NATIONAL RADIO ASTRONOMY OBSERVATORY

VLA ELECTRONICS MEMORANDUM #122

PHASE SWITCHING IN THE VLA

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This memorandum describes three phase switching schemed for the VLA; the initially envisaged scheme shown in the block diagrams for the system given by S. Weinreb dated March-April 1973, and two alternative schemes with faster switching rates. The alternatives have been devised in response to results of testing of the breadboard electronics system during Nov-Dec. 1973 which indicate that unwanted signals introduced into the IF channels in the modems for the waveguide transmission system can exceed the maximum tolerable levels given in VLA EM #116 (which refer to the initial scheme). Before describing these phase switching schemes, however, it is necessary to outline briefly the advantages of using Walsh Functions as the phase switch control waveforms in a synthesis array like the VLA.

1. Orthogonal Phase-Switching-Functions

In the systems described in the following sections the phase of the incoming radiation at each antenna is modulated to enable the response of the wanted signals to be distinguished from other unwanted responses in the system output. As will be apparent later, the modulating waveforms used at the antennas should be orthogonal, i.e., if $f_m(t)$ & $f_n(t)$ are the modulating waveforms at any pair of antennas,

$$\int_{-\infty}^{\infty} f_m(t)\ f_n(t) = 0 \qquad (1)$$

Sinusoids of different frequencies are orthogonal, so in principle one could use sine waves of frequency Nf_o where N takes values 0 to 26, the fundamental frequency, f_o, being chosen high enough so that the difference frequency between any sine wave pair averages out to as low a value as is desired in the integrating period associated with the response of the instrument.

For practical reasons, however, we prefer to modulate the phase by using 180° phase-reversing switches, so the modulating functions are some form of squarewaves which alternate between two constant values. The term "simple-squarewaves" will be used here to denote squarewaves which change state at regular intervals, like strongly clipped sine waves. Simple squarewaves which are harmonically related like the sine waves described above are not all orthogonal. For example, those of frequency f_o and frequence $3f_o$ are correlated, as can easily be seen by considering that simple squarewaves contain Fourier components that are odd harmonics of the fundamental period. A set of fully orthogonal simple squarewaves can be obtained by using frequencies $2^N f_o$, but the highest frequency (N=26) is $6.7 \times 10^7 f_o$ which is impracticably high.

Walsh functions are a more general form of squarewaves that are orthogonal and that provide the required switching waveforms with a minimum range in the time intervals between switching transitions. For simple descriptions of these functions see Harmuth 1969, or Siemens & Kitai 1969. If f_o is the lowest sequency (other than zero) and if both the cal and sal Walsh functions are used, the maximum required sequency for 27 antennas is $13 f_o$ and the minimum interval between switching transitions at any antenna is $1/32 f_o$. This is satisfactory for slow switching, but since the orthogonality between cal and sal functions of the same frequency is destroyed by relative timing errors (c.p. sine and cosine waves and simple squarewaves in quadrature), for fast switching it is better to use only cal or sal functions all of different sequencies. Then for 27 antennas the highest required sequency is $26 f_o$ and the minimum switching interval is $1/64f_o$. So Walsh functions offer two state switching with a relatively low range of sequencies and thus combine the advantages of both sine waves and simple squarewaves discussed above. Their application to the VLA was recognized by B. G. Clark who points out the following algorithm for generating them. For an array with two antennas the switching functions are given by the matrix

$$\begin{array}{cc} & \text{Time} \longrightarrow \\ \text{Antennas} \downarrow & \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \end{array} \tag{2}$$

where the different columns indicate time intervals and the rows indicate different antennas. The matrix for four antennas is given by replacing each element of (2) by the full matrix;

$$\begin{array}{ccc} & \text{Time} \longrightarrow & \\ \text{Antennas} \downarrow & \begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{pmatrix} & \begin{array}{l} \mathrm{Wal}(0,t) \\ \mathrm{Sal}(2,t) \\ \mathrm{Sal}(1,t) \\ \mathrm{Cal}(1,t) \end{array} \end{array}$$

The process can be repeated for greater numbers of antennas. Note that both sal and cal functions of the same sequency are included.

2. The Initial Phase-Switching Scheme

A block diagram of the initially envisaged scheme is shown in Figure 1. The phase switching at the antennas occurs in the local oscillators that convert the 4.5-5.0 GHz signals to the 1-2 GHz band. Synchronous detection is performed in the computer after signals from the various antenna pairs have been multiplied together.

The phase switching is required for two reasons; (a) to eliminate the effects of DC offsets in the samplers (with an analog system it would eliminate offsets in the multipliers), and (b) to reduce the sensitivity to certain spurious signals. The effect of the offsets in the samplers is shown in VLA E.M. #112, equation A22, where the output of the multipliers is found to contain a term $\Delta_1\Delta_2$ where Δ_1 and Δ_2 are the voltage offsets at the samplers. To eliminate $\Delta_1\Delta_2$ the reference function in the synchronous detection must have zero mean, which requires that the phase switching functions be orthogonal. Walsh functions are therefore used for the switching, and switch transitions take place only during the 1 ms blanking intervals that occur every 50 ms. Timing errors do not then arise and both the cal and sal functions can be used. The phase switching can be performed directly from the computer through the data system, and similarly the synchronous detection can be performed in the computer. To reduce the computing load switch transitions occur only during every sixth blanking interval and the integrated multiplier output is transferred to the computer every 300 ms. The fundamental period of the Walsh functions is 9.6s (32x300ms), i.e., the lowest switching sequency is 0.104 zps.

The effects of spurious CW signals which may be injected into the IF channels is discussed in VLA E.M. #116, which distinguishes three cases. In case (a) the unwanted signals are injected ahead of the phase switching mixers, and after synchronous detection these produce a component at the natural fringe rate because of the fringe-rotation phase changes applied to eliminate the fringe motion relative to the sky, and phase changes that occur in the delay system. In case (b) the signals are injected after the phase switching mixer but before the fringe rotation, and the fringe rate component appears at the output of the multiplier. In case (c) the signals are injected after both the phase switching and fringe rotation and produce at the multiplier output a slower sinusoidal component which results from phase changes in the delay system. In case (a) the spurious response is unaffected by the phase switching, and the unwanted signals simply have to be reduced to tolerable levels. Case (b) is the one of principal interest here since it is the one to which the signals injected in the modems correspond. In the synchronous detection the fringe-frequency component from the multiplier is multiplied by the product of the two phase switching waveforms. Since the latter are Walsh functions their product is also a Walsh function, and its sequency is equal to or greater than the difference in the sequencies of the two original functions*. Now some Walsh functions (those with sequencies which are integral powers of 2) are simple squarewaves and therefore synchronously detect sine waves of the same frequency with high efficiency. Responses of other Walsh functions to sine waves are lower, but generally not by an order of magnitude. So when the natural fringe frequency becomes equal to the sequency of synchronous detection for any antenna pair, a spurious response is to be expected, the magnitude of which depends upon the strengths of the unwanted signals and the rate of change of the fringe frequency as it passes through the dangerous value. VLA E.M. #116 derives a maximum tolerable level for the spurious signals in the IF of -63 dB relative to the IF signals in 50 MHz bandwidth for the case of continuum observations. (In deriving this value the synchronous detection functions were, for simplicity, taken to be simple squarewaves at the fundamental switching sequency, and the maximum tolerable level may therefore be underestimated by a few dB.) Since tests of the modem indicate that this required level

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*If two Walsh functions are multiplied together the sequency of the product cannot be less than the difference in their sequencies, as the following consideration shows. Let J&K be the sequencies of the two Walsh functions where J>K. Suppose that in the second function k of the 2K zero crossings which occur each second coincide with zero crossings in the first function. Since coincident zero crossings cancel out in the product, the number of zero crossings per second in the product is 2J+2K-2k which has a minimu value of 2(J-K).

may not be easily achieved, we now consider reducing the effects of the spurious signals by designing the system so that the sequency of the synchronous detection waveform for any antenna pair is always greater than the natural fringe frequency for the corresponding spacing.

3. A System with Fast Phase Switching

If the synchronous detection sequency exceeds the unwanted fringe frequency by Δf, a frequency Δf together with higher components appears at the output of the synchronous detector. These frequency components average towards zero in the integration of the output, and after a time τ their contribution is reduced by a factor of the order of $(2\tau\Delta f)^{-1}$ which is the reciprocal of the number of half cycles of Δf in the period τ. In deriving the results in VLA EM#116 a figure of 10 min. was used for the integrating period, and thus to reduce the spurious output by a factor of 10^{-3} we require $2\tau\Delta f=10^{3}$ or $\Delta f=0.83$ Hz*. Since the amplitude of the spurious output is proportional to the product of the powers of the unwanted components at the multiplier input, the tolerable level of the unwanted signals is increased by 30 dB.

The maximum fringe frequency for an antenna pair with spacing D wavelengths is $\omega_o D \cos\delta$ where $\omega_o = 7.27\text{x}10^{-5}$ rad. s^{-1} is the angular rotation velocity of the earth and δ is the declination of the baseline. For $\cos\delta=1$ and an observing frequency of 24 GHz the maximum fringe frequency for a 21 km spacing is 122 Hz and for the 36.4 km spacing between the ends of the east and west arms it is 212 Hz. A possible arrangement of switching sequencies which ensures that the sequency difference for any antenna pair always exceeds the fringe frequency at 24 GHz is shown in Figure 2. The fundamental sequency is 20.41 zps which is chosen so that one period falls exactly within each 49 ms receiving interval. The maximum switching sequency is 653 zps at which 1° of phase corresponds to

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*It is assumed that harmonics of the fringe frequency, which might possibly be generated by non linearities in the system, have relative amplitudes not greater than 10^{-3}.

4.25 μs. This is within the expected timing accuracy at an antenna through the data system.

With these high switching rates it is no longer possible to perform synchronous detection in the computer, and the best scheme appears to be that outlined in Figure 3. Since the multipliers are digital there is no need to include them in the phase switching loop, and we simply require a second phase switch following the digital sampler in each IF channel. The digital phase switch effectively reverses the sign of the digital data. The effect of the digital phase switches on both the signals from the antennas and spurious IF signals is equivalent to the synchronous detection in the last system described. Orthogonal switching functions are again required and since it is at the multiplier inputs, after the variable delays, that the orthogonality must be maintained, it is better not to use both cal and sal functions of the same sequency.

Generation of the switching functions at the antennas and at the control building can easily be achieved by storing the required sequence of values for each function in a read-only memory or shift register of 64 bit capacity. These can then be shifted out by pulses at 1.306 kHz or the appropriate submultiple, generated by counting cycles of the standard 5 MHz frequency. A delay equal to the propagation time for the signals down the waveguide must be inserted in the waveform for each switch at the central building. The counters can be reset and shift registers reloaded during each 1 ms blanking interval. Because the sequencies in Figure 2 depend on the antenna locations, and the individual antennas will be interchanged for servicing etc., it would be preferable to use identical hardware for each function generator and to set into it the required sequence of values from the computer.

4. A System with Fringe Rotators at the Antennas

Figure 4 shows a system similar to that in Figure 3 except that fringe-rotation phase shifting is applied to a local oscillator at each antenna. Spurious signals introduced in the modems then fall within case (c) of VLA EM#116 and produce only low frequency variations at the multiplier output, the highest possible frequency being 0.44 Hz. If the phase switching and fringe rotation are applied at the same mixer, spurious signals of case (b) i.e., those which suffer fringe-rotation phase shifting but not phase switching are not like to arise*.

The system with fringe rotators at the antennas allows much lower switching rates to be used than those described in Section 3. To achieve the factor of 10^{-3} reduction in spurious responses the sequency of the product of the phase switching waveforms at any two antennas need not be more than 0.44 + 0.83 = 1.27 zps. The special Walsh function generators are still required in this case, but if we can allow slightly less rejection of the unwanted signals, switching directly from the computer becomes possible. With the computer performing the switching the transitions take place in the blanking intervals which occur every 50 msec, and the highest switching sequency that can be used is therefore 10 zps. Since timing errors are absorbed in the blanking intervals both cal and sal functions can be used and the lowest sequency required is 10/16=0.625 zps. The product of the switching waveforms at any two antennas then has a sequency greater than 0.44 Hz by at least 0.185 zps, and the increase in the tolerable levels of the spurious signals relative to that given in VLA EM#116 for case (b) is at least 23 dB. This would probably be satisfactory, at least for the prototype system, and the switching rate could always be increased by adding the fast Walsh function generators later if this

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*They could only arise if the local oscillator had spurious sidebands with the required combination of phase changes, which appears unlikely. Since the frequency conversion at the mixer is not down to base band, the ∿260 kHz sidebands discussed in Section 1.d. of VLA EM#116 should not cause any problem; this point was overlooked in making the statement on p10 of VLA EM#116 that increased suppression of these sidebands would be required with fringe rotation at the antennas.

proved to be necessary. The synchronous detection must be performed in the digital phase switches immediately following the samplers since the switching rates are six times higher than those in the initially envisaged system in which it was possible to do the synchronous detection in the computer.

A further advantage of performing the fringe-rotation phase shifting at the antennas is that the maximum frequency of the spurious output of the multipliers (0.44 Hz) depends only upon the antenna spacings and the maximum frequency of the IF response, and not upon the frequency of the incoming signals. There would therefore be no need to increase the switching rates if the operating frequency of the array were to be increased above 24 GHz at some future time.

5. Conclusions

It seems quite clear that, at least from the viewpoint of minimizing the spurious responses, the fringe-rotation phase shifting should be performed at the antennas rather than at the central building. Another relevant consideration is that fringe rotation at the antennas is advantageous if digital transmission of the IF signals is required in a spectral line system. On the other hand fringe rotation at the antennas introduces some additional timing requirements there and increases the complexity of the equipment remote from the central building. If the phase switching is done at the same mixer as the fringe rotation it can very easily be implemented by using a phase reversing gate in the digital fringe-rotation generator.

The initially envisaged block diagram of the system should be modified by moving the fringe rotation to the antennas. If this proves to be impracticable provision should be made to incorporate the fast switching scheme outlined in Section 3.

References:

Harmuth, H. F., 1969, IEEE Spectrum, 6, 82, (Nov. 1969).

Siemens, K.H., and Kitai, R., 1969, IEEE Trans. Instr. and Meas., IM-18,316.

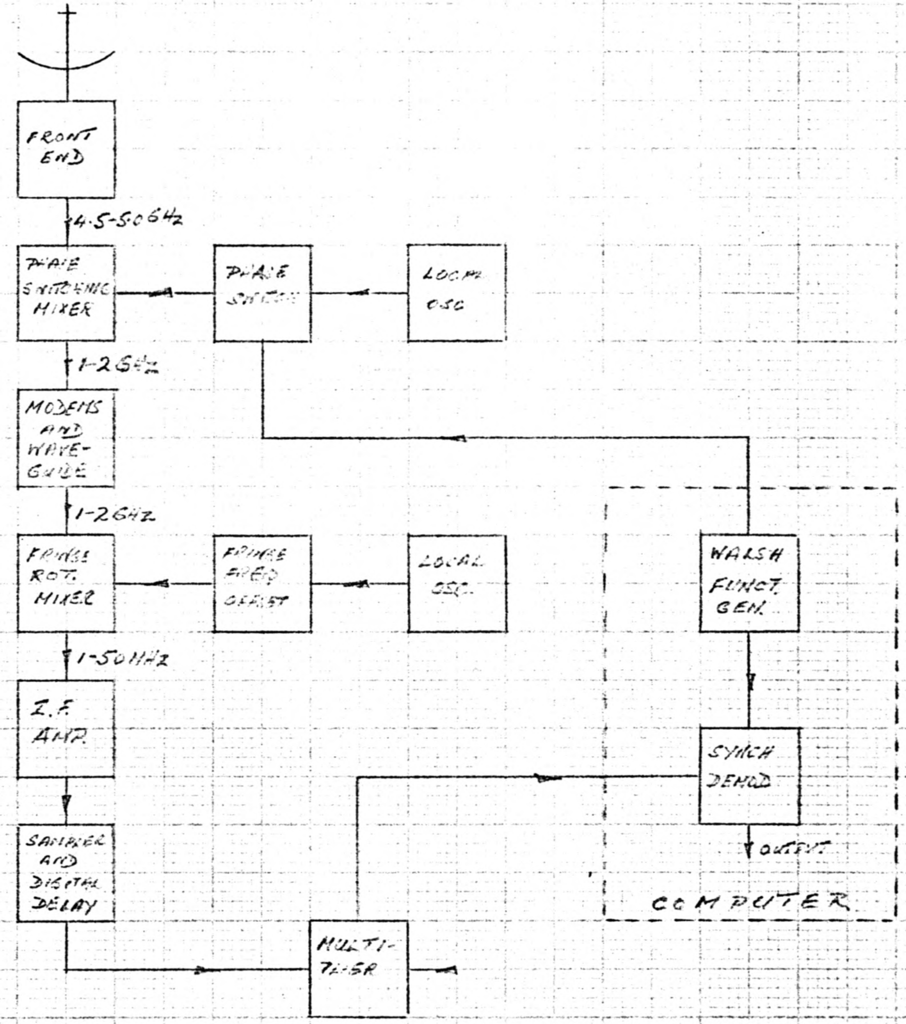

Fig 1 The system as initially envisaged.

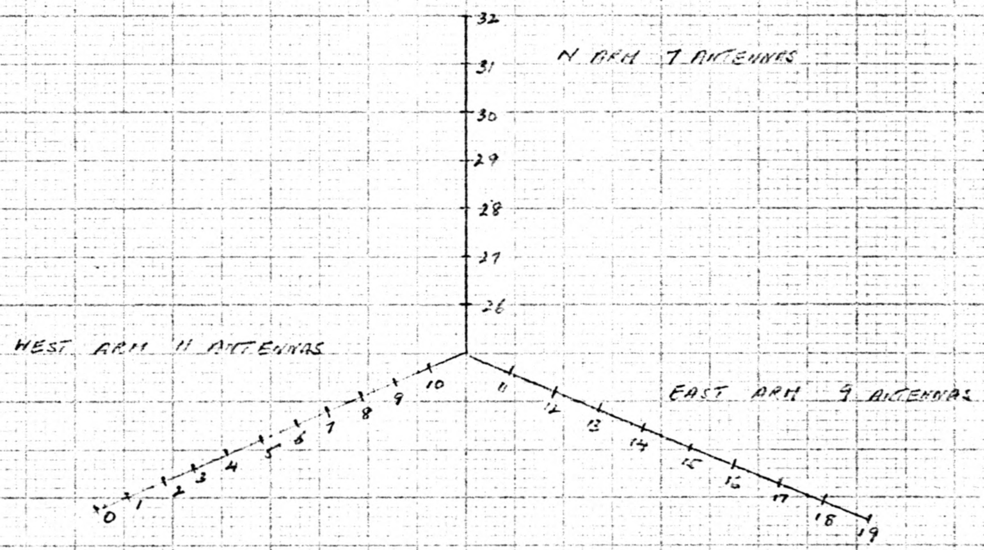

Fig 2. Possible configuration of switching sequencies. Numbers indicate multiples of a fundamental sequency of 20.41 zps.

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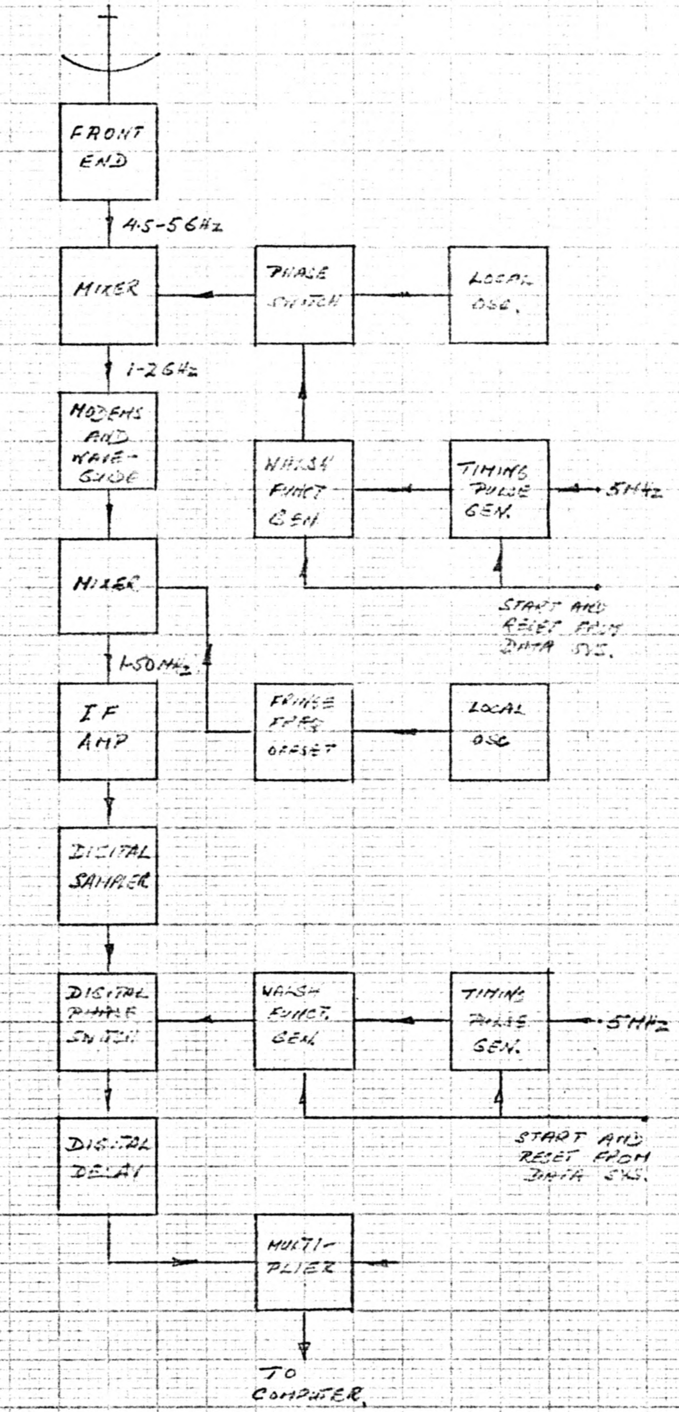

Fig 3. System with Fast Phase Switching.

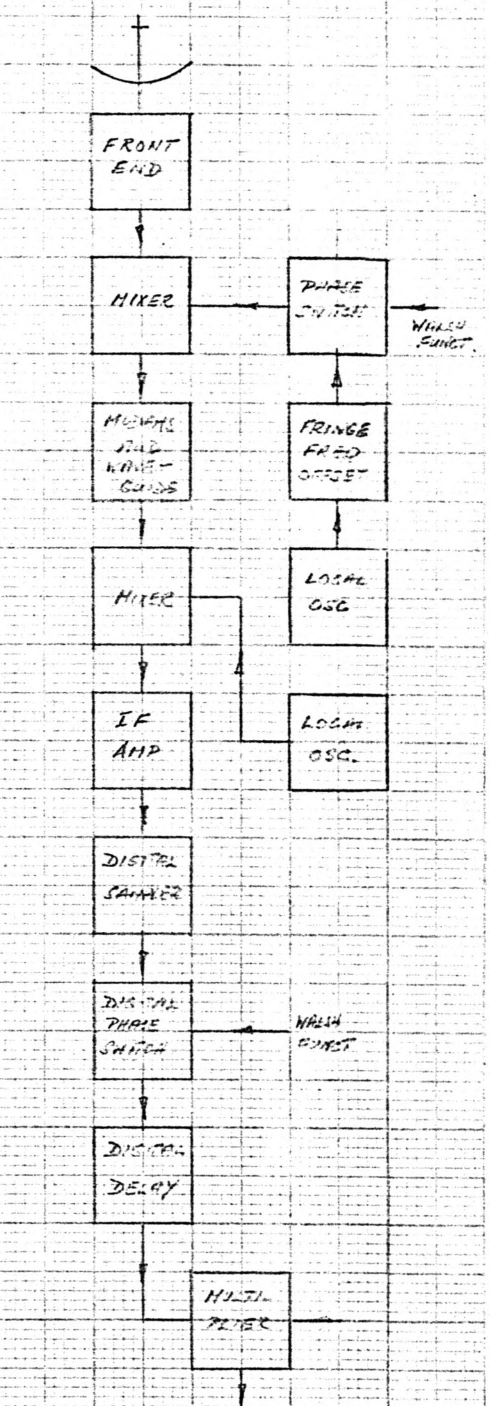

Fig 4. System With Fringe Rotators Located at Antennas.

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