A microwave instantaneous frequency indicator

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RADIO AND ELECTRICAL ENGINEERING DIVISION

A MICROWAVE INSTANTANEOUS FREQUENCY INDICATOR

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OTTAWA

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ABSTRACT

A progress report is presented on a microwave instantaneous frequency indicator based on the principle of instantaneous amplitude comparison of the output of band-pass filters with overlapping pass bands. The use of a permanent magnet focussed traveling-wave tube to restore the losses involved in power division and padding is discussed. The direct-reading and the calibrated accuracy, and the overall sensitivity are studied and experimental results given.

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- F.V. Cairns -

INTRODUCTION

The frequency of a microwave transmission can be determined by a scanning receiver such as the APR-9. When reception is not continuous, because the source of the transmission has a scanning antenna, a time coincidence between receiver tuning and illumination of the receiving antenna is required before there is any indication, and there is usually a waiting period before frequency is determined. When the receiving antenna is also directional, a further coincidence is required and the waiting period can be long. When the transmission whose frequency is to be determined is of short duration, or when some action, such as immediate switching-on of a jammer on that frequency, is required, a waiting period is not acceptable. For these situations instantaneous frequency indicators are required, that is, frequency indicators with omnidirectional antennas and receivers which receive all signals within their frequency band and sort them as to frequency with a set of filters.

One type of instantaneous frequency indicator, by using the principle of instantaneous amplitude comparison, achieves resolution which is an order of magnitude greater than that of the filters. This type of frequency indicator is closely related to the instantaneous amplitude comparison direction finder which indicates the approximate bearing of pulsed signals within a wide band of frequencies. Fig. 1(a) is a block diagram of a 4-channel direction finder of this type. In the case of the direction finder it was found that a marked decrease in error is achieved by using the system shown in Fig. 1(b) where there are eight antennas and a four-channel video amplifier and display system. The detected outputs of the eight antennas are resolved and combined in a resistive network to provide four inputs to the remainder of the system. The same principle has been used in the case of the instantaneous frequency indicator shown in Fig. 2. In this case, the eight antennas oriented at angles of 45° in azimuth are replaced by eight filters with the centers of their pass bands spaced 250 mc/s apart in frequency.

There is a loss in sensitivity in the instantaneous frequency indicator compared with the direction finder because of power division and also because of padding between the components. This loss can be restored by a broad-band low power TWT amplifier. An incidental but important advantage that arises from the use of the TWT amplifier is the protection it affords against crystal burnout. Before permanent magnet focussed TWT amplifiers were available, the penalty in extra weight and power consumption was severe and the scheme did not look attractive. In late 1957 permanent magnet focussed TWT amplifiers became available and it seemed that this approach to instantaneous frequency determination should be investigated.

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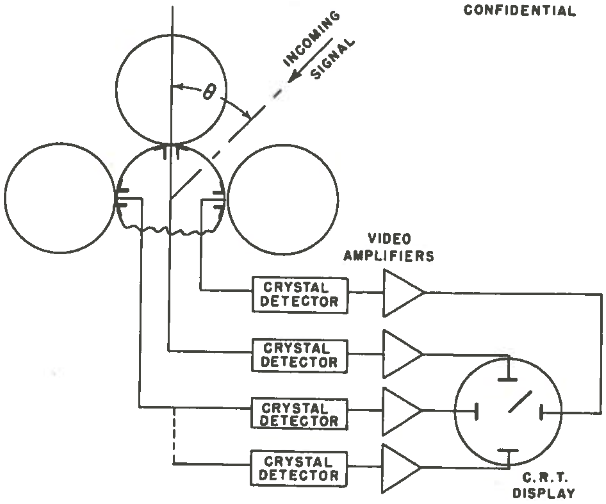


FIG. 1(a) 4-CHANNEL INSTANTANEOUS DIRECTION FINDER

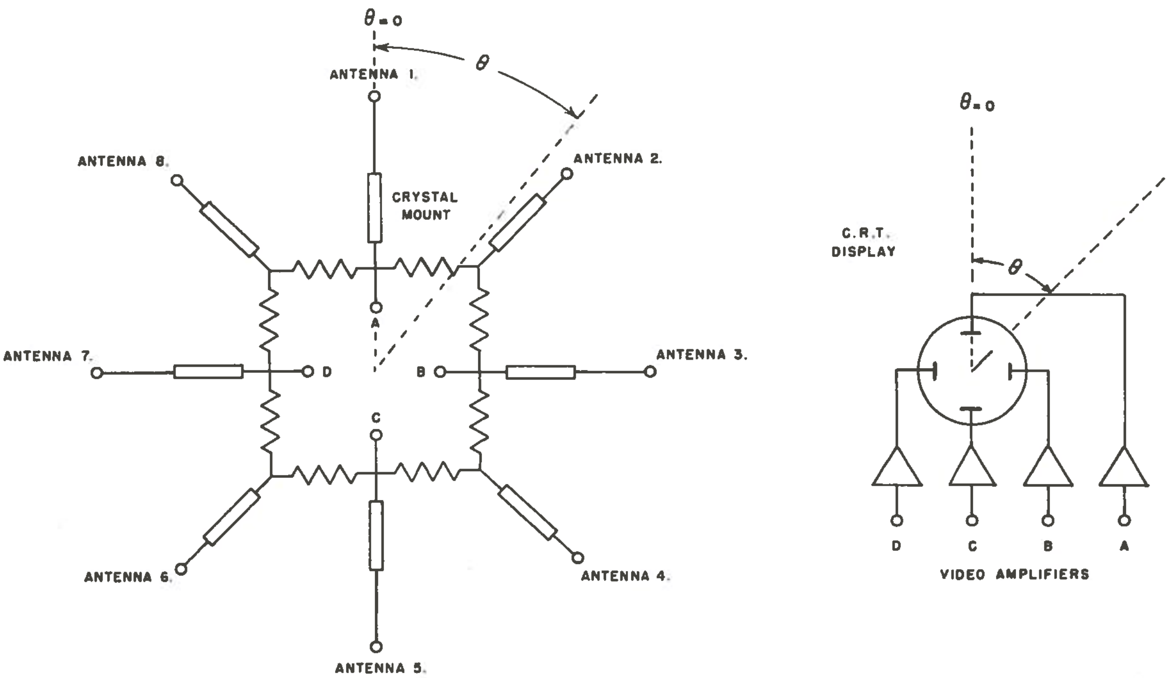


FIG. 1(b) 8-ANTENNA INSTANTANEOUS DIRECTION FINDER

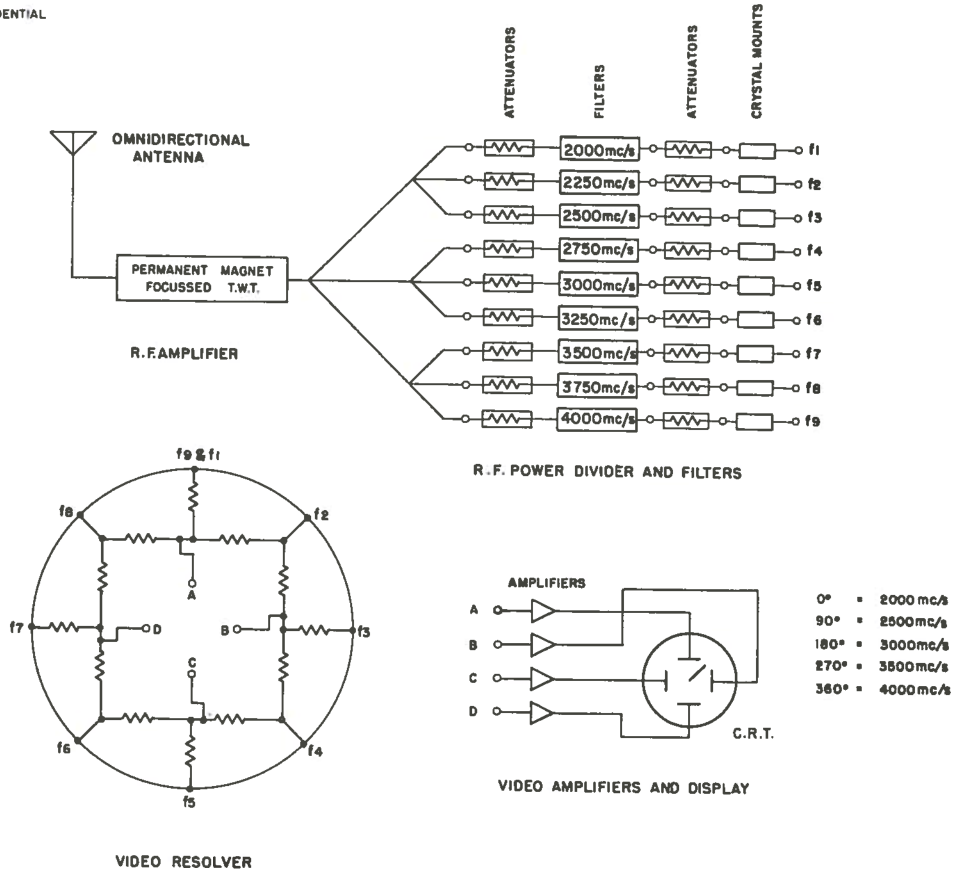


FIGURE 2—BLOCK DIAGRAM OF INSTANTANEOUS FREQUENCY INDICATOR

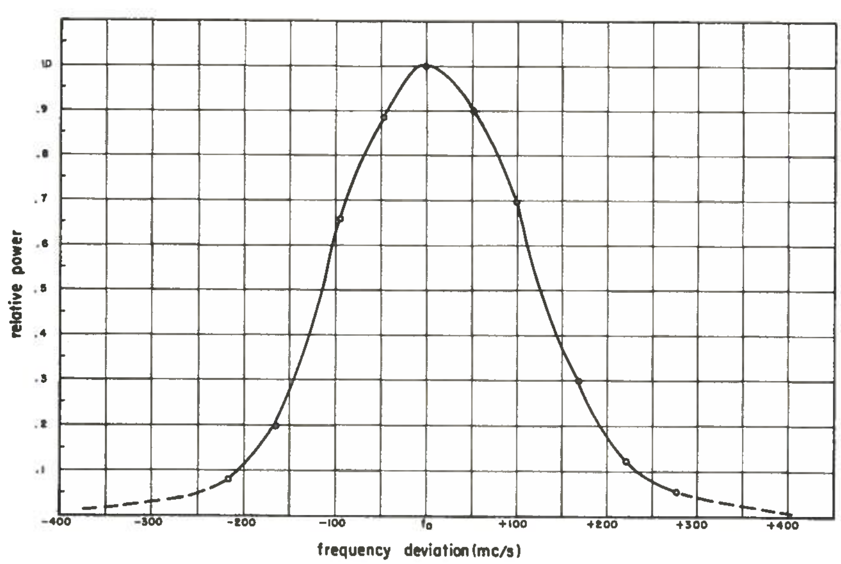


FIG.3 MEASURED FILTER CHARACTERISTIC (250 mc/s FILTER)

PRELIMINARY CONSIDERATIONS

The most convenient frequency band on which to begin the experimental investigation appeared to be S-band. Permanent magnet focussed TWT amplifiers are available for the frequency range 2000 to 4000 mc/s. It seemed likely that the design and construction of filters and other radio-frequency components would be easier in this frequency range.

Experience with a four-antenna instantaneous direction finder (UPD-501) indicated that a maximum bearing error of less than 10° over an octave of frequency is difficult to achieve. An error of 10° in 360° coverage of angle is equivalent to an error of 55 mc/s in a frequency indicator of similar performance covering 2000 to 4000 mc/s. To achieve this, filters with a pass band of about 500 mc/s would be required, and it was thought that this might be difficult. Also, the problem of dividing the incoming signal equally between a number of filters and detector channels is encountered in the frequency indicator, but not in the direction finder. This tends to make the errors of the frequency indicator greater than those of the direction finder. Consideration of these factors led to the decision to study 8- and 12-filter frequency indicators, beginning with the simpler 8-filter system.

A uniform relation between the frequency of the signal and the angular position of the radial line on the cathode-ray tube, and hence a uniform scale, was thought to be an advantage. This required that the response of the filters should be the same for a given frequency deviation rather than a given percentage deviation from the center frequency. This was a minor disadvantage since it meant that each filter had a slightly different percentage frequency bandpass and hence had a slightly different design. As a preliminary step a set of filters with 250 mc/s pass band, and center frequencies 250 mc/s apart were designed, and built in stripline.

It has been assumed so far in the discussion that the incoming signal could be supplied to the appropriate channel only by dividing it equally between the total number of filters. This is not strictly true, as a combination of circulators and filters, or a set of directional filters [1] will deliver the signal to the appropriate channel without the loss involved in power division. So far as is known, broadband microwave circulators are not available, and suitable directional filters were thought to require more development than the more conventional power divider and filters.

A 9-way stripline power divider was therefore constructed. The 9-way split is required because the system referred to as an 8-filter system (analogous to an 8-antenna direction finder) actually has 9 filters. This follows from the asymmetrical or progressive character of the frequency measurement as contrasted with the symmetrical or periodic nature of bearing measurement. In the scheme used in our work the indications for 2000 mc/s and 4000 mc/s are the same (0° on the bearing display) and the 2000 mc/s and 4000 mc/s filters are fed in parallel to the resolver input, corresponding to a single antenna at 0°. A little thought will show that actually two more filters centered on frequencies of 1750 mc/s and 4250 mc/s would add to the accuracy of the system at the two extremes of the nominal frequency range. It seems to be better to refer to this system as an 8-filter system, even though there are more than 8 filters involved, since there are 8 inputs to the resolver and it has many of the characteristics of an 8-antenna direction finder.

The four video amplifiers and the indicator unit of the AN/UPD-501 were used for the instantaneous frequency indicator primarily because they were immediately available in the laboratory. However, the possibility of using the same equipment for direction finding and frequency indicating is also a consideration.

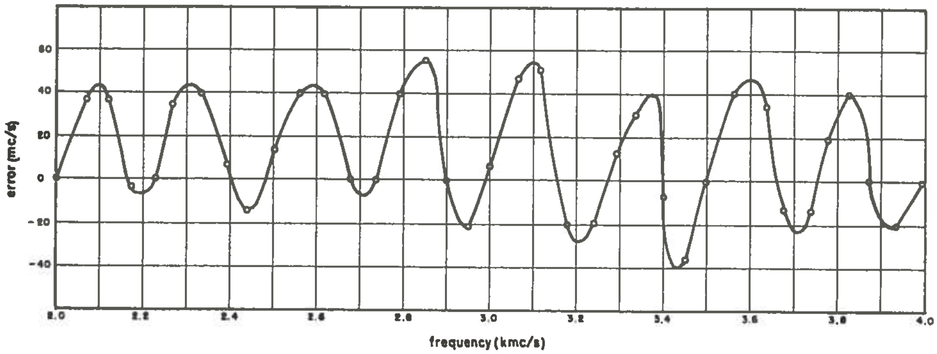
COMPUTED RESULTS

In the first stages of development of the frequency indicator it was thought that an analog computer developed in this laboratory would be useful [2]. This computer is a light analog of the radio-frequency portion of an instantaneous direction finder or other instantaneous amplitude comparison device. The essentials are a pulsed light source and photomultiplier tube receivers. Radiation patterns of direction finder antennas or characteristics of frequency indicator filters are cardboard cutouts. The outputs of the photomultiplier tubes are pulses, which are fed directly into a resolver and thence to the amplifier and display of the AN/UPD-501.

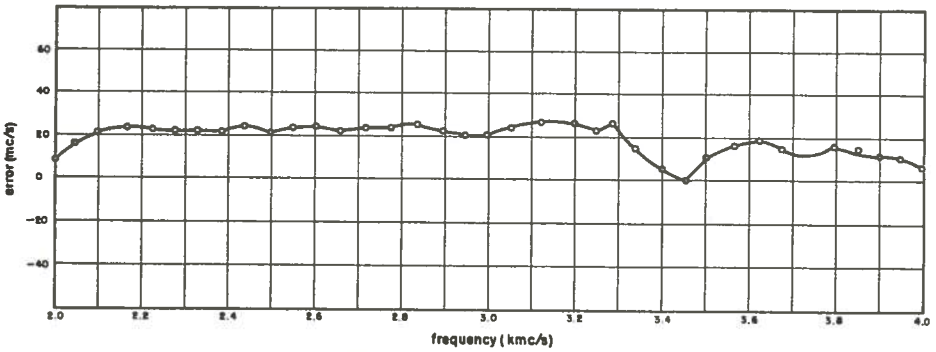
The band-pass characteristic of one of the set of filters was measured and plotted, slightly smoothed, as relative power against frequency deviation (see Fig. 3). Relative power is used as the ordinate rather than the more conventional decibel because the output of each crystal mount is proportional to the incident power, and hence this plot gives a more appropriate indication of the amplitude of the output of the filters.

This characteristic was used in the analog computer to give the error curve shown in Fig. 4. The error shown in this curve is the error that would be found in a frequency indicator with 9 filters with response curves exactly like that in Fig. 3 centered on frequencies 250 mc/s apart and with power division and sensitivity in the 9 channels equal within $\pm\frac{1}{2}$ db. The usual errors of the video amplifiers and display are, however, included in the curve. It can readily be deduced that the large 8-cycle component of error is present because the filter band-pass curve has the wrong shape. The bias in favour of positive error is due to the asymmetrical filter characteristic.

The error is larger than desired. Further, since the computer idealizes the radio-frequency part of the device, the errors in a frequency indicator would likely be larger than those shown.

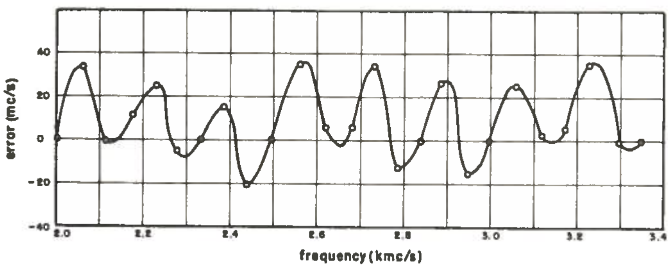


(a) FILTER BANDWIDTH = 250 mc/s

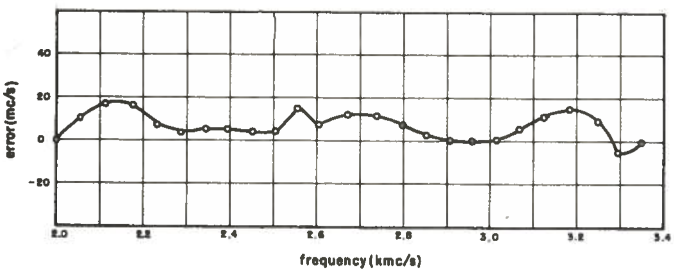


(b) FILTER BANDWIDTH = 375 mc/s

FIG. 4 COMPUTED ERROR CURVES OF 8-FILTER FREQUENCY INDICATOR



(a) FILTER BANDWIDTH = 166 $\frac{2}{3}$ mc/s



(b) FILTER BANDWIDTH = 250 mc/s

FIG. 5 COMPUTED ERROR OF 12-FILTER FREQUENCY INDICATOR

The error due to the shape of the filter characteristic can be eliminated by altering the shape of the band-pass characteristic without increasing the width to the half-power points. However, this is a relatively difficult design problem and is not necessary. The curve of Fig. 4(b) shows the effect of increasing the filter bandpass to 375 mc/s. This computation was done by re-plotting the curve of Fig. 3 on a larger scale (i.e., with the half-power points 375 mc/s apart) and using this curve in the analog computer.

The 8-cycle component of error is small for this filter. If a set of filters with this bandwidth could be made, and if the sensitivities in the various channels could be maintained within $\pm\frac{1}{2}$ db, the error in frequency indication would be less than 20 mc/s. If the asymmetry of the filter response could be eliminated, the minimum error would be less than $\pm$ 10 mc/s. Since it was not known whether the required precision in the radio-frequency circuitry could be achieved analog computations on a 12-filter system were made. The curves shown in Fig. 5 are for filter bandwidths of 166 and 250 mc/s. They are scaled by 2/3 from the widths for 8-filter systems. Only 2/3 of the frequency range is shown because of a limitation of the computer. These curves show that a filter bandwidth of 250 mc/s is adequate for a 12-filter system when the sensitivities in the channels are equal, and also indicate that when the channel sensitivities are equal there is not much advantage in using 12 channels to improve the accuracy.

In Fig. 6 the effect of an inoperative channel in 8- and 12-filter systems is shown, and in Fig. 7 the effect of a particular set of variations of 3 db in the sensitivities of the channels is shown. The 12-filter system shows distinctly less error when the radio-frequency circuitry is not ideal. Care must be exercised in drawing conclusions from a limited number of computations. However, many other similar computations not reproduced in this report tend to confirm the conclusion drawn, although they do not prove it rigorously.

It would have been interesting also to determine the effect of differences in the shapes of the response curves of the filters but the analog cannot perform this computation.

The main conclusion drawn from the analog computations is that the exact shape of the filter response is not important if the pass band is approximately 375 mc/s or more for an 8-filter system, and 250 mc/s or more for a 12-filter system. This is investigated in more detail in Appendix A. Since only filters with pass bands of 250 mc/s had been constructed, it was decided to make a set with wider pass bands. Filters with a pass band of 375 mc/s were found difficult to construct using simple techniques. The maximum that was readily available was 350 mc/s, as shown in Fig. 8. The number of filters required to achieve an accuracy of $\pm$ 20 mc/s will depend on the uniformity of the performance of the radio-frequency circuits. This can best be determined experimentally. The 8-filter system seems to be a reasonable initial choice since it is desirable to avoid the complexity and the additional

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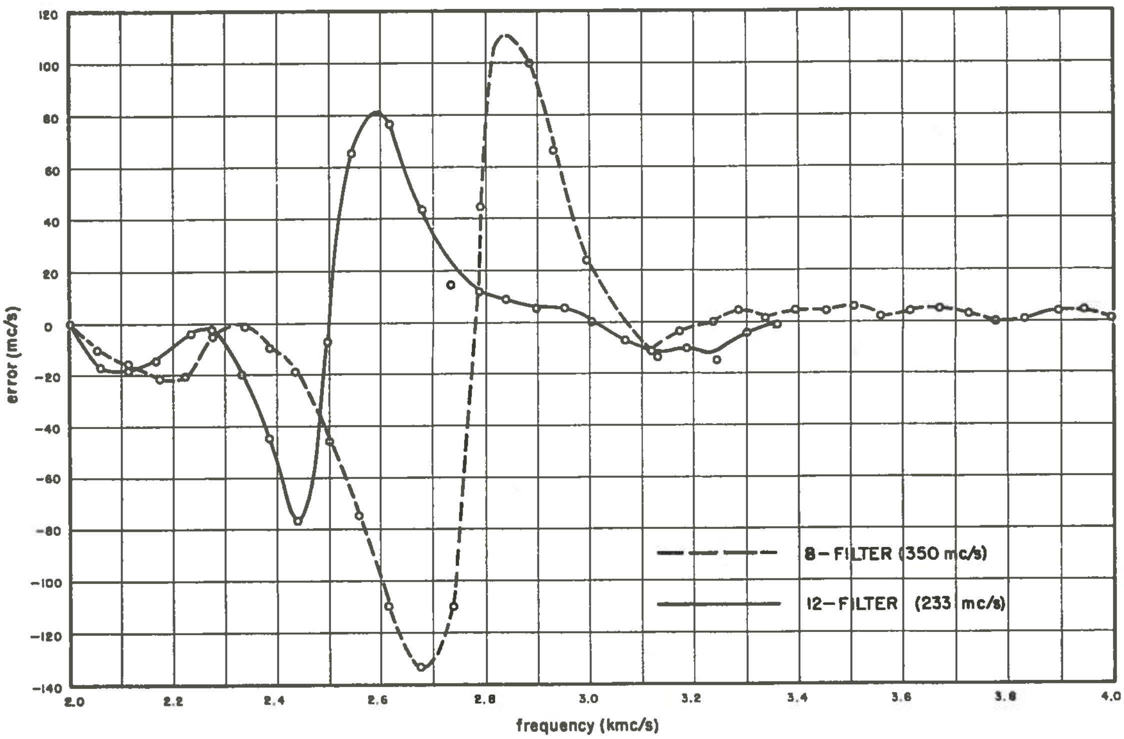


FIG. 6 COMPUTED ERROR OF 8- and 12- FILTER FREQUENCY INDICATOR WITH ONE CHANNEL NOT FUNCTIONING

CHANNEL	1	2	3	4	5	6	7	8	9	10	11	12
RELATIVE SENSITIVITY db	0	-2	-1	-3	-3	-3	-1	0	0	-2	-3	0

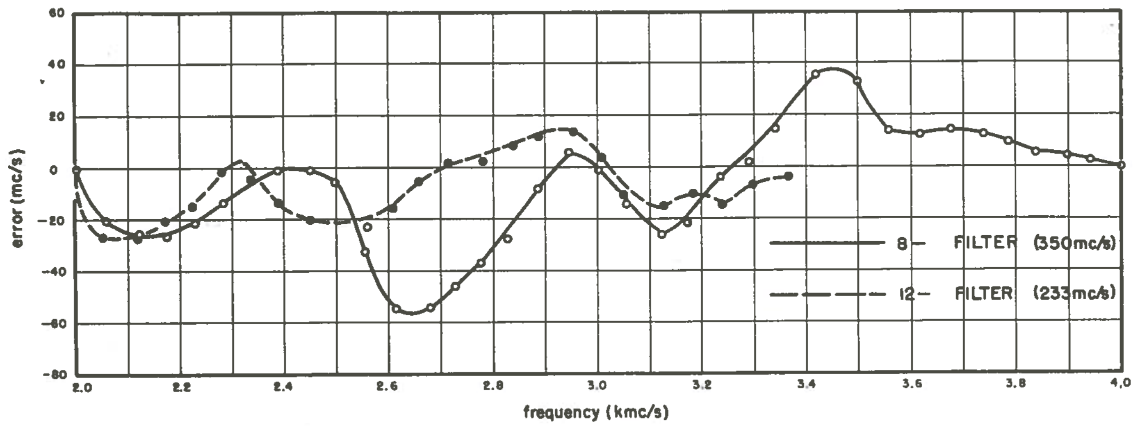


FIG. 7 COMPUTED ERROR OF 8- and 12- FILTER FREQUENCY INDICATOR WITH 3db VARIATIONS IN THE SENSITIVITY OF CHANNELS

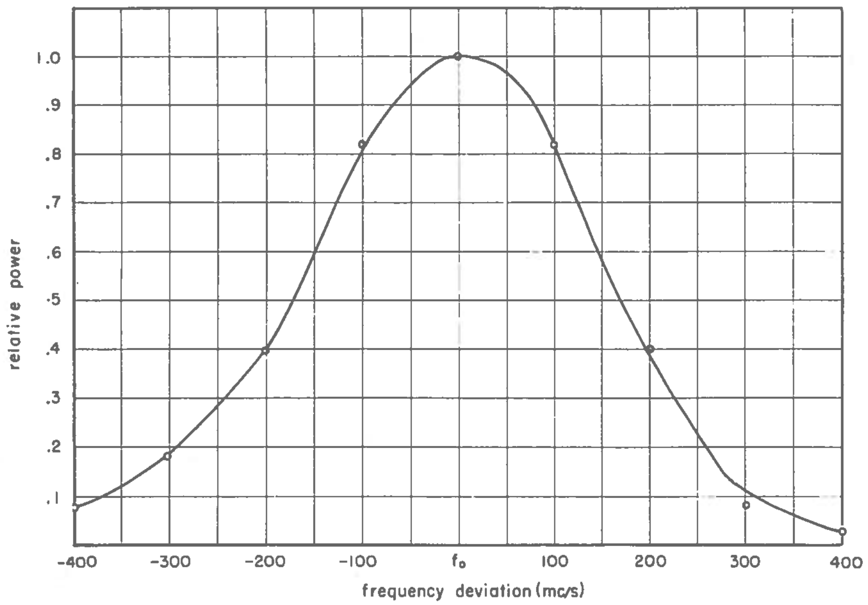


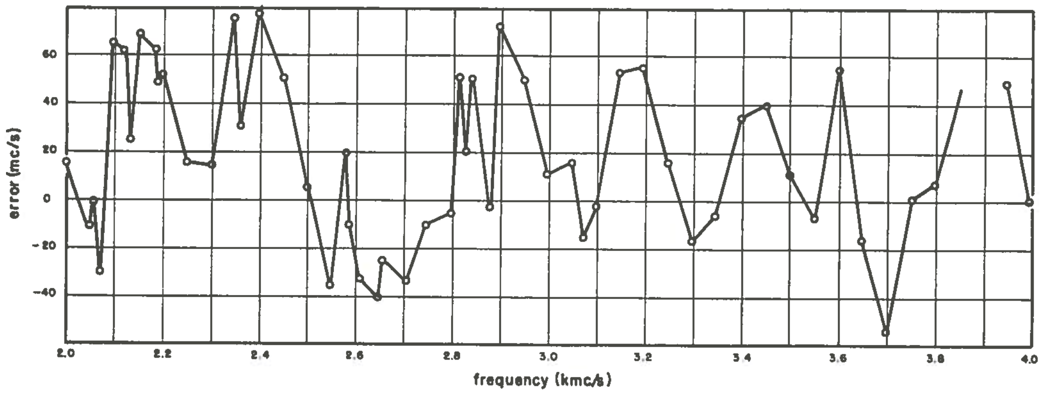
FIG. 8 MEASURED FILTER CHARACTERISTIC: 350mc/s FILTER

loss in power splitting for the 12-filter system unless there are definite advantages.

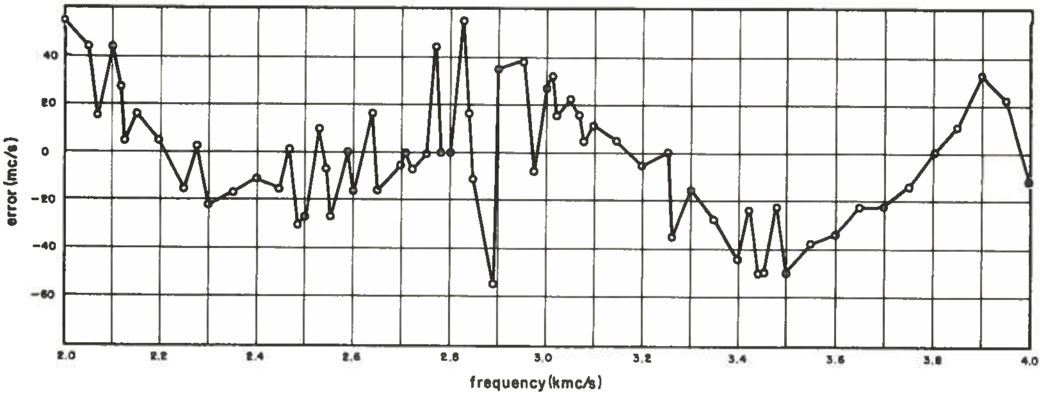
ACCURACY OF FREQUENCY INDICATION

The first 8-filter frequency indicator assembled consisted of a TWT amplifier, a 9-way power divider, 9 stripline filters, an 8 to 4-channel resolving network and an AN/UPD-501 amplifier and indicator unit, as shown in the block diagram of Fig. 2. Some experimenting was done to determine the amount of padding required to obtain an accurate power split and to terminate the filters properly. Fig. 9(a) shows the error curve of 250 mc/s filters with approximately 10 db padding between the power divider and filters and 5 db between the filters and crystal mounts. Unfortunately, because a large enough number of fixed attenuators was not available at the time, attenuation could be achieved only by using lossy coaxial cable. The attenuation of this cable varies considerably as the frequency is changed from 2000 mc/s to 4000 mc/s and an undesired variation in the performance was introduced. The errors, however, are large and do not follow the 8-cycle pattern of the computed error curve.

Fig. 9(b) is an error curve of a frequency indicator with filters with a 350 mc/s pass band. The 8-cycle component of error appears to be low, as computed, but there are still large and erratic errors. These were found to be due to the frequency sensitivity of the power divider. The 2-cycle component of error was found to be due to non-uniformities in the filters and differences in the sensitivities of the crystal diodes.

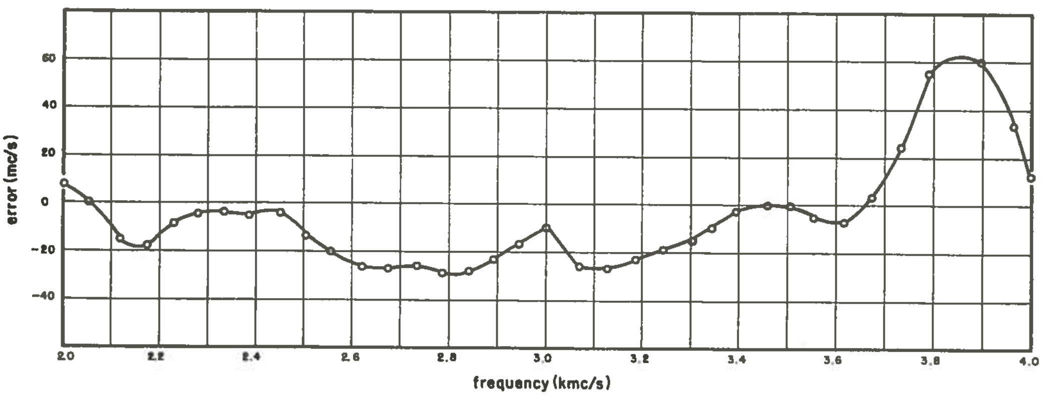


(a) FILTER BANDWIDTH = 250mc/s



(b) FILTER BANDWIDTH = 350 mc/s

FIG. 9 MEASURED ERROR OF 8-FILTER FREQUENCY INDICATOR



FILTER BANDWIDTH = 350mc/s

FIG. 10 COMPUTED ERROR OF 8-FILTER FREQUENCY INDICATOR
WITH PROGRESSIVE ½ db CHANGE IN SENSITIVITY

The rapid change of error with small frequency change is undesirable because it makes the use of either a calibration curve or a direct calibration difficult. It was thought that cascaded directional couplers might be used instead of a power divider to overcome this difficulty. Simple calculations indicated that the losses would be about the same.

The effective couplings for lossless 20 db, 15 db, 13 db, and 10 db directional couplers in an 8-filter system are shown in Table 1. For 10 db coupling, the loss for the last filter is almost 4 db and the reduction of power incident on successive filters is 0.45 db. To determine how serious this might be an error curve for a $\frac{1}{2}$ db decrease in sensitivity in successive filters was computed on the analog computer and is shown in Fig. 10. The portion of the curve from 3750 mc/s to 4000 mc/s is not significant because the computer used the same sensitivity for 2000 mc/s and 4000 mc/s and hence computed on the basis of a 4 db change instead of $\frac{1}{2}$ db change for this portion of the curve. The effect of $\frac{1}{2}$ db progressive change is too large if direct-reading error of less than ± 20 mc/s is desired. However, with a calibration curve or a direct calibration it would not be serious. It is likely that decoupling of 10 db or 13 db would be most suitable.

TABLE 1

EFFECTIVE COUPLINGS OF CASCADED DIRECTIONAL COUPLERS

IN 8-FILTER FREQUENCY INDICATOR

Nominal Coupling	10 db	13 db	15 db	20 db
C_1	10.0	13.0	15.0	20.0
C_2	9.6	12.7	14.9	19.9
C_3	9.1	12.6	14.8	19.9
C_4	8.7	12.4	14.6	19.8
C_5	8.2	12.2	14.5	19.8
C_6	7.8	12.0	14.4	19.7
C_7	7.3	11.8	14.2	19.7
C_8	6.9	11.6	14.1	19.6
C_9	6.4	11.4	13.9	19.6

In the experimental work 20 db decoupling was a necessity as only 20 db directional couplers were available. The loss in this case compares favourably with the 9 db loss in power division and 10 db padding of the previous method and it is probable that this loss can be reduced by about 6 db by coupling more closely.

The error curve obtained with 20 db directional couplers for power division is shown in Fig. 11. This represents the accuracy obtainable with care in the laboratory with commercial attenuators and directional couplers, with selected crystals, and with stripline filters made by the photo-etching process in the laboratory. The error to be expected from apparatus in the field would probably be greater than this.

As this error is larger than desired, two further experiments were carried out. First, a 12-filter system was assembled, and second, a method of direct calibration was tried. The measured error curve of the 12-filter frequency indicator is given in Fig. 12. It can be seen that the error is not reduced to the extent that the computations indicated. Since the data for the 8-filter and 12-filter curves were measured under similar conditions using the same filters and the same crystal diodes where possible, the discrepancy appears to be due to differences between the individual filters. It has been tentatively concluded that unless precisely constructed filters and precision radio-frequency components are used, little is gained by using 12 instead of 8 filters.

An alternative to accurate direct reading of frequency would be a moderately accurate frequency indication with direct calibration by overlaying a signal of known frequency on the unknown signal. A buzzer radio-frequency power source and a calibrated filter cavity would be a method of accomplishing this with inexpensive and light equipment. Some preliminary experimental work on direct calibration has been done in the frequency range 3000 to 4000 mc/s with an AN/UPM-46 test set. The AN/UPM-46 set consists of a buzzer, a cavity, and radio-frequency attenuator. These measurements show that direct calibration is feasible with this type of equipment. The accuracy of the direct calibration is difficult to determine precisely because the cavity of the AN/UPM-46 set is not accurately calibrated and readings must be checked against a second cavity which is accurately calibrated. It does appear, however, that an accuracy of ±10 mc/s or better could be achieved.

SENSITIVITY

The losses in the frequency-indicating system, as compared with those of the direction finder are:

1) 20 db decoupling in the power division. This loss can probably be reduced to 15 db or less, but no measurements have been made to establish this.

2) 6 db to 9 db padding between filters and crystal mounts. Sensitivity measurements have been made with 9 db padding, although error measurements show that the error is not appreciably reduced by increasing the padding from 6 db to 9 db.

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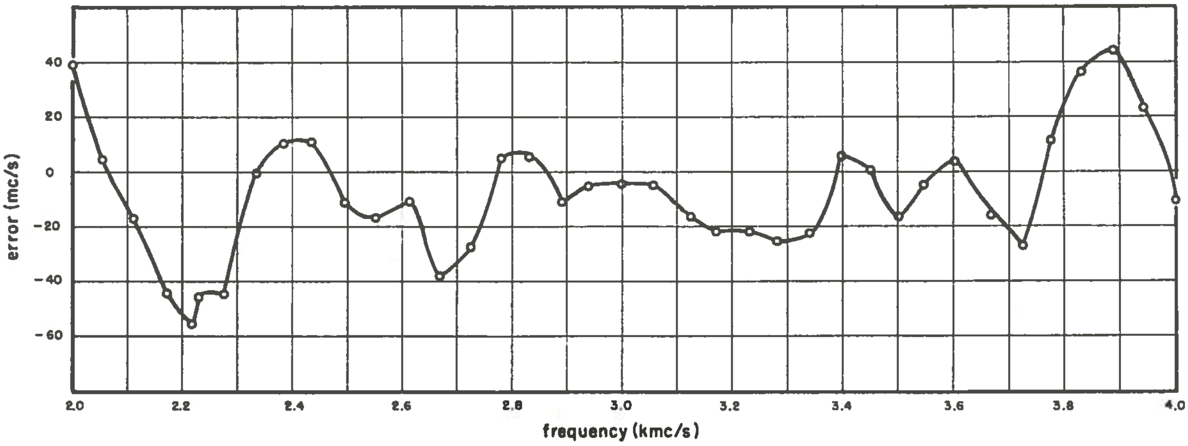
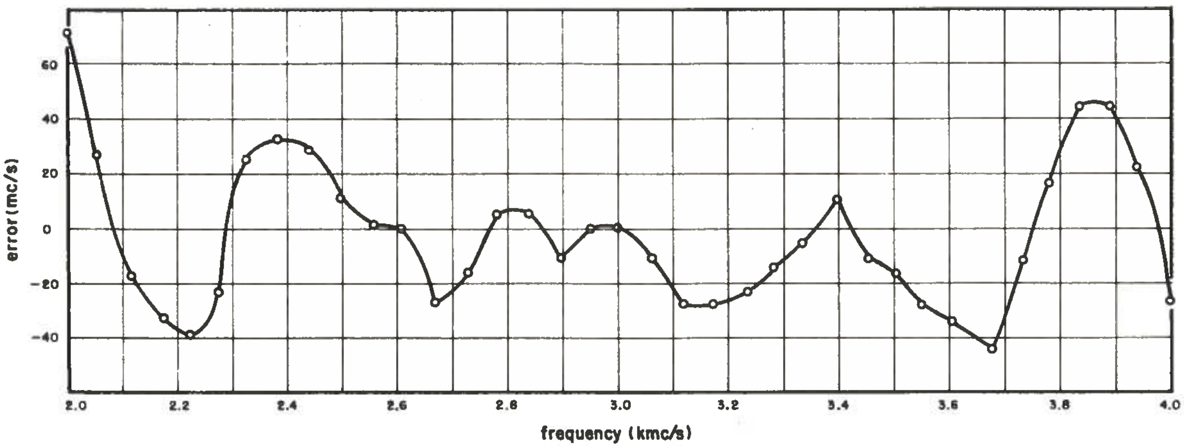


FILTER BANDWIDTH = 350mc/s

FIG. 11 MEASURED ERROR OF 8-FILTER FREQUENCY INDICATOR WITH DIRECTIONAL COUPLERS FOR POWER DIVISION



FILTER BANDWIDTH = 350(mc/s)

FIG. 12 MEASURED ERROR OF 12-FILTER FREQUENCY INDICATOR WITH DIRECTIONAL COUPLERS FOR POWER DIVISION

3) The frequency indicator antenna will normally be omnidirectional, and therefore its gain will be some 6 db less than that of the direction-finding antenna system.

A total loss of 27 db to 35 db can be made up by a TWT amplifier with a gain of this amount, provided the noise from the traveling-wave tube reaching the crystal is less than crystal noise. Because of the relatively large decoupling, this condition is met in this type of frequency indicator with ordinary traveling-wave tubes having noise figures of, say, 25 db to 30 db.

The tangential sensitivity of the frequency indicator, therefore, is that of a crystal video receiver increased by the difference between the gain of the traveling-wave tube and the loss due to the decoupling and padding between the traveling-wave tube and the crystal mounts.

The increase in sensitivity of this experimental frequency indicator with 29 db decoupling and padding, therefore, should be about 10 db at the center of the band where the gain of the traveling-wave tube is about 40 db, and about 5 db at the edges of the band where the gain falls to 35 db. Some further increase in sensitivity is possible by reducing the decoupling, but even with the present equipment the gain in sensitivity is adequate to compensate for the reduced antenna gain. A measured sensitivity curve is shown in Fig. 13. The tangential sensitivity of the frequency indicator with a low noise TWT amplifier added is also shown on the same graph as a matter of interest. The nominal frequency band of the low noise traveling-wave tube is 2700-3300 mc/s, but there is some increase in sensitivity throughout the 2 to 4 kmc/s band.

When two amplifiers are cascaded the output noise of the second tube exceeds crystal noise, at least in the center of the frequency band, and sensitivity is determined by the noise factor of traveling-wave tube #1 and the effective bandwidth. The expression for the effective bandwidth B_e in these circumstances derived by Ayer and quoted in reference 4 is

$$B_e = \sqrt{2 B_R B_V - B_V^2} \qquad (1)$$

where B_R is the r-f bandwidth and B_V is the video bandwidth.

Tangential sensitivity is computed as follows.

Thermal Noise in 350 mc/s bandwidth	=	-88.5 dbm
TWT #1 Noise Figure	=	7 db
TWT #1 Gain	=	23 db
Noise Output of TWT #1	=	-58.5 dbm

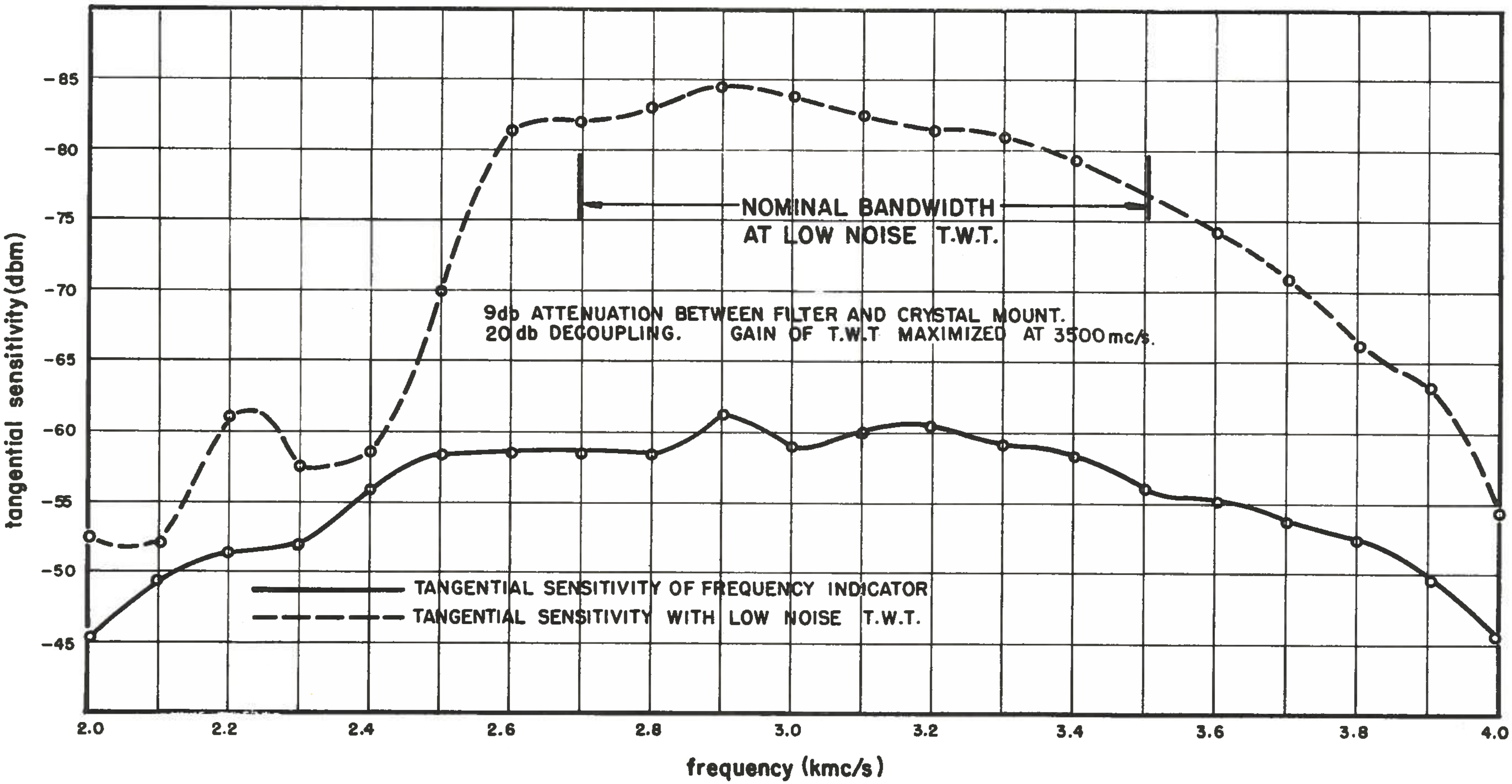


FIG. 13 MEASURED TANGENTIAL SENSITIVITY OF 8-FILTER FREQUENCY INDICATOR (350 mc/s FILTER)

Thermal Noise at Input of TWT #2 with TWT #1 disconnected	=	-88.5 dbm
Estimated Noise Figure of TWT #2	=	25 db
Noise at Input of TWT #2 with TWT #1 disconnected	=	-63.5 dbm

The noise from TWT #1 exceeds the noise from TWT #2 and the noise contribution of TWT #2 can be neglected.

Therefore Noise Input to TWT #2	=	-58.5 dbm
Gain of TWT #2	=	40 db
Noise Output of TWT #2	=	-18.5 dbm
Decoupling and Padding	=	29 db
Noise from TWT into Crystal Mounts	=	-47.5 dbm

This is slightly greater than the noise of an average 1N23B crystal, which is approximately -50 dbm. The video bandwidth of the UPD-501 amplifiers is about 0.5 mc/s.

Therefore $B_e = \sqrt{2(350)(0.5)} = 18.7$ mc/s.

Assuming tangential signal level to be 4 db above noise, the tangential sensitivity of the frequency indicator with two traveling-wave tubes cascaded at the center of the frequency band is equal to: thermal noise (18.7 mc/s bandwidth) + noise figure of TWT #1 + 4 db + loss in resolving network,

$$= -101.3 \text{ dbm} + 7 \text{ db} + 4 \text{ db} + 2\tfrac{1}{2} \text{ db}$$

$$= -88 \text{ dbm}.$$

This computation is not likely to be accurate because the noise from the TWT amplifiers exceeds crystal noise by only a small margin and a relatively small change in the gain of the traveling-wave tubes could reduce the output noise of TWT #2 to the level of crystal noise or below and violate the assumption on which equation (1) is based. Also the noise from individual crystals will depart from the average figure quoted, and the noise figure of TWT #1 can easily be worse than 7 db. This computation, therefore, really indicates the maximum sensitivity that might be expected. It has been included to show the factors involved and to show that the measured values of tangential sensitivity in Fig. 13 are reasonable.

FAST AUTOMATIC GAIN CONTROL

It would be advantageous to have the instantaneous frequency indicator display the frequency correctly for all levels of input signal from the tangential level up.

The first limitation on the dynamic range of the system is the display. The difference in amplitude between a signal which produces a radial line just long enough to read and one which saturates, is only 8 or 10 db, and the difference between an easily readable signal and a saturating signal is only 5 or 6 db. A fast automatic gain control which operated in less than a pulse width, and which limited the output to within 5 or 6 db for inputs from about -55 dbm to about + 30 dbm, would allow readings on almost any single pulse that might be encountered.

Automatic gain control of the video amplifiers presents many problems. It must be fast-acting and operate at a low level; it must be based on the largest signal in any one of four amplifiers, but must control the gain of all four in unison. In the instantaneous direction finder (UPD-501), therefore, a manually switched four-channel attenuator was used and no attempt was made to control gain automatically. The presence of a gridded TWT amplifier in a common channel in the instantaneous frequency indicator renews interest in a fast-acting automatic gain control. Some experimental work on this problem has been done.

The principle followed has been to sample the output pulse of the traveling-wave tube. This pulse is detected and amplified and then applied to the grid with the proper polarity to reduce gain. A pulse stretcher is required in this feedback loop to prevent the traveling-wave tube from oscillating between maximum gain and minimum gain, and a biassed diode is required to set the level to which the TWT output is to be driven.

With distributed line amplifiers of 200 mc/s bandwidth in the loop, the combined delay and rise time was reduced to about 0.2 microsecond and the output of the traveling-wave tube controlled for signals up to about 0 dbm, except for the 0.2 microsecond pulse. The 0.2 microsecond pulse, however, is sufficient to saturate the display on signals about 15 db above the limiting level of -55 dbm.

On the basis of the work done up to the present time it has been concluded that a satisfactory fast automatic gain control will have to be based on either a short (2 to 3 microsecond) memory and a delay of about $\frac{1}{2}$ microsecond or on some form of filtering which discriminates against pulses of less than $\frac{1}{4}$ microsecond. The latter is simpler but it results in loss of information about narrow pulses.

Another possible approach, which is still simpler, is an averaging type of automatic gain control, which would set the TWT gain on a pulse-to-pulse basis. Some compromises would be required to accommodate a wide range of pulse recurrence frequencies, but no basic difficulties are foreseen. The two drawbacks of this scheme are: (1) it fails when only one or two pulses are received, and (2) a strong signal will obscure weaker signals for the duration of the pulse train. The second disadvantage could be very serious, either when a large number of signals is present, or when a nearby radar is being received almost continuously. The study of the problem of automatic gain control for the frequency indicator has not yet been carried far enough to make a decision, and further work is planned.

CW SIGNALS

CW signals cannot normally be observed in a crystal video receiver, but if the signal is chopped, reception is possible. Since the gridded TWT amplifier makes it relatively easy to chop CW signals their frequency could be determined by this frequency indicator. Unfortunately, only one CW signal could be correctly indicated at one time. If two or more signals were present, the frequency indicated would depend on their relative amplitudes and would lie somewhere between the frequencies of these two signals. Since large signals suppress small signals in a TWT amplifier, the frequency indicated would tend towards that of the largest CW signal present.

The TWT amplifier characteristic of discriminating against small signals makes the frequency indicator vulnerable to interference from a powerful CW signal anywhere in its frequency band. It is not likely that this is serious, since the CW signal must compete with the peak power of the pulsed signal and this would usually give the pulsed signal an advantage of about 30 db. However, in the vicinity of a CW radar, for example, the frequency indicator might suffer a considerable loss of sensitivity. Measurements necessary for a quantitative assessment of this problem have not yet been made.

CONCLUSIONS

The work done up to the present time on the instantaneous frequency indicator shows that a direct-reading accuracy of ±30 mc/s with ordinary equipment is obtainable at least in the laboratory, with an 8-filter system. Greater accuracy, about ± 10 mc/s or better, can be obtained by direct calibration with a buzzer and filter cavity. However, the accuracy and frequency range over which this is possible, have not been fully established experimentally. The sensitivity of the frequency indicator with a single permanent magnet focussed TWT amplifier is about the same as that of the crystal video receiver of the instantaneous direction finder and probably can be a little better. The problem of obtaining fast automatic gain control has been studied experimentally and it has been concluded that a frequency memory and delay will be required for satisfactory AGC. If short pulses can be sacrificed, however, some form of low-pass filter will be satisfactory.

The system has been tried on radar signals and appears to operate as it did in the laboratory. It is believed that it will indicate the frequency of nearly all pulsed radar signals with small error. One exception to this is the case of a signal from a pulse-coherent multi-transmitter radar. In this case it will indicate a frequency lying between the frequencies of the transmitters. The exact value will then depend on the relative amplitudes of the signals at each frequency.

FUTURE WORK

It is planned to study the following aspects of the instantaneous frequency indicator more fully:

a) The sensitivity of the system can be improved by using traveling-wave directional filters. Directional filters with a frequency response 350 mc/s wide at S-band with close coupling have been found difficult to construct and adjust.

b) The accuracy of direct calibration, and the frequency range over which it is possible, should be determined more conclusively.

c) Further development of a fast automatic gain control is required, as a satisfactory solution has not yet been found.

d) The sensitivity and perhaps the accuracy of the system could be improved by the use of broadband isolators instead of attenuators between filters and crystal mounts, and by the use of broadband circulators with filters for power division. Developments in these fields must be followed since new or less expensive components may influence the design.

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APPENDIX A

EFFECT OF SHAPE OF FILTER BAND-PASS CHARACTERISTIC ON ACCURACY OF INSTANTANEOUS AMPLITUDE COMPARISON FREQUENCY INDICATOR

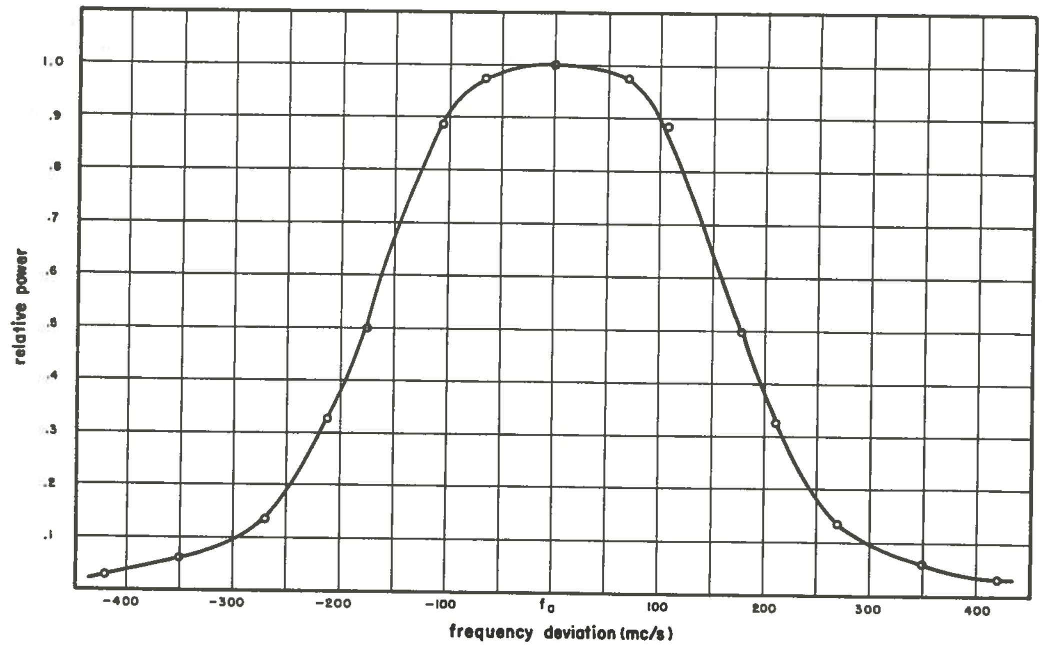
A brief investigation with the analog computer, described in the main body of the report, showed that the width of the filter pass band seemed to be an adequate criterion of its usefulness. However, it was felt that this aspect of the problem should be studied in more detail. The computed band-pass characteristics of two types of filters were plotted. Fig. 14(a) is the characteristic of a two-stage maximally flat filter, and Fig. 14(b) is the characteristic of an optimum filter with monotonic response designed by the method given by Papoulis [3]. Both are 350 mc/s wide to 3 db points. Theoretical characteristics were used so that it would not be necessary to construct the filters. The measured characteristics are likely to be slightly different, but it was considered that performance differences computed on the basis of theoretical characteristics would apply to measured characteristics. The most significant difference between these two filters is very likely the steepness of the skirts. Computations were made on the analog of an 8-filter system with all channels balanced and with one channel inoperative. The errors are shown in Fig. 15 and indicate a slight advantage for the filter with the broader skirts.

The assessment of the merit of the shape of the filter characteristic, however, should be based on the distribution of errors for each frequency as the sensitivities of the channels are varied in a random way through a range which would correspond to the variations between channels found in practice. The number of computations required to determine this error is far too large to be done on the analog computer in its present form. However, a few combinations of sensitivity, varying by 3 db, which represents what might be expected in practice, were arbitrarily selected and the errors computed. The relative merit of the two was based on the maxima of the error rather than the rms value. The results of a number of computations are shown in Tables 2 and 3.

TABLE 2

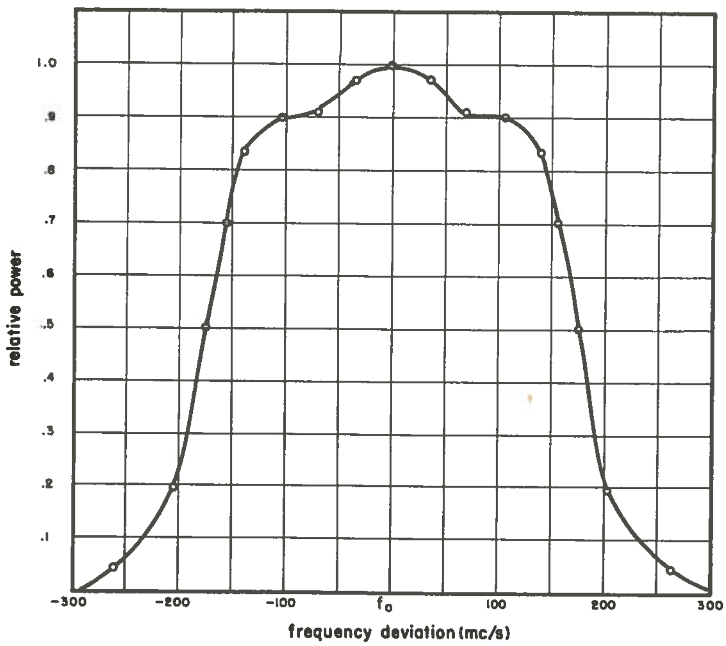
ERRORS OF 8-FILTER FREQUENCY INDICATOR
(Filter bandwidth 350 mc/s)

	Fig. 14(a)			Fig. 14(b)		
Channel Gain	A	B	C	A	B	C
Max. Error (mc/s)	55	60	55	60	80	60
No. of Errors > 50 mc/s	3	4	3	3	5	1
No. of Errors > 25 mc/s	9	11	12	9	8	10



FILTER BANDWIDTH = 350 (mc/s)

FIG. 14(a) BANDPASS CHARACTERISTIC OF A TWO-STAGE MAXIMALLY FLAT FILTER



FILTER BANDWIDTH = 350 (mc/s)

FIG. 14(b) BANDPASS CHARACTERISTIC OF AN OPTIMUM FILTER WITH MONOTONIC RESPONSE

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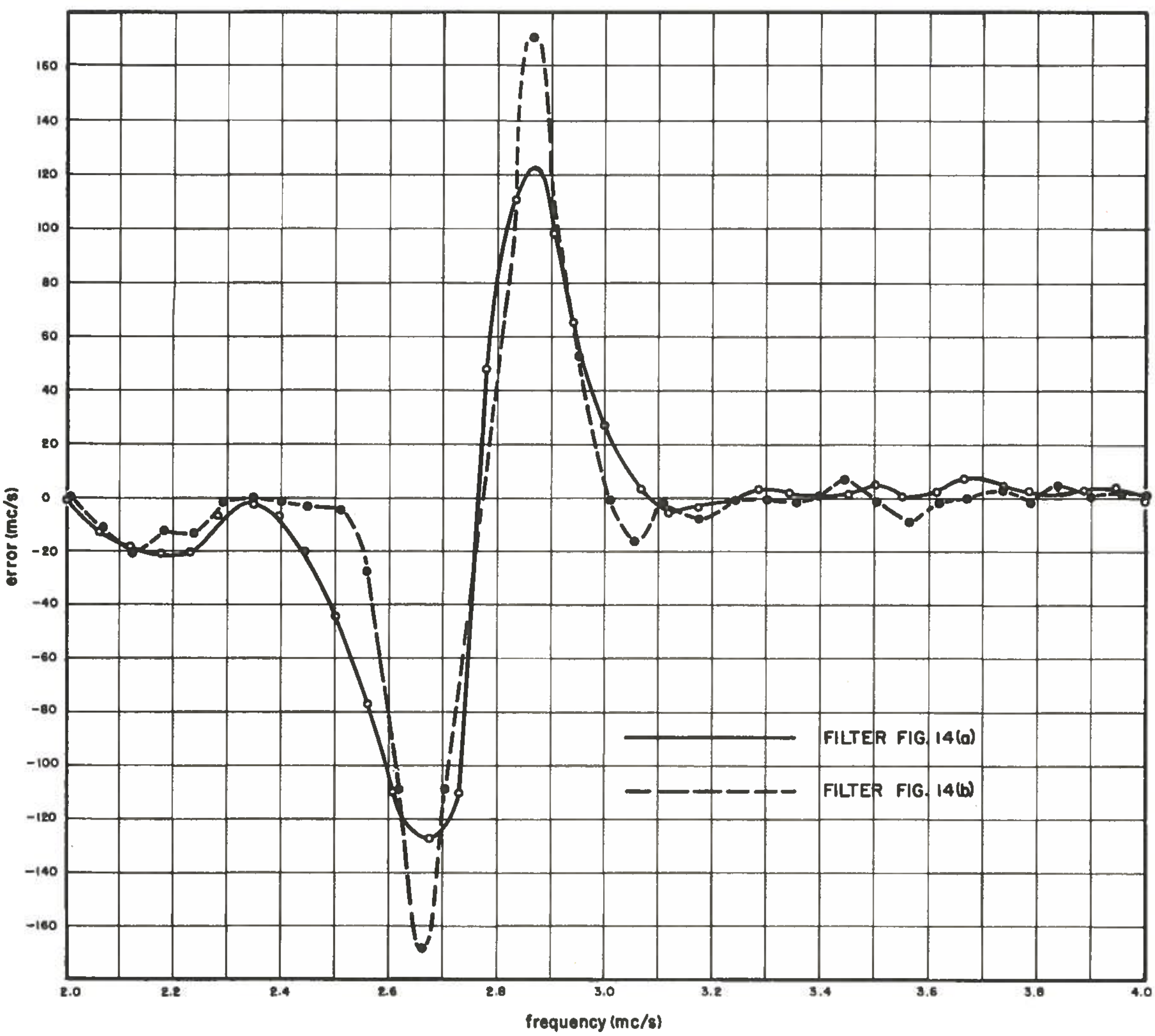

FIG. 15 COMPUTED ERROR CURVES OF 8-FILTER FREQUENCY INDICATOR WITH FILTER CHARACTERISTICS OF FIG. 14(a) AND FIG. 14(b)

TABLE 3

ERRORS OF 12-FILTER FREQUENCY INDICATOR

(Filter bandwidth 233 mc/s)

	Fig. 14(a)			Fig. 14(b)		
Channel Gain	A	B	C	A	B	C
Max. Error (mc/s)	50	45	30	45	50	45
No. of Errors > 35 mc/s	4	3	0	2	1	1
No. of Errors > 15 mc/s	10	9	10	11	9	8

(Errors were computed every 55 mc/s from 2000 to 4000 mc/s on the 8-filter system and from 2000 to 3333 mc/s on the 12-filter system.)

TABLE 4

CHANNEL GAINS USED FOR TABLES 2 AND 3

Channel No.		1	2	3	4	5	6	7	8
Relative Gain (db)	A	-1	0	-3	0	-3	0	-3	-2
	B	0	0	-3	-3	-3	0	0	0
	C	0	-2	-1	-3	-3	-3	1	0

The conclusion drawn from these computations is that the filter band-pass shape does not greatly influence the accuracy on either an 8- or 12-filter system provided: (a) the shapes of the filter band-pass characteristics are identical in all channels, and (b) the pass band is wide enough. This conclusion is not established rigorously by the small number of computations made, but it was felt that these results justified the use of only one type of filter in the experimental work. It seems reasonable, on intuitive grounds, to assume that when the filters are not identical, as in the real system, the influence of the filter shape will tend to be even less significant.