in particular Mr D.V. Tibble, at the Government Communications Headquarters, England for making available the data used in Section 3.1. The results described in Section 2.3 were obtained in an experimental programme conducted jointly by staff in the Advanced Engineering Laboratory and Electronics Research Laboratory, Salisbury.

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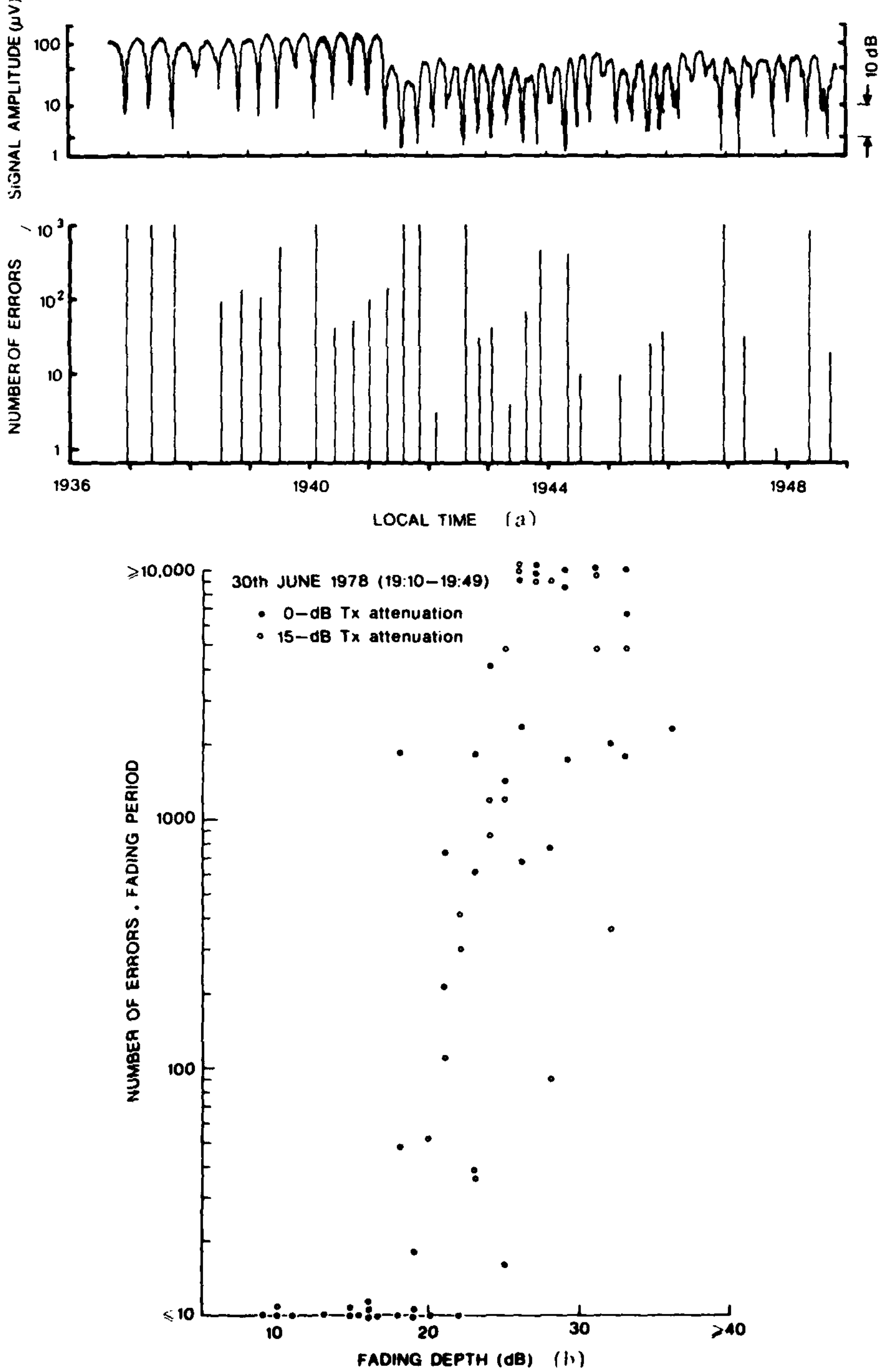



Figure 1. (a) Temporal variations of 605 Hz tone (upper) and errors recorded (lower) on 30 June 1978

(b) Scatter plot of normalised error count and fading depth on 30 June 1978

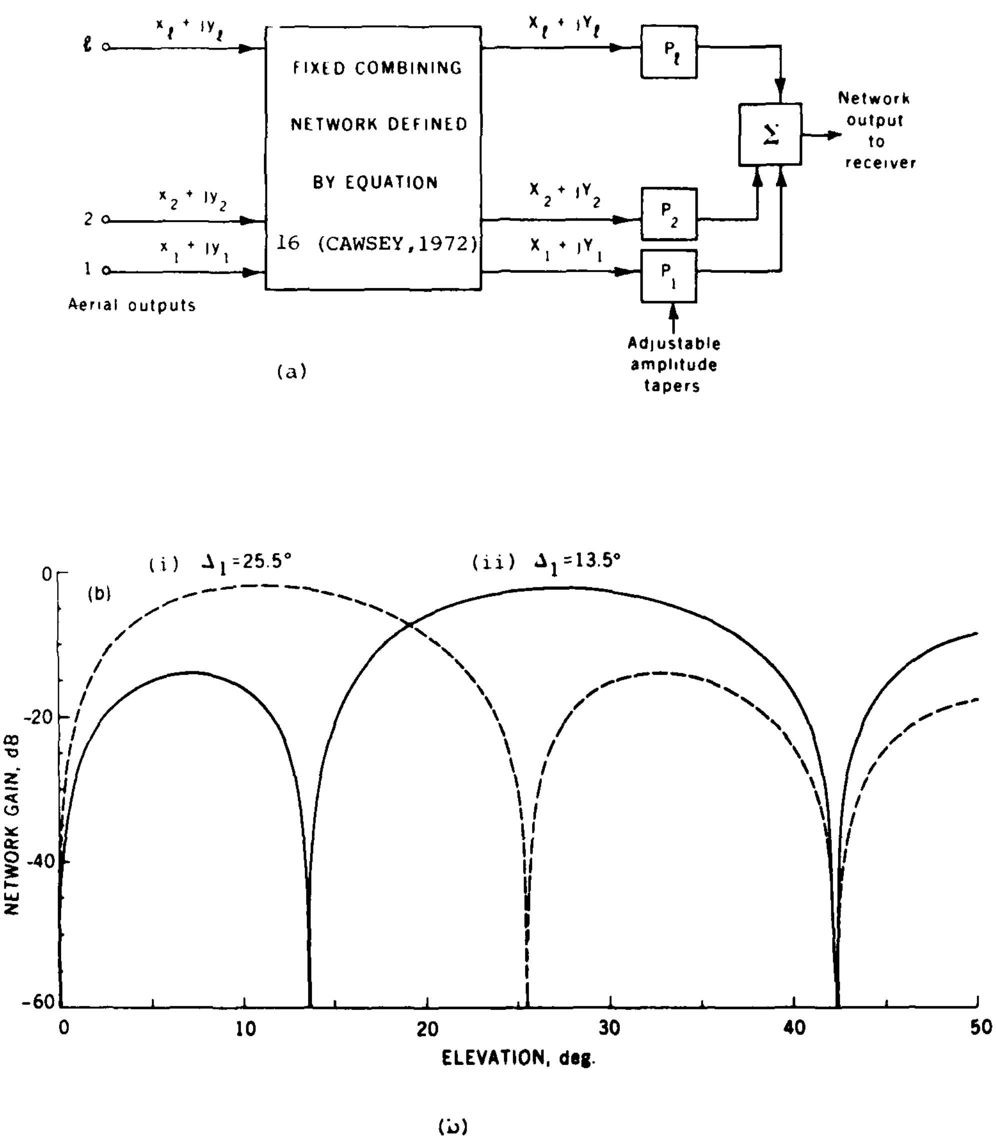
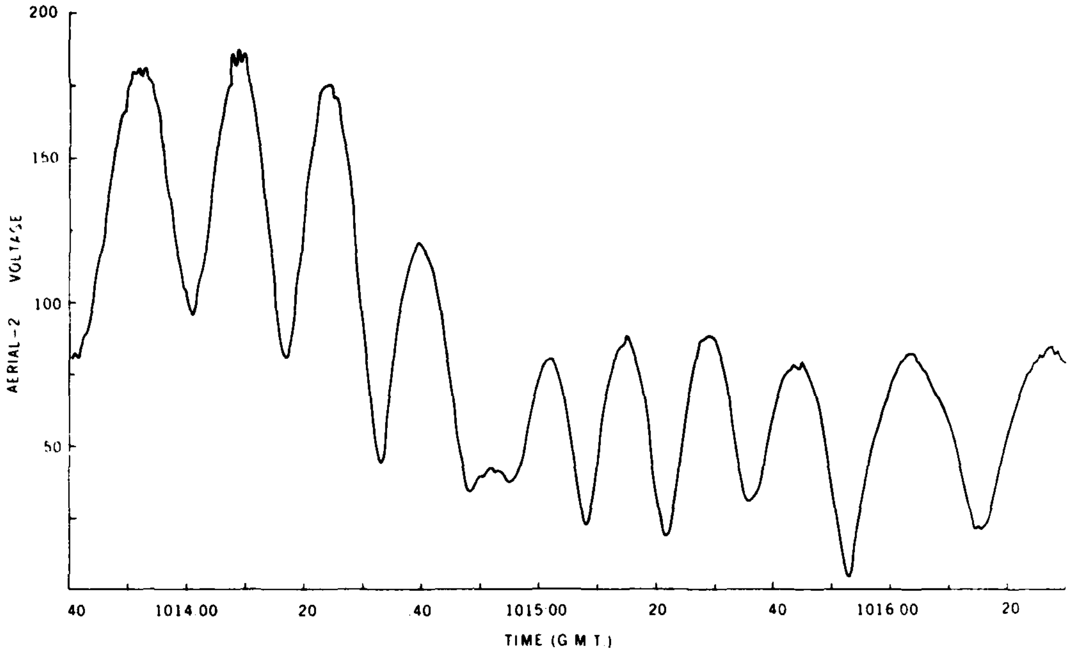



**Figure 2. (a) Null-steering network for vertical array**

**(b) Vertical polar diagram with primary nulls at (i) 25.5° and (ii) 13.5° elevation**

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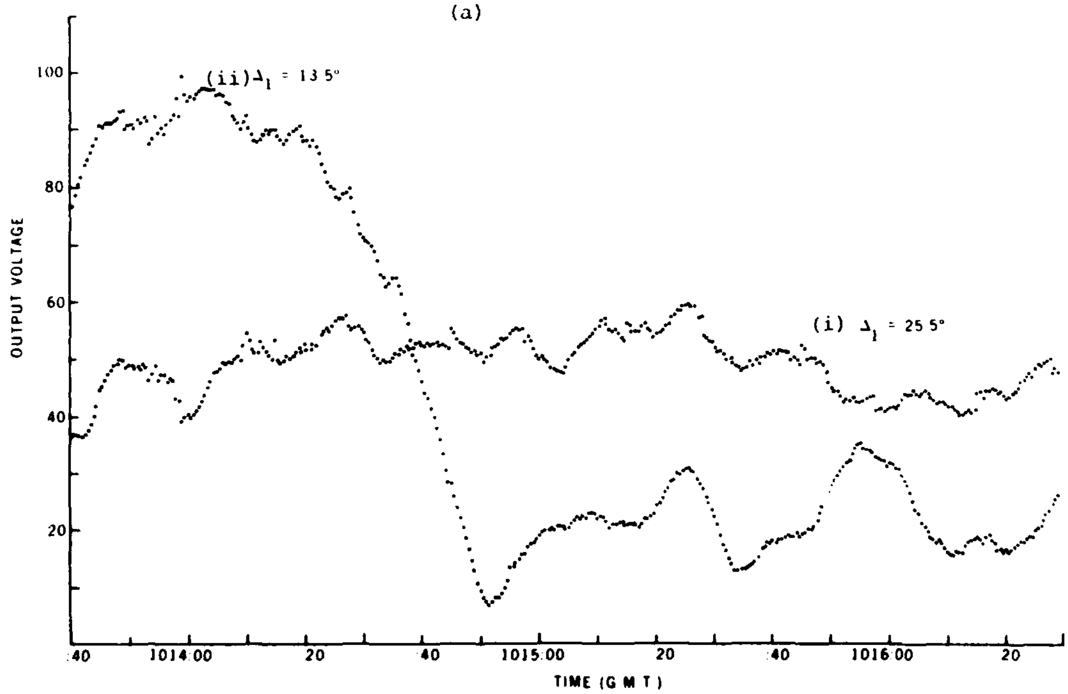


(b)

**Figure 3. (a) Aerial-2 voltage on 22 April 1975**

**(b) Null-steered outputs of networks with primary nulls at (i) 25.5° and (ii) 13.5° elevation**

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