FACSIMILE AND AREAL INTEGRATION FOR WEATHER RADAR

A thesis

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by

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ABSTRACT

Because of the fluctuating nature of the radar echo from randomly distributed precipitation particles, several individual echo measurements have to be averaged to provide a meaningful estimate of intensity. Photography of a cathode ray tube inevitably provides some averaging by integration on film, over the area of the writing spot.

Further areal integration has been achieved by rectangular scanning of fast-processed film at a rate of a few lines per second with a spot of diameter one-half mile. The effective area of integration by first writing and then reading the pattern is one square mile. The areally-averaged signals are subsequently stepped into seven levels, a factor 10 apart in received power, and displayed on a stepped grey scale on facsimile paper. This presentation is well suited for a visual quantitative estimate of echo intensity. Slow scanning results in a low frequency signal that can be sent over a voice-quality telephone line to provide within minutes radar weather maps in grey scale at any number of remote facsimile recorders.

PREFACE

The writer is greatly indebted to Professors J.S. Marshall and K.L.S. Gunn for their helpful advice and guidance. Professor Gunn has taken a continuous interest in the work and has actively contributed to some aspects of it, in particular towards improving the rapid access photography.

Discussions with Professor Walter Hitschfeld concerning the material presented in Chapter 2 on Areal Integration were most helpful. In this chapter, the writer has drawn on unpublished notes on areal integration by Professor Marshall.

The work described in the remaining chapters of the thesis was all performed by the author, with technical assistance which is specifically and gratefully acknowledged in the following paragraphs.

Messrs. P. Seidenfuss and M. Claassen operated and maintained the radar and carried out nearly all the construction associated with the facsimile and scanner system. During the summer of 1963, Mr. M.F. Rose, B.Sc., was constructively helpful in the operational aspects of the facsimile display.

The help of various members of the Stormy Weather Group in the preparation of this thesis has been invaluable. Many of the illustrations in the text were drafted by Miss Ursula Seidenfuss, and the photographic reproductions were made by Mr. Roy Bartley. The author expresses his indebtedness to Miss Diana McLernon for her alertness and diligence in typing the thesis.

Regarding equipment, the Kelvin-Hughes Processor is on loan from the Royal Canadian Air Force. The CPS-9 radar is on loan from the

United States Air Force. Acknowledgement is made to the Instrumental Optics Division of the National Research Council for their application of an anti-reflection coating to the scanner cathode ray tube.

Funds for the construction of equipment associated with the facsimile development, and for the purchase of two facsimile recorders as well as for the routine operation and maintenance of the CPS-9 radar, came from the National Research Council, under Block Term Grant 82. Finally, the writer is grateful for the financial assistance provided him throughout the period of this work by the United States Air Force.

CONTENTS

1. INTRODUCTION

1.1 Radar as a Storm Detector

Meteorological echoes were first observed on military search radars during the Second World War (Maynard, 1945). The observations were made, by necessity, on displays primarily developed for tracking aircraft. These observations revealed some of the characteristic features of the meteorological echoes, as well as limitations of the instruments. Fig. 1.1 is an example of frontal precipitation observed on a 10-cm radar. There is a fairly well defined line of showers lying NE-SW, with individual showers ahead of the line (to the East). Behind the line there is a region of grainy echo from widespread light precipitation. The grainy texture of the echo is caused by fluctuations in the received signal, and does not represent the actual pattern of precipitation intensity. In this sort of picture only the echo outlines convey useful information about the echo structure. (On the other hand, the shadows behind the individual shower cells are due to the inability of the circuits to display extended targets.) The rapid fluctuations in the signal were often used to identify the echoes as meteorological in origin (Kerr, 1951, p. 623). The ability of the radar to detect outlines of precipitation (but to give little additional information) justifies the term "storm detector".

Scanning in the vertical combined with display on a range-height indicator (RHI) made possible studies of the vertical pattern of storms. Differences in the vertical structure of echoes were observed and associated with different meteorological situations. For example, the "Bright Band" (Fig. 1.2) was identified with the OC (melting) level, and was characteristic of widespread precipitation (Byers and Coons, 1947).

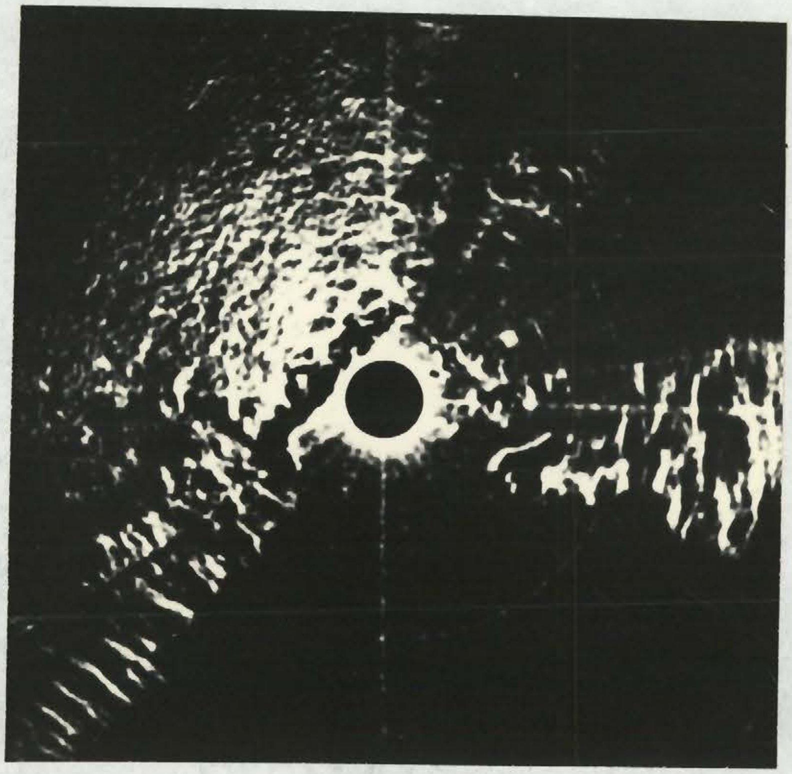


Fig. 1.1

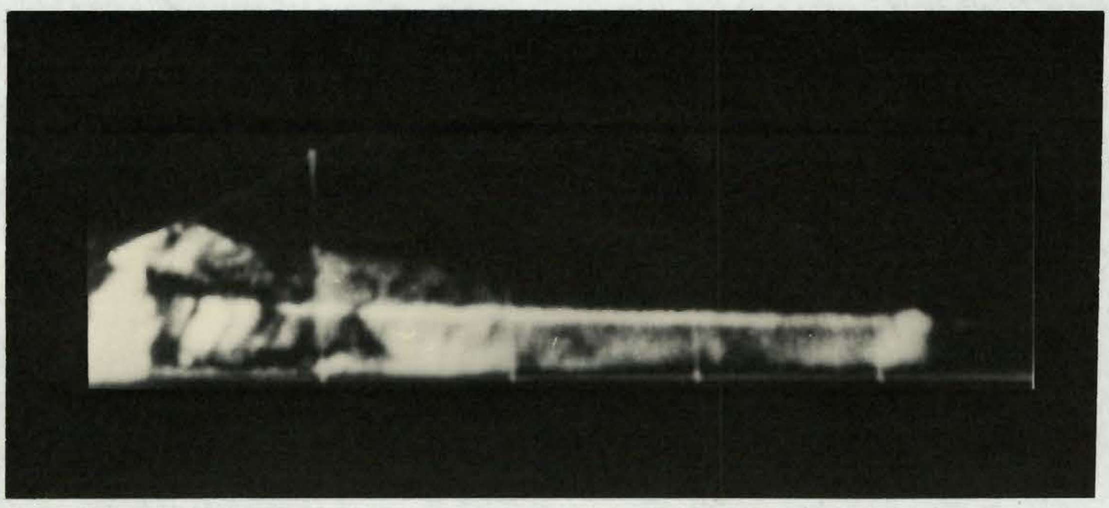


Fig. 1.2

The RHI display of Fig. 1.2 came from a 3-cm TPS-10A radar. To scan in three dimensions with such a radar involved rapid nodding in the vertical combined with slow rotation in azimuth. The scan in the vertical was non-uniform due to large accelerations at the limits of the elevation scan. The display, therefore, showed shading at the top and bottom. In the later CPS-9 radar, the problem of shading was to a large extent eliminated, but at the expense of scanning speed. The multiple RHI as a scheme for scanning in three dimensions involved too long a cycle to be practical.

Synthesis of precipitation maps, not unlike the original PPI in Fig. 1.1, but at a set of constant altitudes, was adopted by the Stormy Weather Group as an alternative to the multiple RHI. The scanning of the antenna for the Constant Altitude PPI (CAPPI) needs only modest accelerations and is therefore compatible with larger and slower antennas currently used.

Maps at a set of constant altitudes are a most efficient three-dimensional display. Because the number of maps in height is limited to the number of displays available during any one scanning cycle, there is some loss of detail in the vertical. However, the signals received during one scanning cycle are sufficient to reveal fine structure in the vertical and only require the development of an appropriate display. (For example, a Height Azimuth Range Position Indicator, proposed in Marshall and Gunn, 1962.)

1.2 Radar as a Raingauge

Early theoretical work (Ryde, 1946, and others) established that at wavelengths long compared with the raindrop diameters, the average power ($\overline{P_r}$) received by the radar is proportional to the sum of the sixth powers of the raindrop diameters in unit volume. This backscattering parameter (ΣD^6) is represented in weather radar theory by Z. Thus $\overline{P_r} \propto Z$. The quantity (Z) has been experimentally related to the rate of rainfall at the ground (R) and found to be

$$Z = 200 R^{1.6} \qquad 1.1$$

with Z in $mm^6 m^{-3}$, when R is in mm hr^{-1} (Gunn and East, 1954). Thus, in its most simple form, we can express the weather radar equation as

$$\overline{P}_r = c R^{1.6} \qquad 1.2$$

where C is a constant. The relationship has been estimated to be correct to within a factor 2 or better (Marshall et al., 1955). To the extent that the relation holds, the radar can be used as a quantitative tool to measure precipitation rates. (The assumption is made that the precipitation fills the pulse volume.)

In equation 1.2, it is the average power that is related to the rate of rainfall. However, the signal from precipitation at any instant is derived from signals returned from all the randomly spaced particles in the contributing region. Since the scattering is incoherent, the instantaneous value of the received power fluctuates randomly about its mean. A successful measurement of rainfall rate must involve averaging over several instantaneous returns. Within practical limits, the more data averaged, the better the measurement (Marshall and Hitschfeld, 1953).

Several methods of averaging have been used in practice. For example, the RHI photograph of Fig. 1.2 was exposed for ten successive scans. The ten grainy patterns were superimposed on film in one exposure, and as a result the coarse pattern has been removed. Although in Fig. 1.2 the averaging on the film surface is qualitative, improving only the details of the pattern, such averaging has since been made quantitative and is basic to the method used in the present work.

Williams (1949) at MIT developed a pulse integrator in which a number of successive returns from a single contributing region are averaged. The instrument is highly useful in radar calibration, but is not applicable to scanning the whole volume surrounding the radar. More recently, a proposal was made by Hall et al. (1963) to use several hundred simplified pulse integrators for scanning in space.

At MIT, the extension from averaging at a point to averaging at all points within radar range was made by Kodaira (1959), who used a quartz delay-line to re-circulate video information and thus average successive returns from each range. Subsequent quantization of the signal by a set of two thresholds, separated by 5 db in received power, resulted in bright echo outlines on the display. On the one side of the bright outline, the received power exceeds the upper threshold; on the other, the echo is below the lower threshold. The width of the outline is a measure of the gradient in echo intensity. The technique has since been extended to display simultaneously several such contours (Niessen and Geotis, 1963).

1.3 Radar as an Operational Tool

Efforts to make the radar into a quantitative instrument were paralleled by its development into an objective instrument for operational use. Introduction of a programmed scan automated the process of collection of the data. East (1957) used a storage tube to accumulate the information and then retrieved it by scanning in rectangular coordinates for presentation on a standard television monitor. However, subsequent introduction of a wide dynamic range into the McGill CPS-9 (Legg, 1960) has precluded the use of storage tubes as the memory in the scan conversion because of their narrow useful dynamic range. Instead, Legg used photographic film as the storage medium. The system described in the present work uses in essence the same technique.

Storage tubes have continued to be used in systems where only a two-tone presentation is required. Recent examples include a scan converter developed by Kodaira (1963) and a similar system by Martin-Vegue and Hiser (1963). Attempts are also being made to use the dynamic range of storage tubes. Schaffner (1963) at MIT is using a storage tube to store intensity information, which is quantized prior to storing. The plan there is to store ten intensity levels, although it is not yet known whether a sufficient dynamic range can be obtained on the storage tube.

A digital memory has been used in the STRADAP processor (Storm Radar Data Processor) developed for the Air Force Cambridge Research Laboratories (Sweeney, 1961; Atlas et al., 1963). In this system, both the pattern and intensity information are carried in digital form and displayed locally, or at a remote location, as an array of digits representing the echo intensity in five-by-five mile squares.

The objectives in developing these various systems fall into one or more of the three broad categories:

(1) Automatic collection of information,

(2) Averaging of the fluctuating signals,

(3) Displaying the information in an easily readable form at both local and remote locations.

Previous work at McGill evolved a scheme to perform the first function; the purpose of the present work is toward the other two objectives.

1.4 The McGill Weather Radar

(a) CAPPI

An automatic method of scanning in three dimensions has been used for several years in conjunction with the McGill CPS-9 radar (Langleben, 1955; East, 1957). The antenna rotates uniformly in azimuth (12.5 seconds per rotation), with each successive rotation at a higher angle of elevation. In seventeen rotations, the antenna progresses from 0° to 15°, after which the antenna descends during the 18th rotation, ready to commence the next cycle.

The constant altitude map is built up on film by displaying on the cathode ray tube only the range interval at the appropriate height during any one rotation (Marshall and Gunn, 1961). After seventeen rotations, the complete map is synthesized on the negative in 3.75 minutes. Fig. 1.3 shows a typical CAPPI map. In the scheme used on the Montreal radar, maps at six heights are produced in succession on any one display, the whole sequence taking 22.5 minutes. The heights chosen for summer precipitation are 5, 10, 15, 20, 30 and 40 kft, and for winter 5, 10, 15, 20, 25 and 30 kft.

(b) Grey Scale

The range of intensities that are of interest (at Montreal) cover a dynamic range of about 60 db (Marshall and Gunn, 1961). The dynamic range of a conventional radar seldom exceeds 15 db, so that four

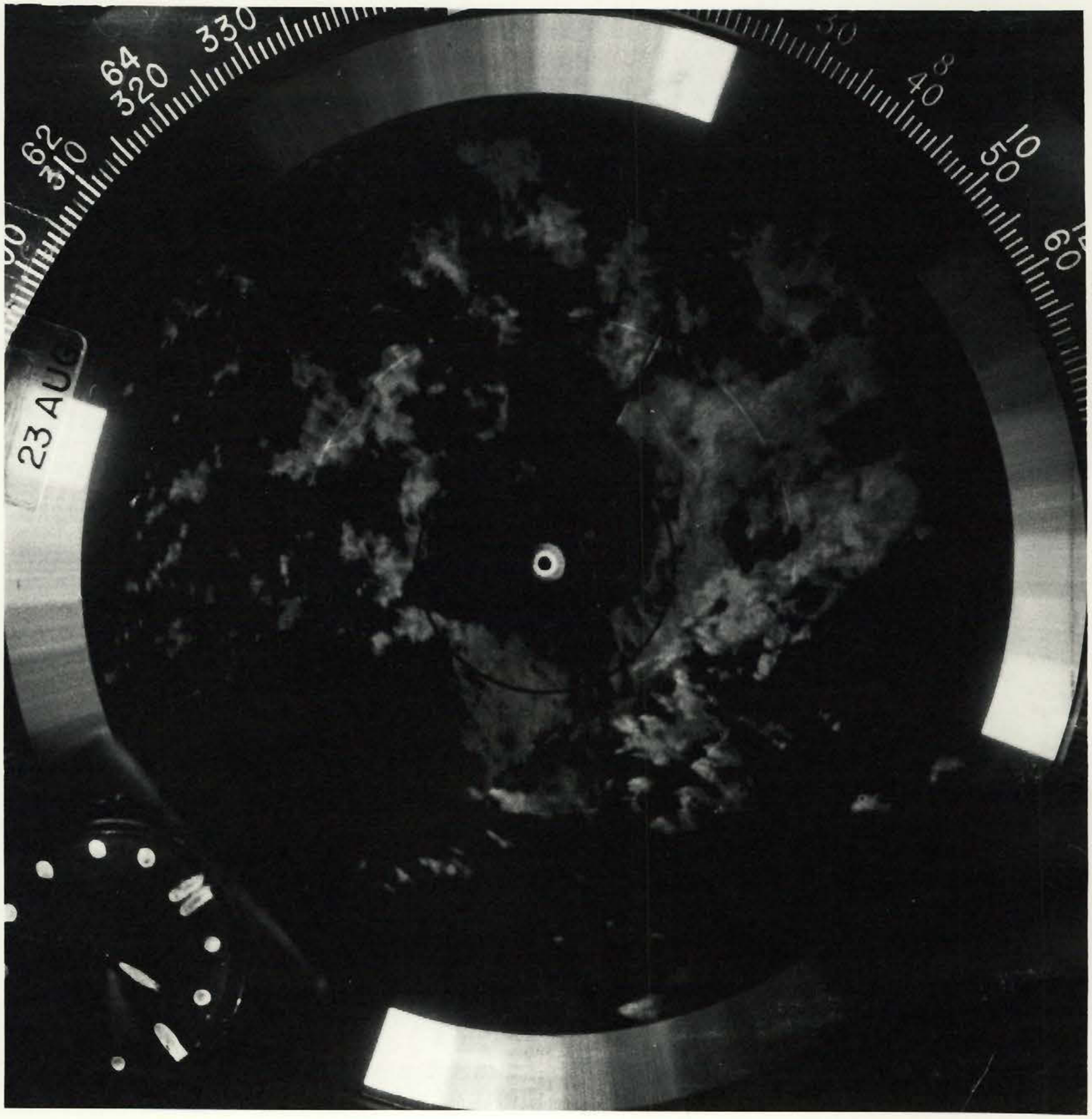


FIG. 1.3

successive scans, each at a different gain, are required to study the whole range of intensities.

A fourfold increase in the dynamic range of the radar was achieved by Legg (1960), so that observation of the whole range of 60 db is possible without any increase in scanning time. By using a logarithmic receiver and an exponential amplifier, Legg established a power-law transfer characteristic between the received power and the luminance on the display CRT. By setting the index of the power law to 0.2, the dynamic range of 60 db in received power is compressed into 12 db in luminance. (The CRT, itself a power law device, is included in the over-all characteristic.) Steps are introduced in the exponential amplifier to display signals in each 10-db interval as a constant brightness on the cathode ray tube. The seven steps in brightness bounding the six 10-db intervals are spaced 2 db or a factor 1.6 in CRT luminance apart. At this stage, the display is quantitative with one exception. The picture is painted out by radially converging lines, so that for an echo of constant intensity the brightness varies inversely with radial distance or range. An optical filter, whose transmission is proportional to range, corrects for the variable brightness (Gunn, 1963). The use of a half-tone filter to obtain the necessary correction preserves the resolution of the display, which a continuous-tone filter would degrade.

A photographic reproduction of the display is a quantitative record of the precipitation pattern. However, the boundaries in grey shades are barely discernible in the pictures because of the fluctuating nature of the signal. Integration over two pulses in range before stepping removes some fluctuations (Legg, 1960), but not sufficiently to make possible quantitative visual inspection of the reproduction. Further processing of the data can reconstitute the information for quantitative analysis. A manual and somewhat laborious analysis can be made, involving measurements on a five-mile grid on a projectected grey scale transparency (see, for example, Russo, 1961). Painting the signals on the surface of the cathode ray tube with a spot of finite size does result in integration on film, but it does not sharpen the boundaries between shades because stepping has taken place earlier in the system.

1.5 Present Work

The purpose of the present work is to provide controllable areal integration and then to quantise the signals into well-defined intensity categories. The integrated, then stepped, picture will be composed of plateaus of grey surrounded by sharp boundaries. A quantitative analysis of the areally integrated picture can then be made visually.

The pictures described in the preceding section (Fig. 1.3) are obtained on 35-mm film in the upper row of blocks in Fig. 1.4. A flying spot then reads the picture in a rectangular scan and transforms the information back into an electrical signal. In addition to the averaging on film by the writing spot, averaging occurs over the area of the reading spot, so that the over-all resolution and the area of averaging are determined by both spots. Stepping of the signal into the seven intensity categories and subsequent display leads to the integrated, then stepped, picture.

A suitable form of displaying the signals is facsimile, because its use leads to an economic means of remoting the display for operational

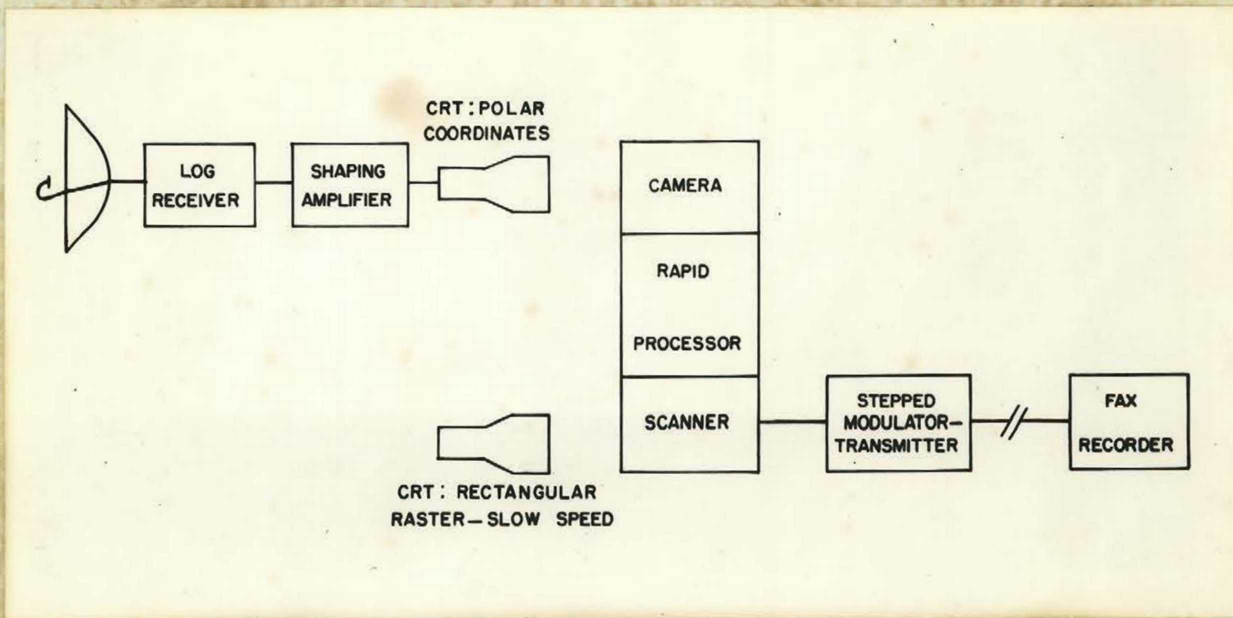

CRT: POLAR
COORDINATES
LOG
RECEIVER
SHAPING
AMPLIFIER
CAMERA
RAPID
PROCESSOR
SCANNER
STEPPED
MODULATOR-
TRANSMITTER
FAX
RECORDER
CRT: RECTANGULAR
RASTER-SLOW SPEED

Fig. 1.4

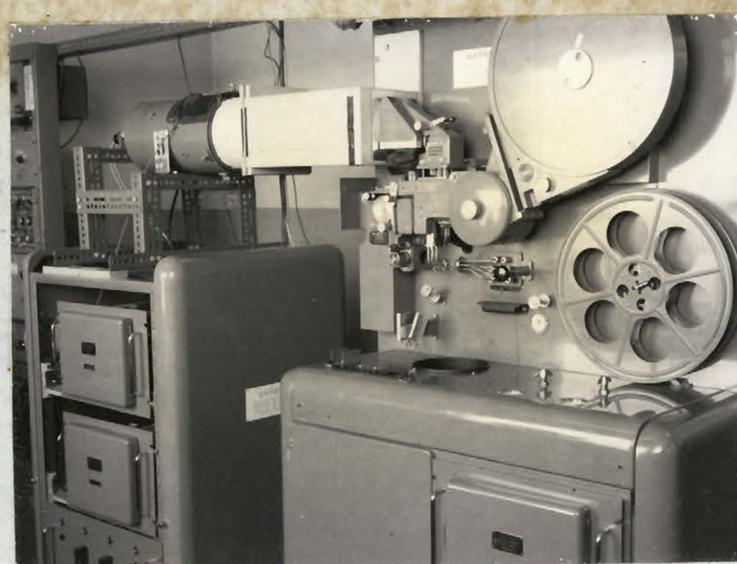


Fig. 1.5

use. Towards this end, the scanning is done slowly at a rate compatible with facsimile. Operation "in real time" is achieved by using rapid-access photography to produce in seconds the 35-mm negative of the first display. The essential parts of the system are shown in block form in Fig. 1.4. (The processor and the scanner are shown in Fig. 1.5.) Every 3.75 minutes a grey-scale transparency is completed and moved to the rapid processor. After processing, the motion of the film advances the frame to the scanning aperture, where it is read by the flying spot, which is generated on the lower CRT. The steps are inserted in the modulator-transmitter.

Facsimile display of areally-integrated maps offers several advantages. The records are available immediately at several locations, and the cost of each outlet and its connection with the transmitter, even if several miles away, is relatively inexpensive. Furthermore, each station accumulates its own records of the immediate history and these can be viewed in a normally lit room. An around-the-clock operation of a facsimile display during the summer months in 1963 in the Aviation Briefing Office at the Montreal Airport demonstrated both the usefulness of such a display, and its ready acceptance into the operations of the Briefing Office (Rose, 1964).

Fig. 1.6 shows two maps at 5 kft of the same precipitation on facsimile. (Each of the two pictures is 5.5 inches wide and 4.25 inches high.) The seven intensities are distributed between the two pictures: Intensities 1, 3, 5 and 7 appear in the left picture, while intensities 2, 4 and 6 appear on the right. By limiting the number of shades in each picture, a great improvement in the distinction between grey shades is achieved.

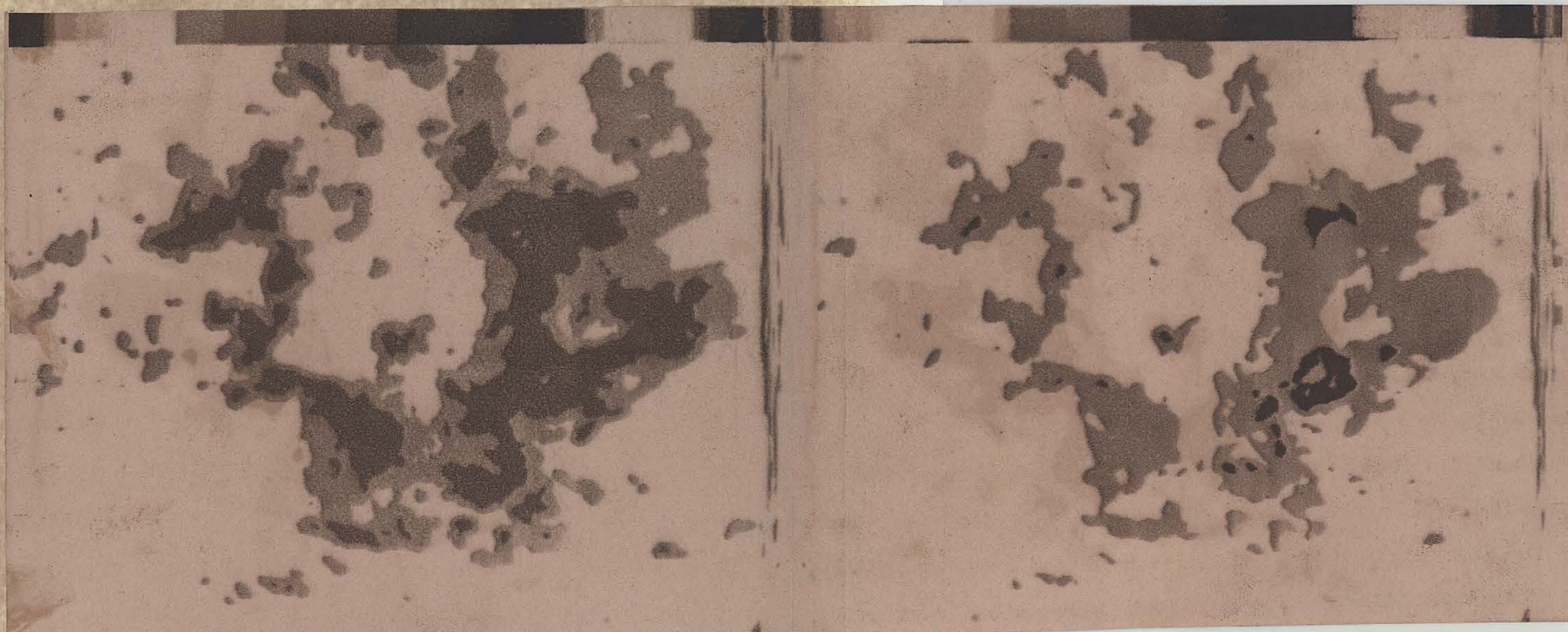


Fig. 1.6

Left Picture

Shade	Intensity Level	Approx Rainfall Rate mm hr^{-1}
white	0	< 0.1
light grey	1	0.1 - 1.6
medium grey	3	1.6 - 25
dark grey	5	25 - 400
black	7	> 400

Right Picture

Shade	Intensity Level	Approx Rainfall Rate mm hr^{-1}
white	0	< 0.4
light grey	2	0.4 - 6.4
dark grey	4	6.4 - 100
black	6	> 100

The scale on each map is 50 mi $inch^{-1}$. The coverage of the map is a rectangle 275 miles by 212 miles. A pair of maps at one height emerges from the recorder every 3.75 minutes. The situation shown in Fig. 1.6 is the same as the CAPPI photograph of Fig. 1.3. Additional facsimile pictures appear in the Appendix.

The 35-mm records of the "un-integrated" maps, both from the regular cameras and from the rapid processor, are not the most useful records for research use because of insufficient pre-threshold integration. The pictures on facsimile do have the benefit of areal integration, but suffer from grain of facsimile paper and are not archival. Archival stepped pictures on film are the best form of presentation for research use. A small number of such pictures was produced by displaying the signals on a cathode ray tube, instead of on facsimile, and photographing the CRT on 35-mm film. In this scheme three cathode ray tubes are used: (a) the PPI CRT, (b) the Scanner CRT, (c) the Slow-Scan Display CRT. Fig. 1.7 shows a stepped picture produced this way. Being also available on a transparency, the picture has sufficient dynamic range to display (for visual analysis) all seven intensities on one picture.

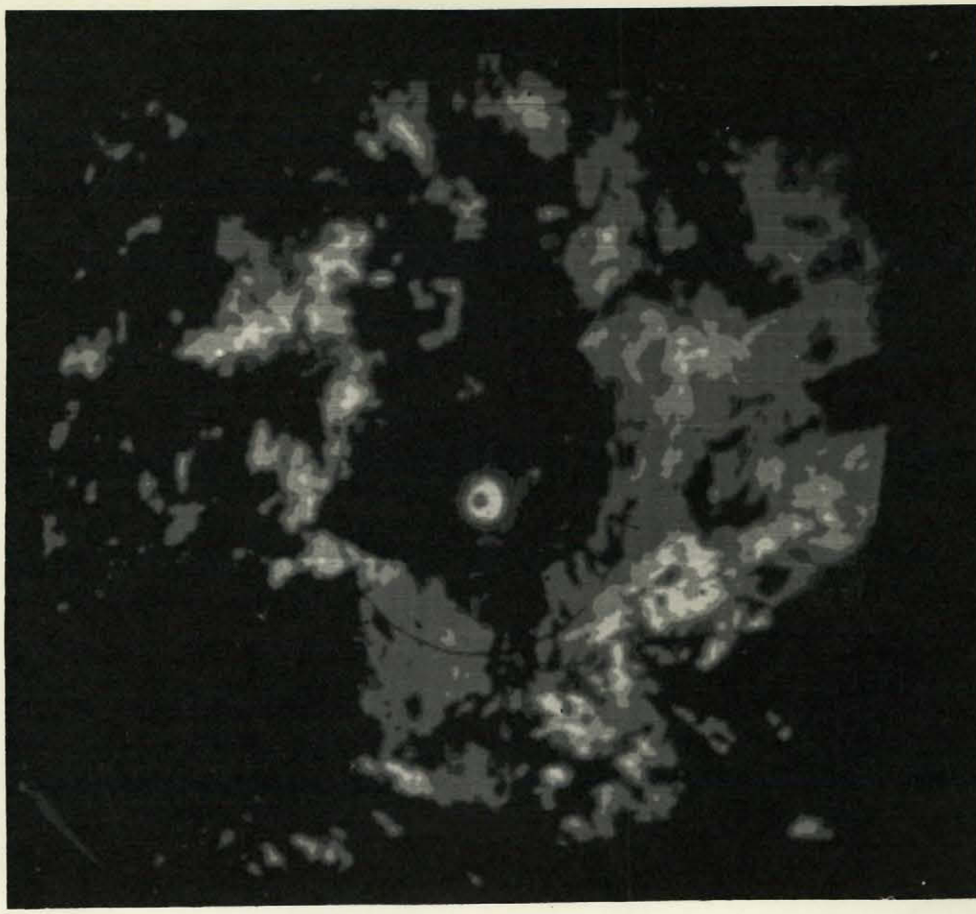


FIG. 1.7

2. SIGNAL FLUCTUATIONS AND INTEGRATION

2.1 Fluctuations in Signal

The signal returned from a random array of scatterers is fluctuating, and one instantaneous value of intensity has little significance. The intensity level of an individual return falls within the range from -20 db to +10 db of the most probable level (Marshall and Hitschfeld, 1953). The standard deviation of the distribution is 5.57 db, and as a useful guide one can say that most of the returns fall within two standard deviations on either side of the mean. Averaging k measurements leads to an improvement of $\frac{1}{\sqrt{k}}$ in the scatter of the signal. A single measurement, or a unit datum, is the instantaneous return from the whole illuminated volume bound by the beamwidth of the antenna and by the half-pulse length. In general, a number of data obtained from the same volume in space at successive times can be averaged (integration in time) or data from adjacent non-overlapping volumes can be averaged (integration in space). In the first case, the number of data is limited by the time available to collect them. In the second case, the limitation is the loss of resolution that can be tolerated. The most common practice is to average successive data from overlapping volumes at successive time intervals, so that the average is obtained partially by integration in time and partially by integration in space.

Averaging over several data leads to a decrease in the range of fluctuations only if the data are independent. In averaging successive returns from the same volume, the time between successive returns should exceed the time required for the particles to alter their radial displacements from the antenna by a sizable fraction of a wavelength. While a small contribution toward achieving the independence is made by a coherent motion of the scatterers with the wind, the major mechanism is the independent motion of the individual scatterers. The time to independence, which is proportional to the wavelength, is of the order of 2 to 20 milliseconds for rain at 3 cm. Measurements of this important parameter are unfortunately scarce. Hitschfeld and Dennis (1956) have found some evidence that the times for snow are longer: up to 30 msec at 3-cm wavelength.

Considerations of the physical mechanisms leading to decorrelation suggest that there may well be a range-dependence of the decorrelation time. When the beamwidth becomes several thousand feet, the time may become shorter. Such a dependence, if substantiated experimentally, would be significant because the number of data decreases with range. Since the number of data per unit area is our ultimate interest, and in the case of the CPS-9 it is only about 4 per square mile at 140 miles, it is vital that these be independent data.

2.2 Resolution in Space and in Intensity

In weather radar, good resolution (i.e. a small contributing volume) is required to avoid partial beam filling at ranges beyond about one hundred miles, which would lead to a degradation of peak intensity. Because of the fluctuating nature of the signal, resolution is also directly related to the measurement of echo intensity, and in this respect it differs from resolution as used in describing a surveillance radar. Intensity resolution needs to be considered in assessing the capability to observe intensity gradients in the precipitation. Before any integration is introduced, the steepest gradient that can be observed is a change in intensity over the full dynamic range of the radar from one pulse volume to the next. The minimum recognizable change in the average intensity is limited by the signal fluctuations. Averaging returns from adjacent volumes decreases the range of fluctuations, and so decreases both the minimum detectable gradient (which is desirable) and also the maximum (which is not desirable). The extent of integration involves a compromise between the two effects. Introducing time integration of the data from overlapping pulse volumes reduces fluctuations without a corresponding decrease in the maximum detectable gradients.

Integration in range is most easily introduced into the radar either by introducing a filter into the video stages of the receiver, or by narrowing the pass-band of the intermediate frequency stages. Extension of averaging to the second coordinate of the radar scan (azimuth) is a natural one, but it introduces some disadvantages. Pulse-to-pulse integration in azimuth can be either confined to pulses practically within one beamwidth by increasing the number of pulses per beamwidth, or it can be extended to include several adjacent beamwidths. Whatever the choice, it applies equally to all ranges, while the dimension of the unit area varies with range. Integration over the same unit of area at all ranges, or areal integration, is a useful alternative. Such averaging preserves at maximum range whatever tangential resolution there is at maximum range, but at close ranges this averaging sacrifices resolution in position in order to improve intensity resolution.

The scale of intensity gradients in precipitation makes a unit of resolution of one mile a reasonable capability for a weather radar. A useful criterion is to specify that the resolution should be one mile out to the range at which the beamwidth is one mile. (For the

CPS-9 with the one-degree beam this range is 57 miles.) Beyond this range out to the maximum range the resolution would be determined by the beamwidth, although the unit of resolution at other points in the system will remain one mile. Decreasing the beamwidth below one degree is costly, especially if the system described here is to be used with a radar operation at a wavelength of 10 cm. Because of the attenuation by rain, the change from 3 cm to the longer wavelength is mandatory for quantitative intensity measurements. In the work described here, the AN/CPS-9 radar was used. In Fig. 2.1 its beam pattern is sketched in relation to the one square mile area at three ranges. The rate of rotation of the antenna is 29° sec^{-1}. With the "long pulse" pulse repetition frequency of 186 sec^{-1}, about six pulses

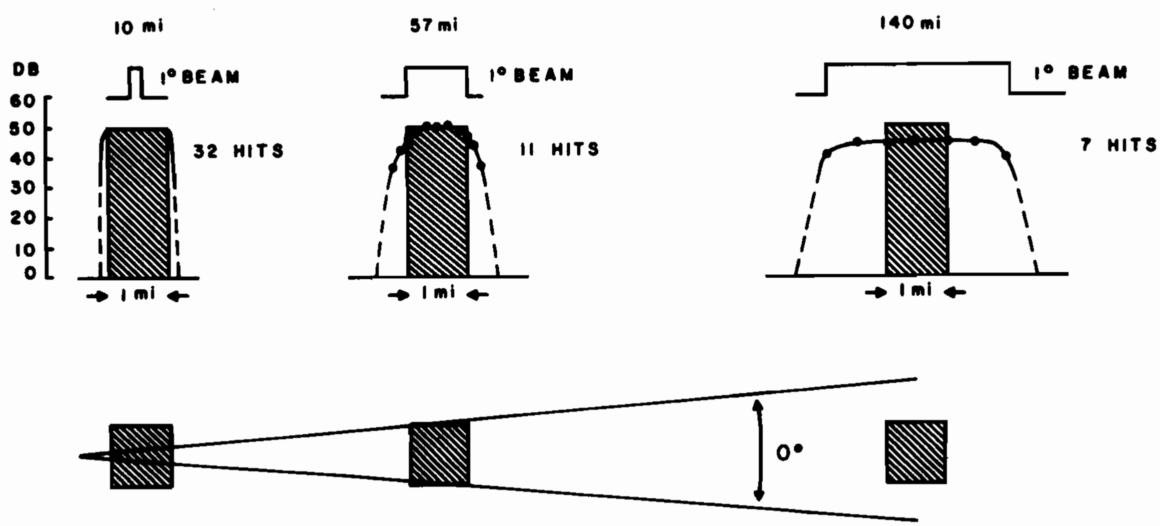


Fig. 2.1

are transmitted each time the antenna rotates through one beamwidth. As the antenna scans past a one-mile square target at 57 miles, signals are received on eleven successive pulses. The tangential gradient at the edges of the echo is actually sharper than one beamwidth, but is displaced away from the true edge of the target, so that in effect the tangential dimension of the target has been stretched to nearly two miles. The fact that the antenna gain (two-way) at $\pm\frac{1}{2}^{\circ}$ is 6 db less than on axis reduces somewhat the stretching from the oversimplified case of uniform power distribution implied in Fig. 2.1. Additionally, the meteorological targets do not have infinite gradients such as those in Fig. 2.1, but more likely approximate those observed after smoothing by the antenna beamwidth. Actually, Donaldson (1963), in making numerical calculations, assumed a "square law" model of a precipitation target which he has used to study the distortion by the antenna beamwidth. In either case, if the signals are then quantized into 10-db intervals, the most intense core will again appear about one mile in size but will be surrounded by a ring of lower intensity, extending another half-mile on either side of it.

The number of data contributing to one square-mile area for the CPS-9 is plotted against range in Fig. 2.2. The number varies inversely with range, from 65 at 10 miles to 4 at 140 miles. The dashed line is a plot (against the right ordinate) of the standard deviation of the distribution after averaging (compared to 5.57 db for the original distribution).

The total number of data at each range (k) can be broken into three factors, k_r, k_θ and k_t, each subscript denoting where the data originated. The three factors are plotted separately in Fig. 2.3.

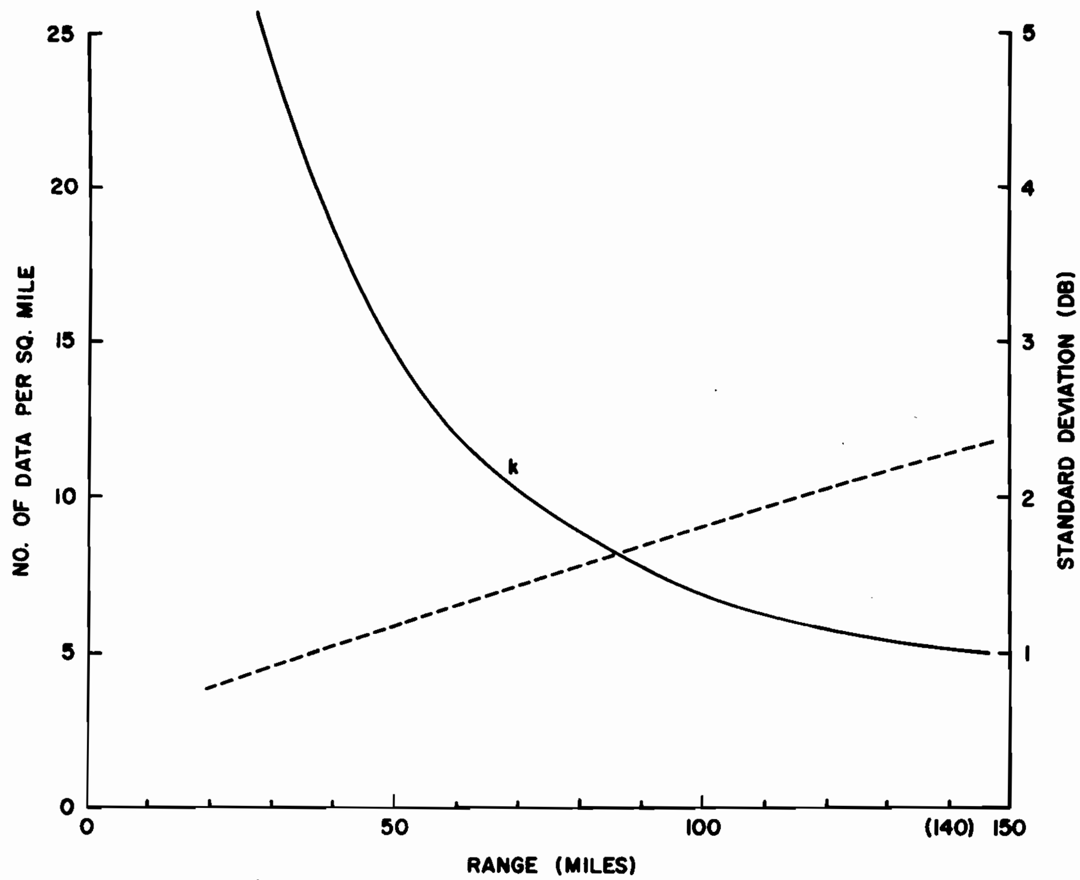

25
20
15
10
5
0
NO. OF DATA PER SQ. MILE
5
4
3
2
1
STANDARD DEVIATION (DB)
k
0
50
100
(140) 150
RANGE (MILES)

FIG. 2.2

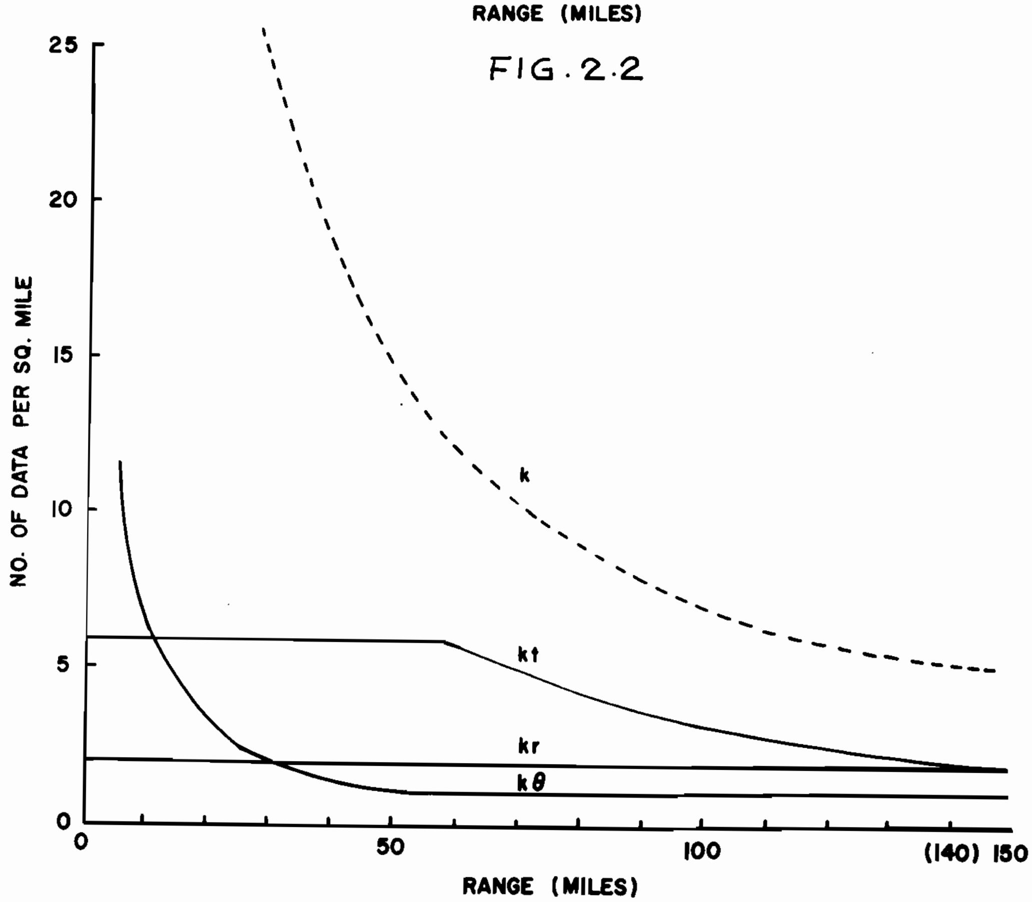

25
20
15
10
5
0
NO. OF DATA PER SQ. MILE
k
kt
kr
kθ
0
50
100
(140) 150
RANGE (MILES)

FIG. 2.3

The quantity k_θ denotes the number of contiguous, non-overlapping beamwidths within a tangential distance of one mile. The value of k_θ varies from six at ten miles to one at 57 miles. Beyond 57 miles k_θ remains unity because the square mile is contained in one beamwidth. The number of returns within the beamwidth contributing to one square mile (k_t) is six out to 57 miles, then falls off inversely with range as the beamwidth exceeds the unit area. The product $k_t.k_\theta$ is just the number of pulses within a tangential distance of one mile at any range r.

One point that emerges from Fig. 2.3 is the transition at range 57 miles at which the one degree beam is one mile, equal to the side of the unit area. Beyond the cross-over range the integration is all within the beamwidth ($k_\theta = 1$). The only contribution in azimuth is therefore from k_t. The effective value of k_t may well be less than that given in Fig. 2.3, if the decorrelation time exceeds the time between pulses. The fact that the square mile is smaller than the beamwidth beyond 57 miles is only a limitation on resolution, but it does not affect integration. Within each square mile there are k data contributing to the mean intensity; for example, four at 140 mi.(Fig. 2.2). If the four data are independent, the standard deviation of the fluctuations is reduced by $\sqrt{4}$, even though two of the data are directly correlated to those in the adjacent square mile.

2.3 Areal Averaging by the Writing Spot

The received signals are painted in polar co-ordinates on the screen of the cathode ray tube. Successive traces overlap, leading to averaging by the writing spot. The integration at the writing stage is over an area of 0.5 by 0.5 miles, the size of the spot. Further averaging results from reading the information from film with a spot

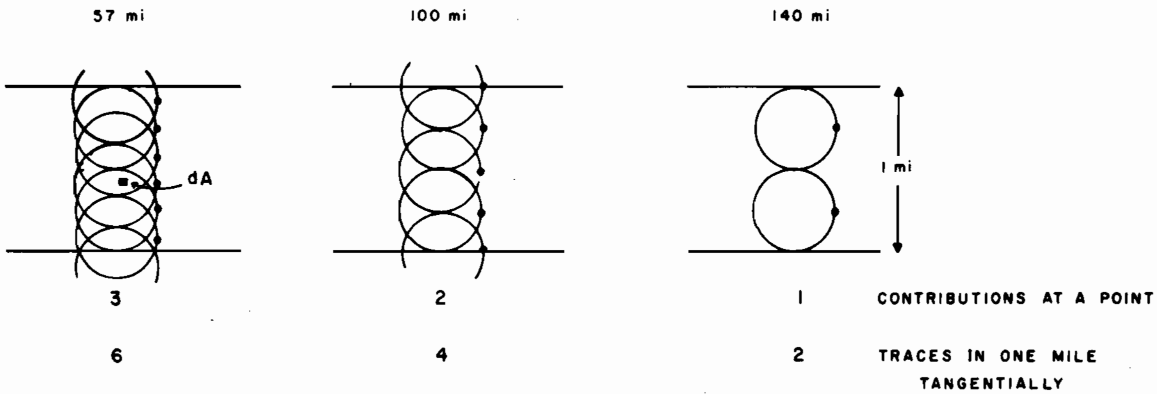


Fig. 2.4

0.5 miles in size in the scanning process.

On the display in the CPS-9 radar, successive traces are only slightly overlapping at the edge of the CRT (Fig. 2.4). At the range of 57 miles, the brightness of a small element of area (dA in the figure) is made up of contributions from three traces. At shorter ranges, the number of overlapping traces increases, but the area of the running mean remains the same, that of the writing spot. The number of pulses contributing to one mile tangentially at the three ranges is listed in Fig. 2.4, anticipating the increase of the unit area to one square mile in the scanning process.

2.4 Signal Shaping

The preceding parts dealt with the geometry of the collection of data by the rotating antenna, and the geometry on the display CRT. Now, before the signals are applied to the display, they are shaped in the video circuits. Integration over the two pulses in range is performed at the output of the logarithmic receiver before the signals are stepped in the first set of thresholds. A low-pass filter (resistor-capacitor) is used to filter the fluctuating component of the signal. Integration at this point in the system has been used by Legg (1960) to provide pre-threshold integration for the CAPPI display on the first cathode ray tube. Before the scan-conversion system described here was installed, the photographs of the display represented the final product. The extent to which the display achieves any kind of grey plateaus is solely determined by the range integration, because it alone comes before stepping. The areal integration on the screen of the display helps to smooth out the fluctuations, but coming after the signal stepping does not improve the sharpness of boundaries.

After integrating over two data, the distribution is narrowed so that about 90% of the data fall within a 10 db interval in power level (estimated from Marshall and Hitschfeld, 1951, Fig. 3.3). After quantization into 10 db intervals, the signal will therefore fluctuate between two, or three levels, depending on the mean intensity in relation to the thresholds.

The seven discrete intensity levels are displayed on the cathode ray tube as equal factors in brightness. The characteristic is sketched in Fig. 2.5 (solid curve). On the abscissa the thresholds are separated 10 db in received power (P_r). Each step is arranged

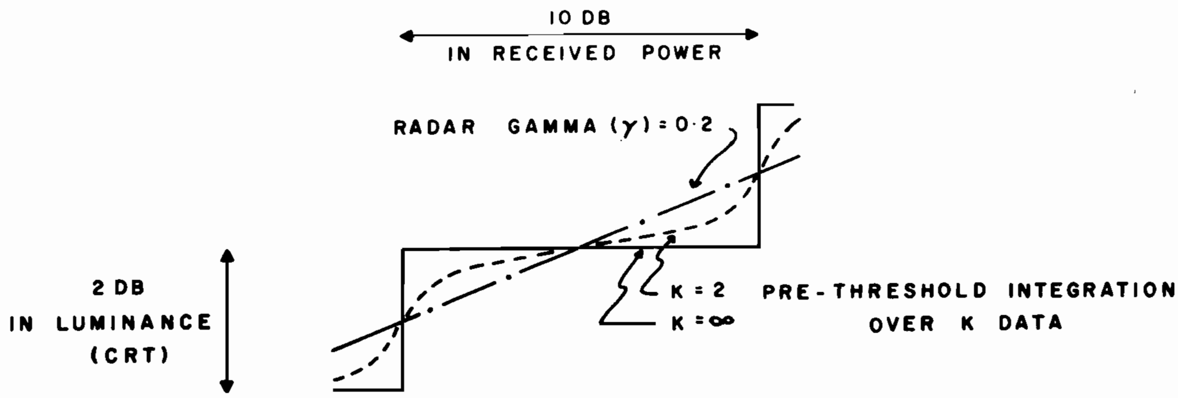


Fig. 2.5

to be 2 db in luminance (ordinate). Because of the overlap of traces, the total brightness of an element of area is made up of contributions from several traces and will therefore be of any intermediate value between the discrete intensities. The dashed line in Fig. 2.5 shows the average brightness of a number of data with a pre-threshold integration over two data. Ideally, the solid curve of Fig. 2.5 would be achieved if the pre-threshold integration were over a large number of data. Instead, for k = 2 there is a "plateau" for which the input ranges over 6.5 db, and a transition region over 3.5 db in received power. For comparison, the chain-dotted line of slope $\gamma = 0.2$ represents a continuous power-law characteristic.

The actual characteristic response of the stepping amplifier departs from the one shown on Fig. 2.5. While in the figure the transition range of the threshold itself is infinitesimal, in the actual case the transition occurs over a range of about 2 db at the input, and as a result the A-scope trace as in Fig. 2.6 shows shading between the horizontal lines. Ideally, there should be no shading.

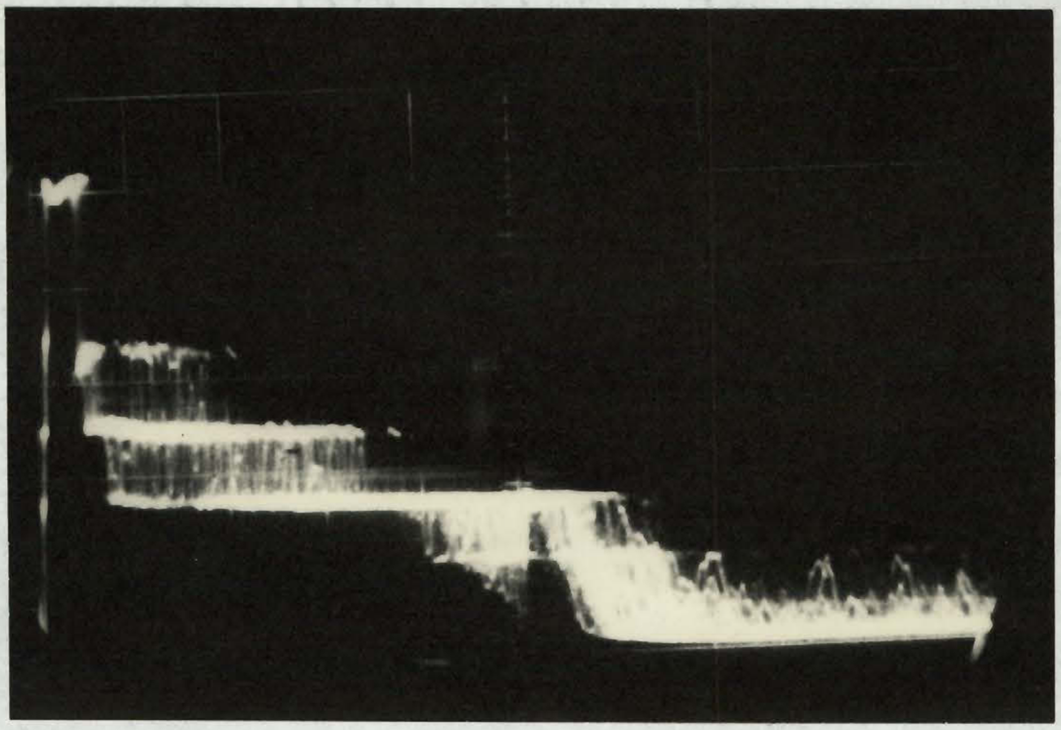


Fig. 2.6

The effect of this finite step on the dashed line of Fig. 2.5 is not easily assessed without numerical computations on the actual distribution. However, qualitatively one can say that the dashed characteristic is thus even closer to the continuous response at a slope of 0.2 (radar gamma). The resultant picture on film is therefore fairly continuous-tone transparency. Because of the integration on the screen by the size of the spot, the fluctuations from individual traces are not resolved on the screen or the reproduction.

2.5 Further Integration by Scanning

A reading spot transforms the information on the 35-mm film into an electrical signal by scanning the frame in a rectangular raster. The detail variations in signal intensity have been previously removed by the integration in range and the subsequent integration by the writing spot on the first CRT. The modulus of the scanning lines is 0.5 miles on the scale of the map and the size of the spot is also

0.5 miles. The signal derived at any instant depends on the average transmittance through the area on the film on which the spot is imaged. As the spot reads each line, the signal represents a running mean along the scanning line. In an analogous way to the stretching of echoes by the antenna beam, the scanning spot stretches the images of echoes on film and causes a further decrease in gradients of the precipitation patterns. The signal obtained by scanning the image now has the benefit of areal integration in two successive stages. Passing the integrated signal through a quantizing amplifier with the second set of steps and then displaying it on the final display results in a picture as in Fig. 1.7. Here the grey shades are true plateaus and are bound by sharp edges, creating an impression of a higher contrast between shades than would the equivalent picture without the boundaries.

The half-mile reading spot averages out mainly the grain and noise pattern introduced by the radial display. The spoking is caused by a transverse modulation of the spot position at a frequency of 60 c/s. The modulation appears to be caused by the magnetic fields due to 60-cycle wiring. The modulation creates an interference pattern with the raster of converging radial lines, resulting in an intensity modulation. The use of the reading spot to average instrumental noise represents an unnecessary sacrifice in fidelity and intensity resolution. The grey plateaus on the final display are uniform because stepping the signal removes the distracting instrumental non-uniformities. The shape of the boundaries is, however, distorted by the spurious modulation.

The one-mile areal integration can be accomplished by other combinations of writing and reading spot diameters. While equal spot sizes were used here, one could use either of the following two alternatives:

a) small writing spot (0.2 mile) - large reading spot (1 mile)

b) large writing spot (1 mile) - small reading spot (0.2 mile)

Neither of the two alternatives is economically sound because in each a high resolution is provided at a cost in one part of the system, and is then thrown away at a subsequent stage. From the point of view of performance, the first alternative would at first appear attractive in that the averaging comes at the last point in the system beyond which only the grain of the final display surface could affect the presentation. On the other hand, the spoking and other spurious intensity modulation will likely be enhanced if the writing spot is made small. The main difficulty would be caused by gaps between traces at the extreme range, unless the pulse repetition frequency is raised correspondingly. Additionally, averaging out spurious variations in film density of amplitude equal to, or greater than, the separation between two shades leads to severe distortion of intensities. This is discussed more fully in chapter 4. The second alternative is even less attractive unless the display non-uniformities can be sufficiently suppressed that only the natural signal fluctuations are to be averaged.

3. FACSIMILE DISPLAY

3.1 The Facsimile Recorder

Two facsimile recorders manufactured by Muirhead Instruments Co. (Model D-611-F) are used to display the radar maps at Montreal Airport. One recorder serves as a monitor at the transmitter near the radar console, the other is in the Aviation Briefing Office one mile (cable length) away. Plans in the immediate future call for installation of a third recorder at the University, twelve miles away.

The recorders were manufactured for wire-photo reception in newspaper offices. The picture is produced on a chemically treated paper which darkens when current passes through it. The signal is applied to the paper by a flying contact. The paper passes between a blade and a plastic cylinder carrying a helical wire. Rotation of the cylinder, once every 500 msec, results in a transverse motion of the instantaneous contact between the blade and the helical wire. The paper is pulled by a pair of rollers at a rate of 1.2 inches/min, resulting in a line density of 100 lines $inch^{-1}$. The helix is rotated by a synchronous motor, driven from a stable frequency source. Once the recorder is started, the stability of the local frequency source determines how well the recorder will remain in synchronization with the transmitter. This differs from television practice where a synchronizing pulse is received after each line. With a stability of three parts in 10^6 a horizontal shift of 10% in the picture occurs in about 3×10^4 rotations, or 4 hours.

The block diagram of the D-611-F recorder is shown in Fig. 3.1. Following first through the signal channel in the upper section of the figure the received signal on a balanced audio line is first amplified,

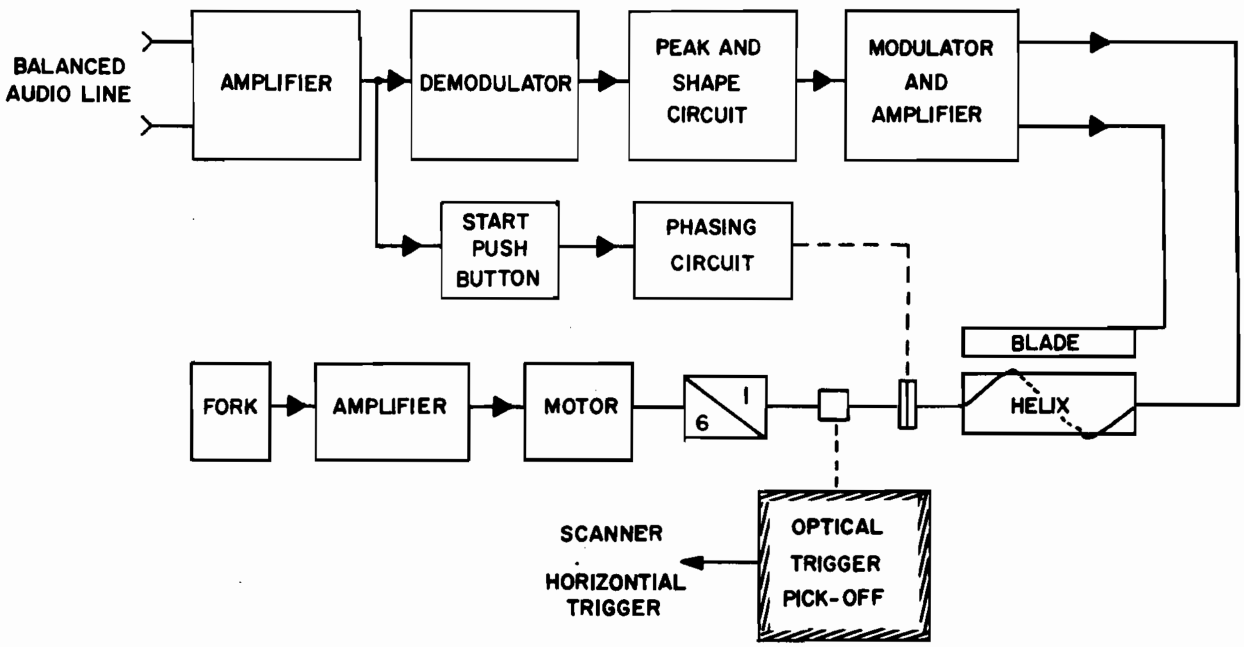


Fig. 3.1

and then demodulated. The detected video envelope is shaped to match the response of the paper, after which it is made to amplitude-modulate an 8 kc/s carrier. The modulated carrier is rectified and without filtering is applied to the two marking electrodes. On facsimile paper black marking is produced by the maximum current through the paper. The specifications for facsimile transmission laid down by CCIT (International Telegraph Consultative Committee) call for a polarity of modulation on the audio line in which black corresponds to the minimum signal on the line. The necessary polarity reversal is accomplished after the incoming carrier envelope has been detected in the demodulator (Fig. 3.1). At the same time high frequency compensa-

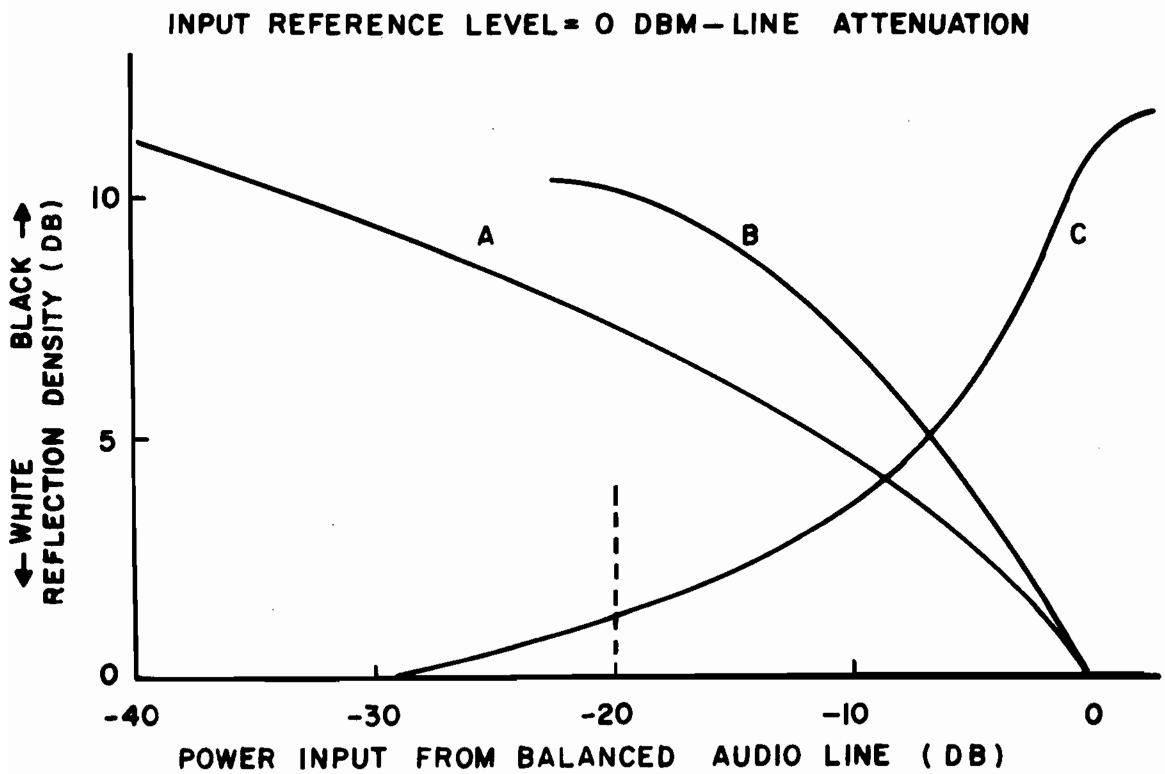


Fig. 3.2

tion is inserted to make up losses on the line.

Non-linear shaping of the picture signals before remodulation results in a wide dynamic range at the input. Fig. 3.2 shows a plot of paper reflection density against input signal strength. In accordance with telephone practice the dynamic range on the telephone line is 32 db (or a factor 40 in voltage amplitude). Operation over a wide dynamic range on the telephone line offers several advantages. While the noise on the line can usually be kept 32 db below the maximum signal level, the common disturbance is variation in path attenuation. The use of a wide dynamic range and a logarithmic distribution of information over the dynamic range minimizes the effect of attenuation.

While on the one-mile path used here attenuation was not a problem, there was for a period a transmitter instability of ±1 db. The change was noticeable on the paper but it did not result in a loss of intensity information. If the shaping stage is disabled, the input dynamic range is narrowed to 18 db. The resultant characteristic is shown as curve B in Fig. 3.2. The curve is of some relevance because for a period the system described here was operated with this characteristic. (Section 3.5).

Some facsimile systems, notably the Department of Transport weather chart system, use a simplified receiver circuit, omitting the demodulator and modulator stages. The signal is amplified in the first stage shown in the block diagram, is bypassed directly to the output and applied to the paper. The response of such a system is shown as curve C in Fig. 3.2. The signals producing the dark greys are crowded on the input power scale resulting in a system somewhat more sensitive to variations in path attenuation than the recommended response of curve A. Of course, the three curves imply that the same recording paper is used in the three schemes. The overall response curves can be changed considerably by using recording papers with widely varying characteristics.

Returning to the block diagram in Fig. 3.1, the method of starting the recorder in phase is indicated: The phasing signal is received from the transmitter once every line, when demanded. The signal closes a relay in the phasing circuit and so operates the clutch at the right instant. In the manual version used here a push-button is pressed to allow the signal to reach the phasing circuit. The optical trigger pick-off has been added to one of the recorders to derive a trigger pulse once per rotation of the shaft on the driving side of the clutch. The trigger pulse, whose recurrence frequency has the same stability as the tuning fork frequency source, is used to synchronize the horizontal sweep of the flying spot scanner. It therefore follows that the recorder supplying the pulse will remain in synchronization once it is started in phase, even if its frequency drifts. It was found advantageous to install the recorder supplying the trigger in the remote location in the Briefing Room. The trigger is brought back to the radar via available spare conductors. The remote recorder runs for extended lengths of time, up to 12-16 hours at a time, and the users do not have to re-synchronize the recorder every four hours. The horizontal drift now occurs on the monitor recorder at the radar, but there it is more acceptable.

3.2 Facsimile Presentation

(a) Format

The usable width of the record is 11 inches. At the standard speed of 120 lines per minute the length of record produced in one CAPPI cycle is 4.5 inches. A reasonable format, 9 by 11 inches, could have been produced in two cycles (7.5 min), but one map every two cycles is not sufficiently frequent for the users. Thus, we settled on one map per cycle. To fit in with the format of 4.5 high by 11 inches wide, two maps of the same precipitation are displayed side by side, with the seven intensities distributed between them. Each picture is actually 5.5 inches wide and 4.25 inches high. Between successive pairs of pictures, a 1/4-inch strip is inserted displaying a test pattern of the appropriate shades of grey (Fig. 3.3). The position of the boundaries between shades in the test pattern is of

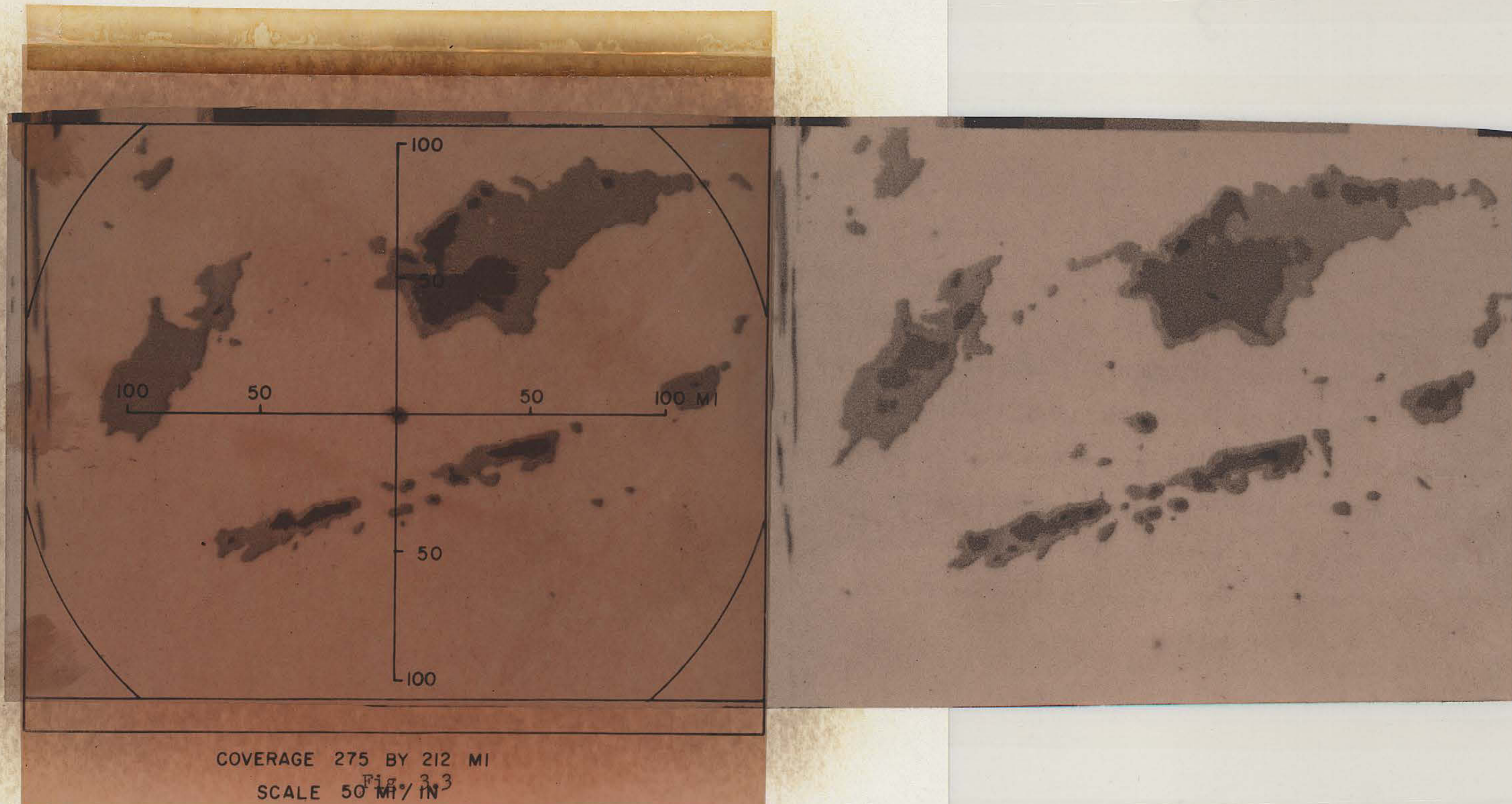


Fig. 3.3

Left Picture

Shade	Intensity Level	Approx Rainfall Rate mm hr^{-1}
white	0	< 0.1
light grey	1	0.1 - 1.6
medium grey	3	1.6 - 25
dark grey	5	25 - 400
black	7	> 400

Right Picture

Shade	Intensity Level	Approx Rainfall rate mm hr^{-1}
white	0	< 0.4
light grey	2	0.4 - 6.4
dark grey	4	6.4 - 100
black	6	> 100

some value in monitoring the performance. A set of six pairs of pictures emerges from the recorder every 22.5 minutes. The CAPPI heights displayed are in succession 5, 10, 15, 20, 30 and 40 kft. The scale on each map is 50 mi inch^{-1}. The coverage of the map is a rectangle 275 miles by 212 miles. The circle of 140 miles range of the original CAPPI display falls within the rectangle in the corners limiting the coverage of those areas, as shown on the overlay of Fig. 3.3.

The seven intensities are distributed between the pair of pictures side by side, as listed in the lower part of Fig. 3.3. In this way the relatively narrow range of reflection density of the facsimile paper is divided into 4 in the left picture and 3 in the right picture, instead of 7. Thus a great improvement in distinction between grey shades is achieved. By displaying the alternate levels in each picture, the separation in received power level between thresholds in each picture is 20 db instead of the 10 db on the original transparency. The width of each grey plateau is therefore twice what it would be for 10-db separation.

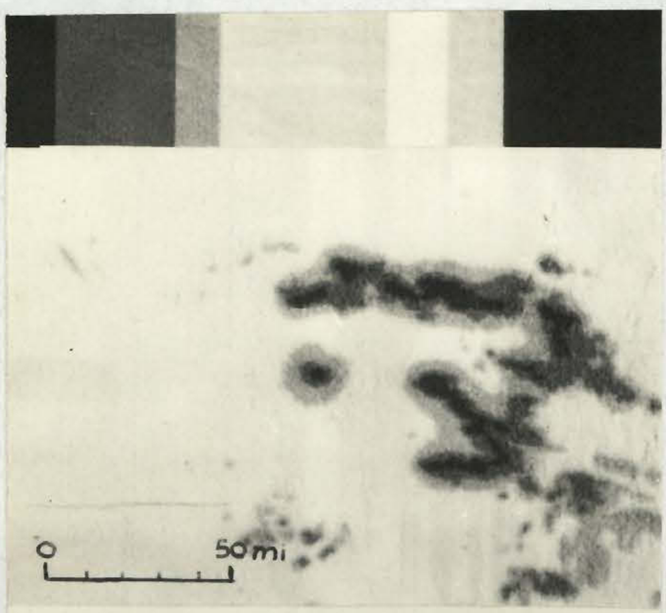
3.3 Visual Analysis of Facsimile Pictures

One objective in displaying the grey scale pictures on facsimile is to allow a visual quantitative estimate of the echo intensity. The areal integration and subsequent stepping of the signal makes the information well suited for visual presentation. The spurious detail introduced by the fluctuating nature of the signal and by the shortcomings of the PPI display has been removed by the integration .

The problems encountered in displaying grey scale pictures have been summarized by Legg (1960). He was mainly concerned with analysing positive reproductions of a PPI display. This display actually falls short of achieving plateaus of grey with sharp outlines because of insufficient pre-threshold integration. He points out that a qualitative judgement can be made by inspection of the picture. Also, the partially stepped picture is an adequate archival record of precipitation. At worst, it becomes a continuous-grey picture retaining the intensity information, which can be recovered by means of photometric measurements. In the case of facsimile the requirements are more demanding. Photometric measurements are not easy, being on a reflection scale, nor are they practical operationally. In an operational system the user wants the information with minimum effort on his part, and certainly without resorting to photometric measurements. For this reason the number of grey shades that can be displayed is not only a function of the dynamic range, but also of the ability of the eye to identify the shades.

Studies of the ability of the eye to distinguish between grey shades were carried out by Blackwell (1946). The findings are well summarized by Legg (1960), establishing in essence that for large areas of grey with adequate illumination, the least perceptible step in luminance is the same throughout a large range of brightness. The smallest step, sometimes known as Fechner Fraction (James and Higgins, 1960) is 2% of the background luminance, which is surprisingly small. The result of this finding is in agreement with the Weber-Fechner law, establishing that the response of the eye is essentially logarithmic.

In the specific problem here, additional factors were found to modify the basic findings. The grain of the paper surface affects the size of a perceptible step. Both the amplitude and the spatial frequency of the grain are of relevance. If the texture is finer than the unit of resolution (0.01" on facsimile), it is not disturbing to the viewer because it is integrated by the eye. The most disturbing grain is one whose spatial frequency is about the same as the unit of resolution (by electrical analogy it is within the pass band of the filter - the eye). Such grain is annoying in the large plateaus, but is severely detrimental in the case of small echoes which themselves are only a few units of resolution in extent. Besides adding texture to the plateau, the grain affects the sharpness of a transition in reflection density (Fig. 3.4). In this case the amplitude of the grain is important in relation to the size of the density step. A subjective estimate suggested that graininess began to be objectionable when the amplitude appeared about equal to the step. One guide became



Grey background and grain result in a loss of one usable shade. Insert shows an improved grey scale.

Fig. 3.4

soon apparent: The facsimile reproductions with the best resolution (finest grain) are those on which the scanning lines are clearly discernible. Since there are two lines on facsimile per mile, the line pattern is just acceptable. If the grain obscures the line structure, it tends to be coarser and therefore highly distracting. On the other hand, spurious intensity modulation on a much coarser scale, such as 60-cycle power line modulation, surprisingly is not objectionable, although its presence mars the appearance of the pictures. The 60-cycle modulation would produce vertical bars with a horizontal spacing of

about 0.4 inches. Because the ripple is introduced after stepping, the pattern is continuous and the eye could easily learn to ignore it in picking out the grey contours. (Actually we have no problem in suppressing the 60-cycle modulation.)

Assuming that the grain of the picture is fine enough, the number of shades that can be operationally displayed depends on the method used in estimating the intensity of an echo. Referring specifically to the geographical scale of 50 mi $inch^{-1}$ and the intensity scale described in section 3.2, one can establish two possible means of identification of the echo intensity. One way is to count the steps from the background up to the maximum intensity. This was possible in most cases of summer precipitation, and of course presents no problem in winter when the gradients are gentle. In convective and cold front situations during the summer of 1963 the steepest gradients were about 50 db in 1 to $1\frac{1}{2}$ miles, and in these it was not possible to discern and so count the steps. However it was always found possible to ascend to the maximum echo from some other direction where there was a less steep gradient.* If counting is used, the total number of grey levels that can be displayed is to some extent a function of dynamic range but mainly of resolution, or better still the ratio of the width (or sharpness) of a transition to the smallest width of a grey plateau in the direction of the gradient. Fig. 3.5 illustrates how the sharpness of boundaries affects the ability to count steps. The picture on facsimile was made 7" by 11" and then reduced photographically to the

Fig. 3.5

*The gentler gradients behind the storm are usually real and are only partly a result of distortion caused by attenuation due to the intervening storm.

standard width of 5.5". The steps, incidentally, are separated by 16 db instead of the usual 20 db to display some realistic fourth shade. The contours can be identified easily, even though both the plateaus have been narrowed by shrinking the threshold separation, and the precipitation is one of the more intense storms of the summer 1963. For example, the intense core in the north-east reaches 48 db above the lowest threshold in one mile. However, if the number of well-defined shades is reduced to about four (in addition to background), the eye can make an absolute estimate of the intensity. It is easy with three shades in the right picture. It can just be done with four shades if the distribution of the shades is modified, from one with equal density steps to one that takes into account the relative areas of the shades and the environmental viewing conditions.

There is a basic difference whether the echoes are presented as grey-to-black on a white background as in Fig. 3.3, or grey-to-white echoes on a black background as on a photographic print, for example in Fig. 1.3. There are at least two reasons why the presentation with white echoes is better. First of all the most intense echoes are the ones of greatest interest to the analyst and their presence is not known _a priori_. On the "white echo" presentation they are near the white end of the scale and are least affected by glare. A "black echo" display needs adequate lighting to minimize the danger of not discerning the intense core. At a low illumination or adaptation level there is a "black point" below which a dark grey will appear as black (Evans, 1959). A small patch of black on the background of this dark grey will merge with the surrounding. By increasing the illumination, and thereby raising the adaptation level, one lowers the black point sufficiently to cause the dark grey to appear lighter than the black patch.

Another difficulty with the black echo display is caused by light specularly reflected from the surface of the picture, or glare. If the diffuse reflection density of the black is 11 db, the diffusely reflected light is about 8% of the reflection from a white surface. If, for example, the glare term is 5%, the total reflected light is 13%. A measurement of the total light by means of a spot photometer will yield a density of only 9 db. Fig. 3.6 is a plot of the effect

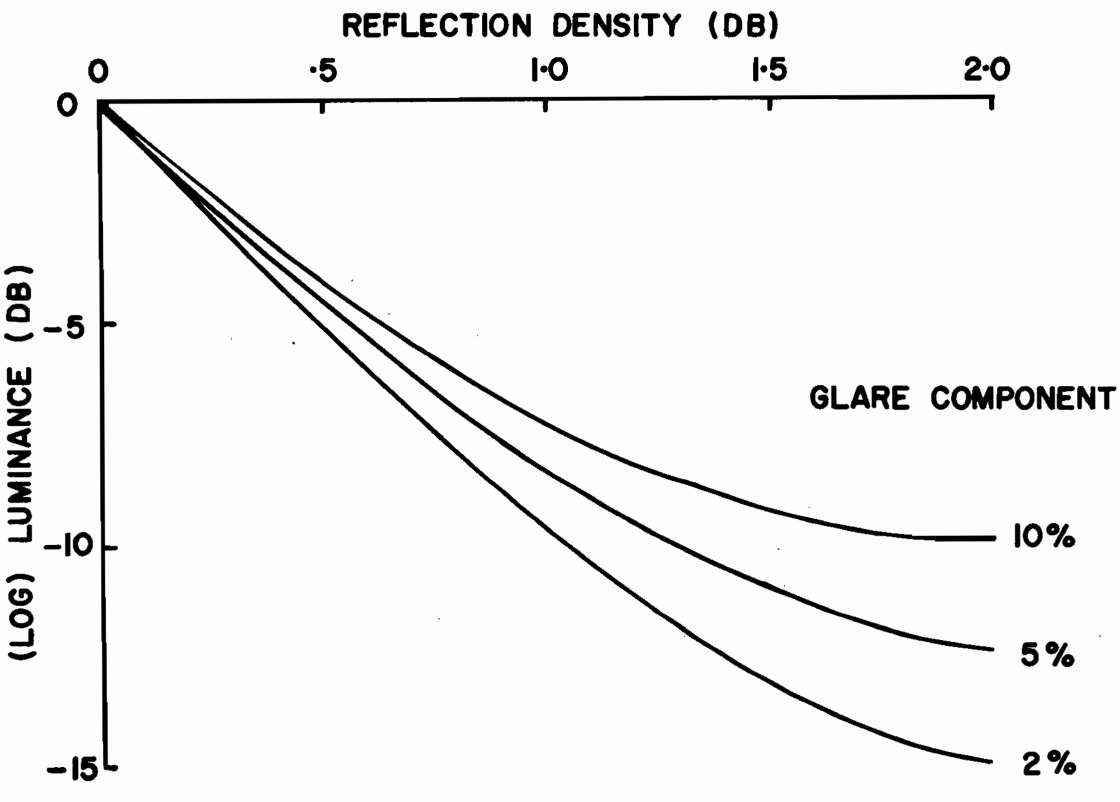
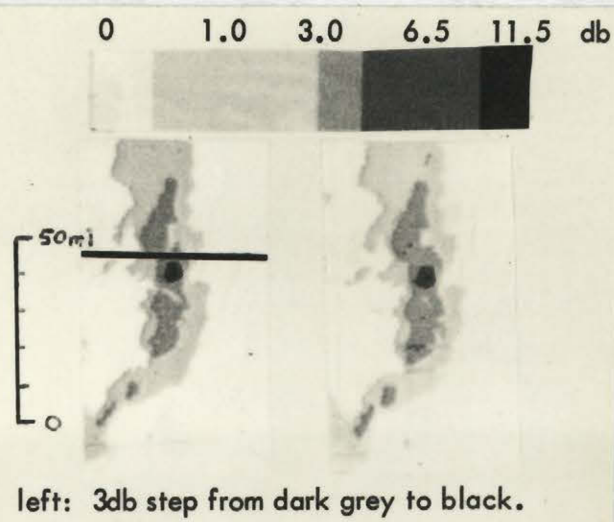


Fig. 3.6

of a glare term on the reflection density. Curves for three values of glare are shown: 2, 5 and 10%. A similar problem arises in cameras and other optical instruments where it is usually referred to as flare. In both cases it reduces the apparent contrast in the dark end of the grey scale.

An attempt was made in the early transmissions during the winter 1962/63 to display white echoes on a black background. It soon became apparent that such a display could not be run operationally. Rapid wear of the marking blade resulted from the fact that over 90% of the area was maximum black. Carbon accumulation on the helix caused severe vertical streaking in the picture so that after four hours the recorder had to be cleaned and the blade replaced. Several modes of operation were tried and are briefly listed in section 3.5. The



left: 3db step from dark grey to black.
right: 5db step.
above: four shades used in the example on the right.

Fig. 3.7

presentation offering the best compromise is shown in Fig. 3.7. In order to compensate for the loss of ability to distinguish between grey shades at the black end of the scale, the step from dark grey to black is made 5 db of the total 11.5 db. The four shades used in the left picture are shown at the top of Fig. 3.7. The step from background to the first shade is made only 1 db. The viewer intuitively knows that the first shade is in the picture because usually darker shades are also present. The eye only has to find the outline. In the case of the highest intensity echoes, difficulty arises as shown in the lower part of Fig. 3.7. While in the test pattern the 5-db step from dark grey to black appears comfortably large, in the actual echo it is barely enough. On the left a 3-db step to black is definitely not sufficient.

It should be noted that all the reflection densities quoted refer to the original facsimile picture. Reproduction through two processes to obtain the photograph in Fig. 3.7 has led to compression of light greys in the toe of the paper characteristic. Incidentally, the seventh intensity is not real; the sensitivity of threshold seven was lowered to display the sixth intensity as black in the left picture for purposes of illustration.

3.4 Facsimile Paper

(a) Sensitometric Characteristics

To be suitable for a grey scale display the recording paper must have an adequate range of contrast from black to white. Typically, the range is a factor 12, or about 11 db: The light diffusely scattered from the darkest patch is 8% of that scattered from the white portion. The paper is not archival, and if exposed to light after marking, it exhibits a shift in the grey tones. The contrast range of 11 db is typically the highest range of facsimile paper. (For comparison, the best glossy photographic print has a range of 16 db (factor 40) and a full-matte print has 13 db.) The main limiting factors are the surface texture of the paper after recording and the ratio of line width to line modulus in recording.

Examination of the paper under magnification reveals a texture of black elements mixed with light grey elements, analogous to granularity of a photographic emulsion, but on a larger scale. At maximum marking power the residual white grains are reduced, but in the limit they contribute to the reflected component.

In the black areas of the picture the marking lines tend to merge, but there remains a periodic variation in density as one traverses the record across the scanning lines. In the mid-greys the spaces between lines in effect result in a half-tone shade. In a black patch the remaining spaces contribute to the reflected light, limiting the maximum contrast. Because the spaces between lines vary with marking current, their relative contribution to the total reflected light also varies. In this respect they differ from the glare component which is fixed and to a first approximation independent of the reflection density.

Three types of paper were used in the D-611-F recorder:

Muirhead Instruments, type E

Hogan, type 63S

Muirhead Instruments, type H

The first two were found to be quite similar. They have typically a 10-db contrast range immediately after marking. The reflection density of the black then increases to about 11 to 12 db about 24 hours after marking. Part of the increase can be accounted for by a gloss acquired by the surface, so that the contrast range increases just as it does with a photographic print after its surface is made glossy. As the maximum black increases in density the dark greys do also and tend to merge with the black, while tones near white remain unaffected. The higher contrast range does not offer any advantages, however, because it is not available immediately after recording when the pictures are used operationally. In general the archival quality of the type E paper is worse than that of the type H paper. The type H paper has a range of 9 to 10 db after marking, which can be maintained operationally without undue demand on the recorder. The increase in density in the first 24 hours is not more than 1 db and the pictures could be stored for several months, although this is not an operational requirement.

(b) Measurements of Density

Density measurements were made in the laboratory 24 hours after recording. Measurements with a spot photometer (SEI)* were difficult to make because of the glare problem.. More accurate values were obtained by photographing a facsimile step wedge on a 4 x 5 inch high contrast plate (Kodak, Contrast Process Ortho). The plate was then processed together with a sensitometric test strip. The densities of the facsimile paper were obtained through the transfer characteristic of the film, determined by means of the test strip. A set of grey cards then served for a direct comparison in quality control at the recorder. Placing a card next to a grey patch on facsimile paper and comparing by eye proved to be an adequately sensitive method. The cards were made from grey "color-vu"** paper of known reflection density. Following the technique

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* Exposure Photometer, Salford Electrical Instruments, Great Britain.

**The Craftint Manufacturing Company, Cleveland, Ohio.

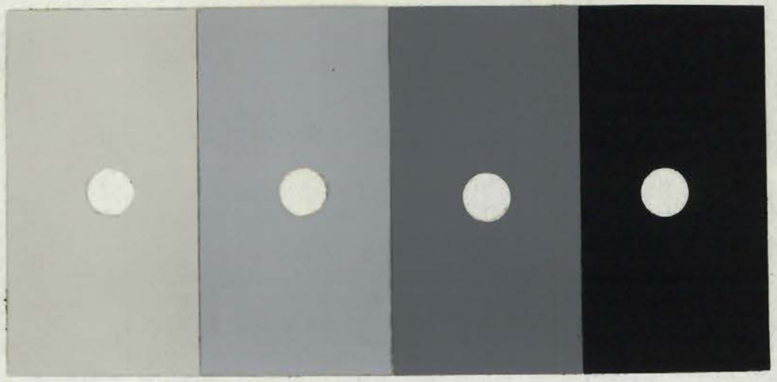


Fig. 3.8

used in spot photometers, the cards have a hole with a sharp outline (Fig. 3.8) and are placed over the grey patch on facsimile. The patch must be big enough to fill the hole in the test card. The difficulty of measuring the reflection densities directly suggests that for viewing the product care must be taken in locating the display and arranging the lighting of the facsimile pictures, if the full use of the contrast range is to be made.

(c) Electrical Characteristics

The signal applied to paper is derived from an amplitude-modulated carrier by full wave rectification. The marking current is pulsating D.C., but the individual pulses are not resolved on the record. Fig. 3.9a is a plot of the paper resistance against applied voltage. Because of the variation of the resistance with signal, the amplifier output impedance is matched to the paper only at maximum marking level where efficiency is important. The density of the paper is a function of the marking current rather than marking voltage. (The characteristic

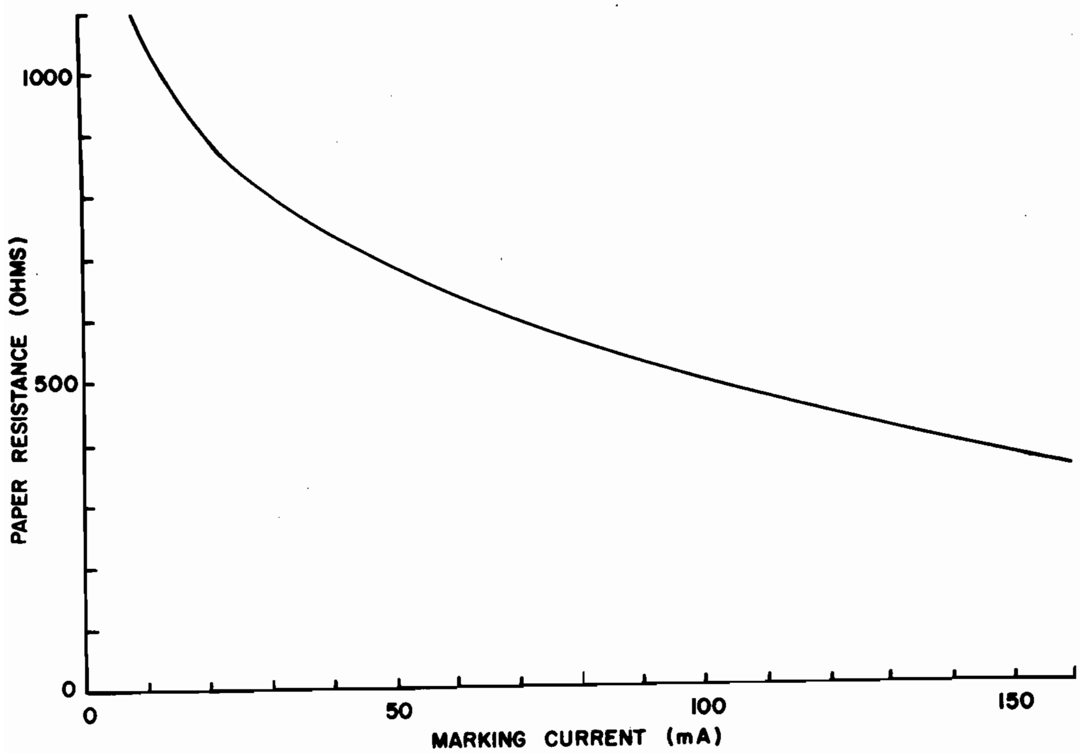


FIG 3.9a

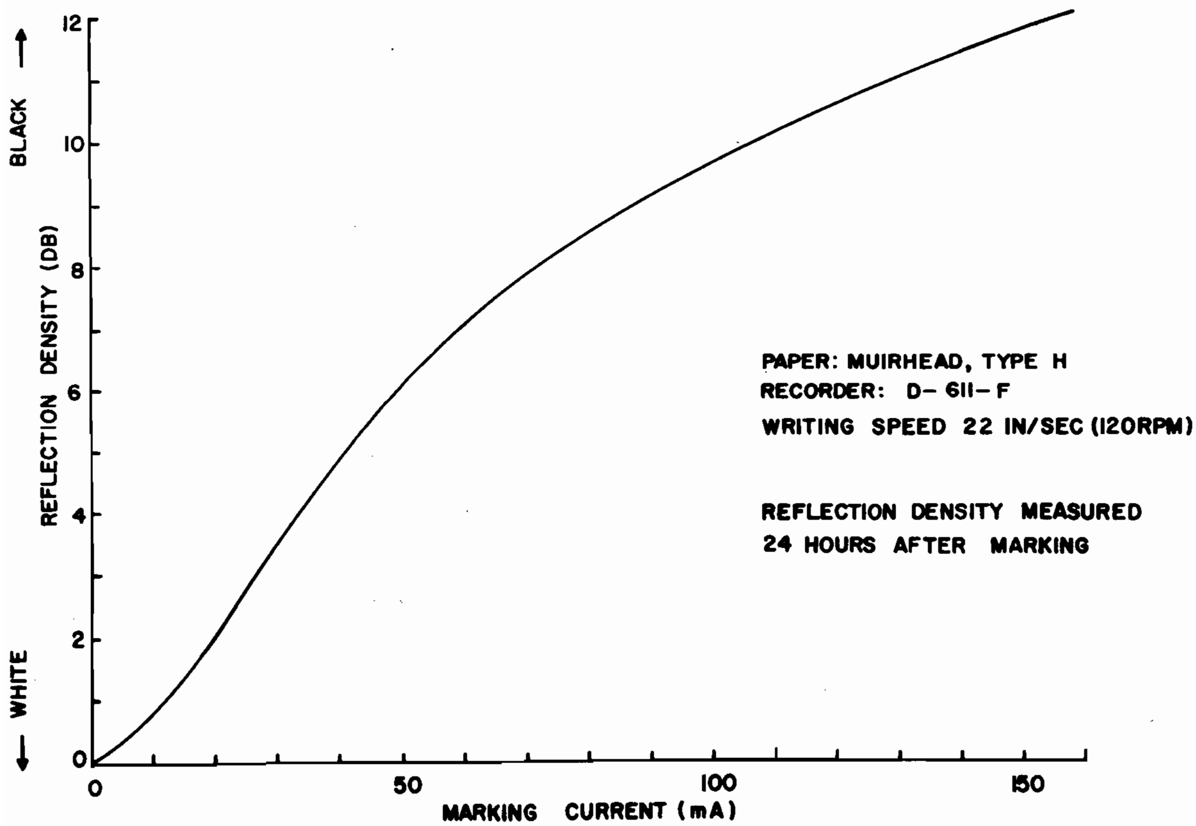
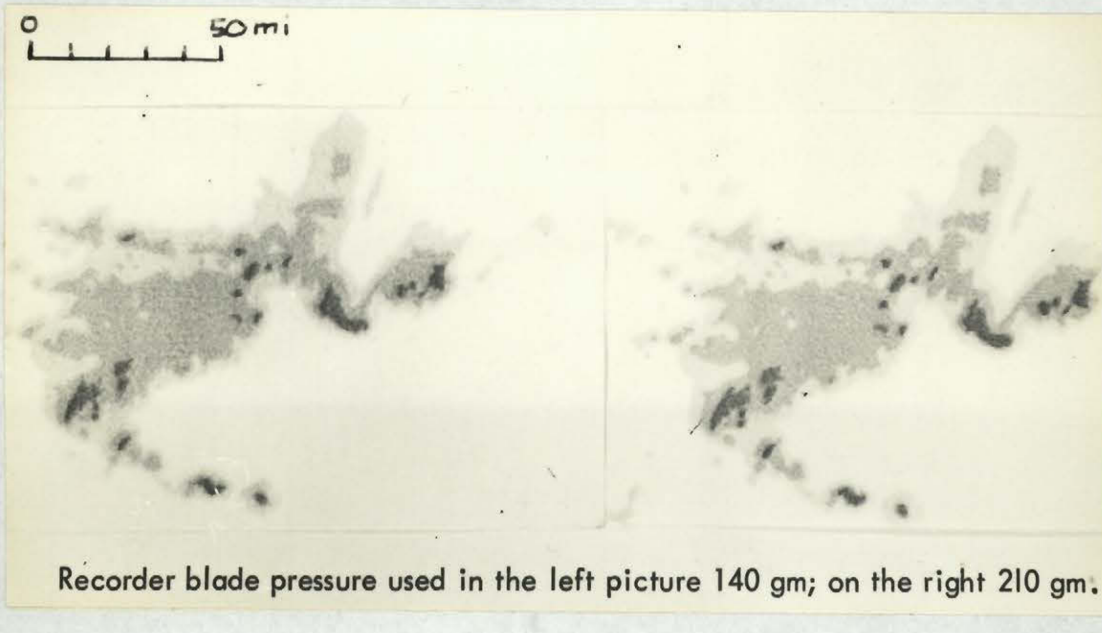


FIG 3.9b

is shown in Fig. 3.9b.) In the light greys the mismatch results in variations in the marking current as the resistance of the paper varies slightly from point to point, resulting in a worse graininess in the near whites than in the dark greys. A useful test would be to devise a marking amplifier whose output current is stabilized by feedback (constant current source) and thus hope to improve the graininess. The characteristics of the paper were found to deteriorate as the moisture content of the paper decreased. A roll stored in the machine for one or two days had usually higher resistance and a worse graininess. Similarly, rolls from different batches showed some differences. Consistent performance appears to require rather close tolerances on the moisture content.

The uniformity of the record depends to a large extent on the pressure exerted by the writing blade on the paper. Raising the blade pressure above the recommended 140 gms resulted in a marked improvement



Recorder blade pressure used in the left picture 140 gm; on the right 210 gm.

Fig. 3.10

in texture and sharpness (Fig. 3.10). A pressure of 100 to 120 gms resulted in a poor record. The recommended value was, however, not exceeded in operation to avoid damage to the helix wire.

The pressure of the writing blade is necessarily unbalanced in normal operation. The side on which the helix wire enters under the blade has to be reduced to avoid knocking and damage to the helix wire. The picture on that side therefore shows coarser grain than the other side, and unfortunately this is the side with four active shades where grain is particularly detrimental.

3.5 Signal Polarity

During the experiments both the black background and the white background pictures were produced. At the same time both positive and negative modulation polarity at the transmitter was tried. The system evolved through three stages before the final display form was arrived

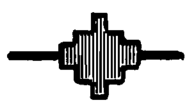
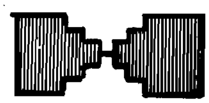
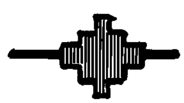
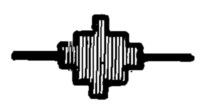
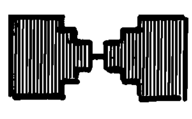
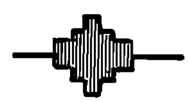
TRANSMITTER			LINE	RECORDER		
	MODULATOR			DEMOD-MOD		PAPER
	ON/OFF	MAX ECHO				BACKGROUND
April 63	20 db	MAX CARRIER		Reversal Curve B Fig. 3.2		BLACK
June 63	20 db	MAX CARRIER		Direct Curve C Fig. 3.2		LIGHT GREY
Aug 63	34 db	MIN CARRIER		Reversal Curve A Fig. 3.2		WHITE

Fig. 3.11

at. In previous sections reference was made only to the last form. The intermediate stages in the development will now be briefly described.

The relevant variables are tabulated in Fig. 3.11. From April to June 1963 white echoes were displayed on a black background. Since the recorders had the polarity reversal of the modulation built in, the modulation at the transmitter was positive. The positive modulation (max echo-max carrier) is a natural one and rather straightforward to align and understand, particularly for a stepped modulator. One difficulty encountered was a leakage of carrier through the modulator gates so that with all gates open (no echo) the signal was only 20 db

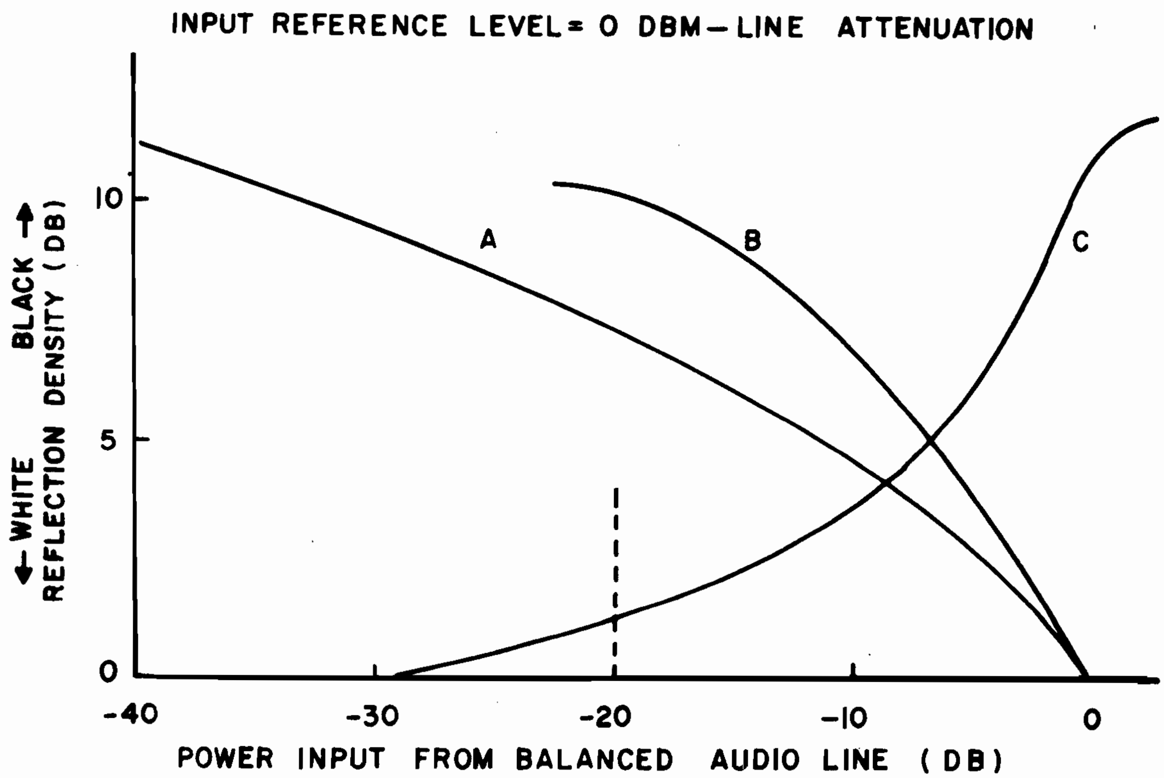


Fig. 3.2 (Repeated)

below the maximum. Referring to curve A in Fig. 3.2 (repeated in this section) the maximum black could never be achieved and the no-echo reflection density would be only 7 db. The shaping stage in the recorder was deliberately disconnected and the narrow dynamic range characteristic (curve B, Fig. 3.2) was used. Except for the more critical stability requirements due to the narrow range, the electrical performance was satisfactory.

After early trials it soon became apparent that there was little hope of using the black background display. The maintenance problems were unmanageable, although the pictures were quite pleasing when the recorder was in good condition. In June 1963 the polarity of marking was reversed to provide grey echoes on white background. First attempts at reversing the polarity of modulation at the transmitter were unsuccessful. As the echo increases, the carrier amplitude must decrease and the adjustment controls of the transmitter become interdependent and rather difficult to adjust routinely.

A quick solution was found in bypassing the demodulation and remodulation stages in the recorders, and feeding the amplified signal from the line to the marking amplifier (curve C in Fig. 3.2). The polarity of the transmitter output remained the more natural one: maximum carrier for maximum echo. The maintenance of the recorders was reduced to the point that Meteorological Officers in the Briefing Room could keep the recorder operating adequately. However the result left much to be desired. The limited dynamic range of 20 db on the line led to slight marking of the background on the paper. As shown in Fig. 3.2, the marking (at -20 db) produced a density of about 1 db. Being at the white end of the scale the 1 db loss represented a loss of one usable shade, and as a result only three shades (intensity levels

Fig. 3.12

1, 3 and 5) were displayed in the left picture. In addition, the pictures exhibited vertical streaking about 2 inches long, after an intense black marking (Fig. 3.12). Presumably the maximum marking locally changed the shape of the blade or caused a local deposit.

To eliminate the shortcomings in the pictures the system was changed in August 1963 to the final form. The bypassed stages in the recorder were reinserted, while the polarity of modulation at the transmitter was made negative (max echo-min carrier). The recorder was brought back essentially to the characteristic recommended by the manufacturers. The transmitter circuits were modified to eliminate the leakage and thus extend the dynamic range to better than 40 db. An alignment procedure for the modulator was evolved which enabled the sensitivities of the thresholds to be adjusted, as well as the individual shade controls, without interaction. While the shade adjustment is not as straightforward as one would like it to be, the system is quite practicable because the circuits are sufficiently stable that the output voltages have not drifted significantly over a three-month period.

4. FLYING SPOT SCANNER

4.1 Scanner Geometry

The rectangular raster, generated on the screen of the cathode ray tube is 120 mm by 93 mm. The raster is composed of 850 interlaced lines. The two sets of alternate lines produce the two adjacent pictures on facsimile. An optical system, shown in Fig. 4.1, is used to image the raster on the transparency. The raster is imaged by the objective lens (L1) on the film negative. The reduction (in linear

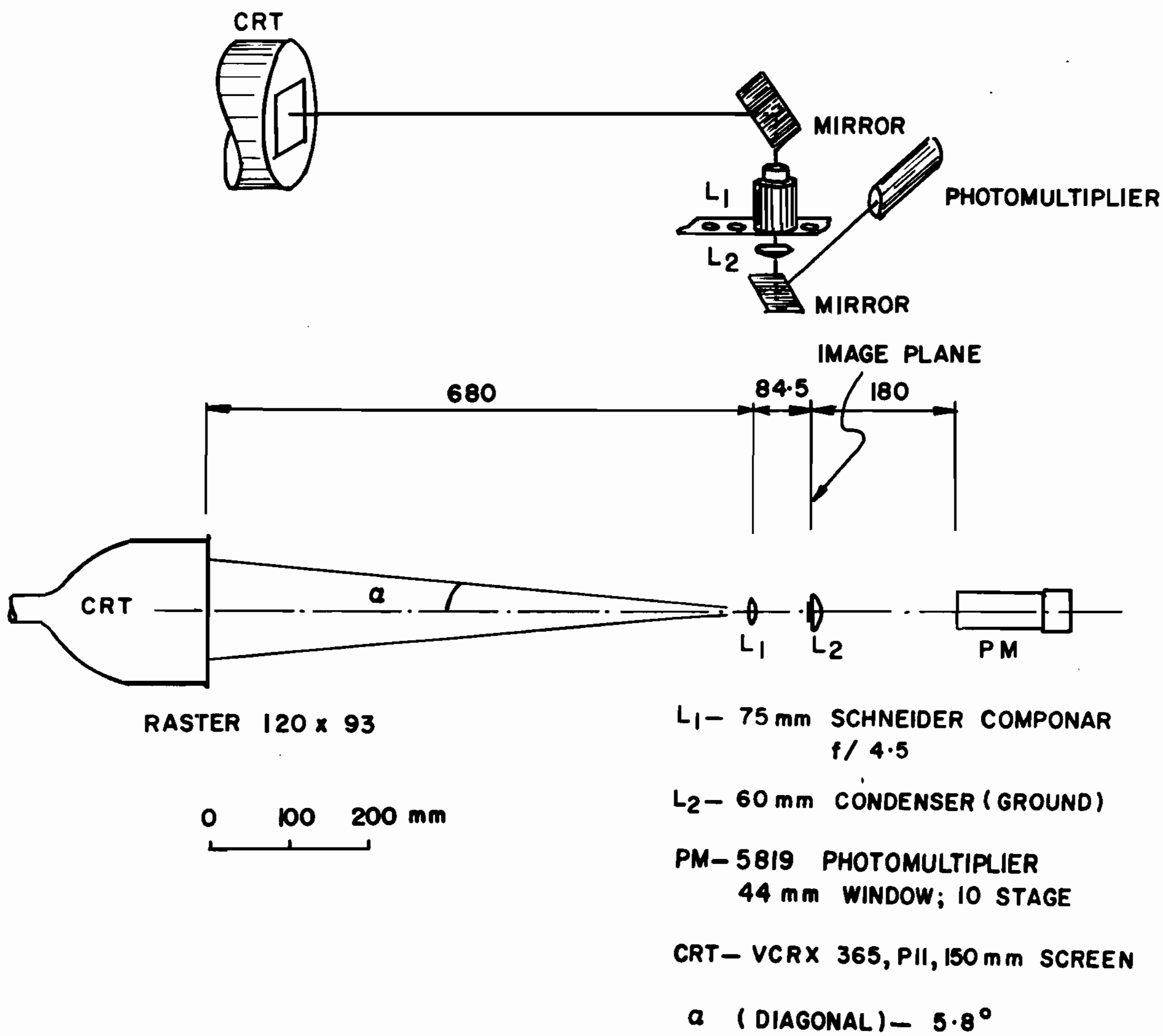


Fig. 4.1

dimensions) is 8.1 to 1. As the spot on the screen traverses each line, the spot in the image plane scans the photograph of the precipitation. A fraction of the light is transmitted through the film. The fraction depends on the transmission coefficient through the film emulsion over the image area of the spot. The transmitted light is thus modulated by the information on the transparency. A condenser lens (L2) behind the film gathers the transmitted light and directs it at the photocathode of the multiplier phototube.

4.2 Uniformity

The fidelity of the scanning system depends to a large extent on the uniformity of response over the whole frame. Any non-uniformities in the scanner are super-imposed on the original echo pattern as a spurious modulation. The two sources of non-uniformities are the cathode ray tube and the optical system. The contribution of the CRT is both a variation in light output over the area of the screen, and a high frequency component caused by the granularity of the phosphor. Scanner tubes are manufactured to tight specifications in this respect. The cathode ray tube used here is not a special scanner tube, but rather a high quality radar display tube. It was chosen for practical reasons, in that the tube-mount and the deflection elements were available for this particular tube (VCRX 365). The uniformity of the tube luminance was found to be within 1/4 db over the area of the raster. The noise amplitude caused by the phosphor grain is 1/4 db in light output. The figures are adequate but not exceptionally good. It turns out that the performance of a high-quality radar tube falls short of a good scanner tube.

The uniformity of the optical system depends on the proper design and alignment. As in any optical system, the axial alignment must be adequate. The condenser lens is chosen to image the exit pupil of the objective lens on the cathode of the multiplier tube. This assures that all the light passed through the objective is intercepted by the photocathode. As the image of the spot traverses the optical gate, the image formed on the photocathode is stationary and independent of the spot position. One consequence is that the information is not affected by non-uniformities in the photocathode.

The condenser lens has a focal length of 60 mm and forms a 36-mm image of the 15-mm objective aperture. Thus, all the light passing through the objective pupil passes through a point in the plane of the film, then spreads out to cover the stationary 36-mm disc on the photocathode. One could, for example, use a phototube with a smaller aperture and accept only a fraction of the total light without a loss of uniformity.

The choice of the objective lens also affects the uniformity. Proper mounting of the lens avoided vignetting by any aperture except the one in the image plane. It is, however, surprising that some expensive lens assemblies suffer from this elementary defect. The maximum angle of the rays from the object affects the uniformity and should best be kept small. The objective lens with the rather long focal length of 75 mm was chosen to limit the off-axis rays to 6^{o}. In a camera the response falls off as the fourth power of the cosine of the angle. While in the camera the significant quantity is the light per unit area falling in the image plane, in the scanner the signal is derived from the whole flux passing through the image plane. As a result, the response of a scanner varies only as $\cos^2 \theta$. The defect is therefore smaller, but on the other hand the requirement is correspondingly more stringent than in the case of a camera. For the angle of 6° between the marginal ray and the normal the fall-off is 1%. Also, when an objective lens with a long focal length is used, e.g. 75 mm, the design of the condenser is made easier. The plane of the objective is the object plane of the condenser, and as the separation is increased the condenser can be made weaker.

A small edge effect is caused by the contribution of the diffusely scattered light in the film emulsion. The condenser lens is designed to collect efficiently the specularly transmitted component. A fraction of the diffuse component reaches the phototube and part of it is blocked at the edges of the frame. Again the error is only 1%.

4.3 Scanned Format

The CAPPI picture with its peripheral test pattern occupies a circle 17 mm, and is positioned in the 19-mm circular aperture of the scanner. The scanned area is so chosen that the raster is wholly contained in the aperture. The scanned material is a negative which, in the absence of echo, has only the density of the film base so that maximum light is transmitted. If the spot were allowed to overscan the 19-mm aperture the light would be blocked by the opaque edge, resulting in a step of maximum contrast. Such a step is not desirable because at the recorder it would cause severe wear of the blade. The scanned rectangle is shown in Fig. 4.2. The dimensions were chosen to give a reasonable north-south coverage without scanning much beyond the range of 140 miles in the corners. The range from 140 miles to 170 miles is reserved for the grey test pattern.. Of the four patterns normally painted out on our displays three are blanked on the rapid

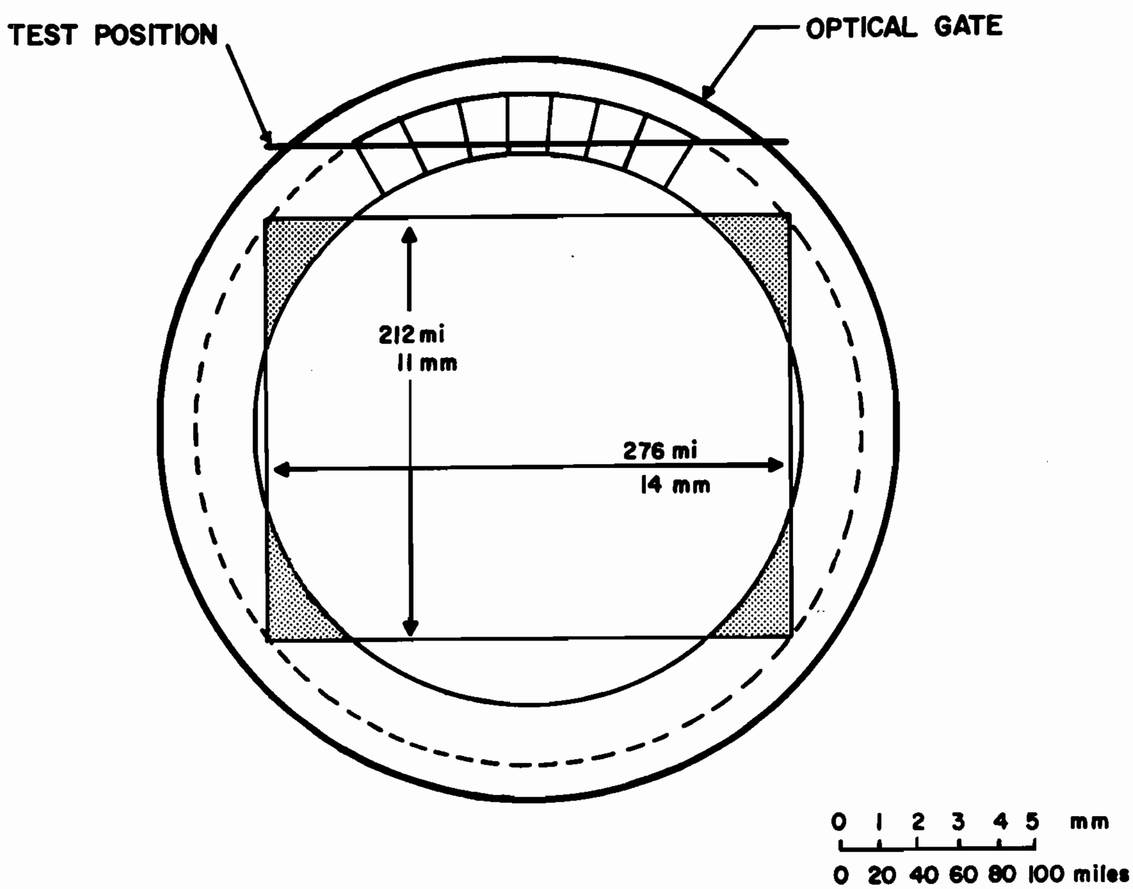


Fig. 4.2

processor display, leaving only the north pattern for monitoring purposes. The space normally reserved for the remaining three patterns is blank since the CAPPI circuits could not be easily modified to extend the radar coverage beyond the 140-mile range, and yet display the test pattern in the north. In the chosen format, the scale on facsimile paper is conveniently 50 mi inch^{-1}.

4.4 Photometric Relations

The photometry of the scanning system is to a large extent the same as that of a camera and in part is followed here. The spot can be assumed to be a Lambert source of an area A and having a luminance of B foot - lamberts* with a cosine distribution with direction. The total flux (F) intercepted by the lens of the diameter d is

$$F = \frac{BAd^2}{4u^2} \qquad 4.1$$

where u is the object distance.

This expression is derived further to give the flux per unit area, or illumination (E) in the image plane (see, for example, Marshall and Pounder 1957, p 587).

$$E = \frac{B}{4N^2} \cdot T_s \qquad 4.2$$

where N is the f/ number of the lens.

T_s is the transmission coefficient through the lens (nearly unity).

The flux per unit area is the relevant quantity in a camera, in that it determines the exposure of the emulsion. Thus the sensitivity of a camera is determined by f/ number alone. In a flying spot scanner the total flux through the image plane reaching the photocathode contributes to the signal. The total flux, given by equation 4.1 can be rewritten:

$$F = \frac{B}{4N^2} \cdot T_s \cdot a \qquad 4.3$$

where a is the area of the spot in the image plane.

T_s can now, for convenience, include the attenuation by the film base.

---

*A source, 1 sq foot in area with a luminance of 1 foot-lambert emits 1 lumen. The forward flux is $1/\pi$ lumen/steradian.

In general the flux reaching the photocathode thus depends on the speed of the lens and also on the spot size in the image plane. However, for a given application the required dimension of the spot image is fixed. In this case the relation reduces to the standard camera relation.

At audio scanning frequencies used here, the noise originating in the photomultiplier and its load is negligible compared to the signal. The minimum flux at the photocathode is 6×10^{-8} lumen, compared to the dark current equivalent of 2×10^{-9}. The maximum flux now used is 11 db above the minimum. There are still 10 db in hand on either side of the dynamic range now used, before on the one side noise becomes a problem, or on the other side the CRT luminance becomes excessive. The phosphor grain presents a more serious problem. As the spot moves across the screen the output current fluctuates, but the term "noise" is only partly applicable. One component of the noise is fixed and independent of spot brightness. The second component is in the form of a modulation of about 1/4 db. At the brightness levels at which the scanner is operated, the modulation component is the larger of the two.

4.5 Photometry and the Image on Film

The material to be scanned is a negative transparency on which most of the area has not been exposed and is therefore clear. The areas of echo have a density depending on the exposure and the film characteristic. The seven steps on film cover a density range up to 11 db above base. The step from base to shade one is made typically 2 db; the other steps are 1.5 db. The densities of the emulsion referred to throughout this work have been measured on a Kodak 1A densitometer and are therefore diffuse densities. The quantity of importance in the flying spot scanner is nearly the specular density, which in general is the higher of the two.* The modulation of light flux by the film can be described as follows. Let the maximum flux reaching the photocathode in the absence of echo be F_o, as determined in section 4.4. Then, as the spot is imaged on a denser portion of the film where the transmission coefficient is T_s, the flux is

$$F = F_o \cdot T_s \qquad 4.4$$

The current from the phototube (i) is proportional to F, such that

$$i = (G F_o) \cdot T_s \qquad 4.5$$

where G is the phototube sensitivity (15 amps/lumen) and F_o is 0.6×10^{-6} lumen.

The output current is thus linearly related to the transmission coefficient. At first it would appear advantageous to distribute the seven intensity levels linearly on the transmission scale of the transparency. Such an arrangement would offer two advantages. (1) If there are variations in the transmission through the film within the area of the spot, the output is proportional to the total light flux, which in turn is equally weighted by the transmission coefficient.

$$F = F_o \int_{\text{area of spot}} T_s \cdot da \qquad 4.6$$

*A half-tone screen is an example of a filter for which the specular and diffuse transmission coefficients are identical because the diffuse component alone is zero.

(2) At the output of the phototube the seven intensity levels will be equally spaced on a voltage scale. The equal spacing is well suited for the stepping circuits that follow the photocell.

Difficulties are however encountered with equal transmission steps which tend to outweigh the advantages. The equal density steps on film were chosen because the logarithmic quantity density is the more natural quantity to describe a photographic process. In addition, the uniformity and stability of the system have to be considered. Non-uniformities in the optical system are fractional errors, as are variations within the area of the CRT screen. Temporal variations or instability of spot luminance is also a fractional error. If the steps are logarithmic, these disturbances tend to affect all intensities equally. The equal transmission steps are difficult to produce on the first cathode ray tube. Because of the third power relationship between signal voltage and luminance of the first display CRT, the video signals are compressed near the low intensities to produce equal factors in luminance on the display. The compression in the low intensities would have to be even greater to produce equal transmission steps. Also, the stability of the first CRT would affect the system in the same way as does the scanner CRT.

For these reasons, equal density steps of about 1.5 db are produced on film. The first step from base is made 2 db to avoid penetration of the lowest threshold by the background output of the scanner leading to a noisy picture on facsimile. The overall transfer power law from antenna received power to the density scale on film is (9 db/60 db) = 0.15. The density is thus proportional to the power level (log P_r). Since the density is itself a logarithmic function of T_s, the transmission coefficient, T_s, turns out to be:

$$T_s = \frac{K^{0.15}}{P_r^{0.15}} \qquad 4.7a$$

where P_r is the received power, range normalized

and K is a constant nearly equal to the radar sensitivity.

The phototube current, i, is

$$i = (GF_o)\frac{K^{0.15}}{P_r^{0.15}} \qquad 4.7b$$

The current is 10μa when the spot is imaged on the clear base. For each 1.5-db step, representing 10 db in target strength, the current

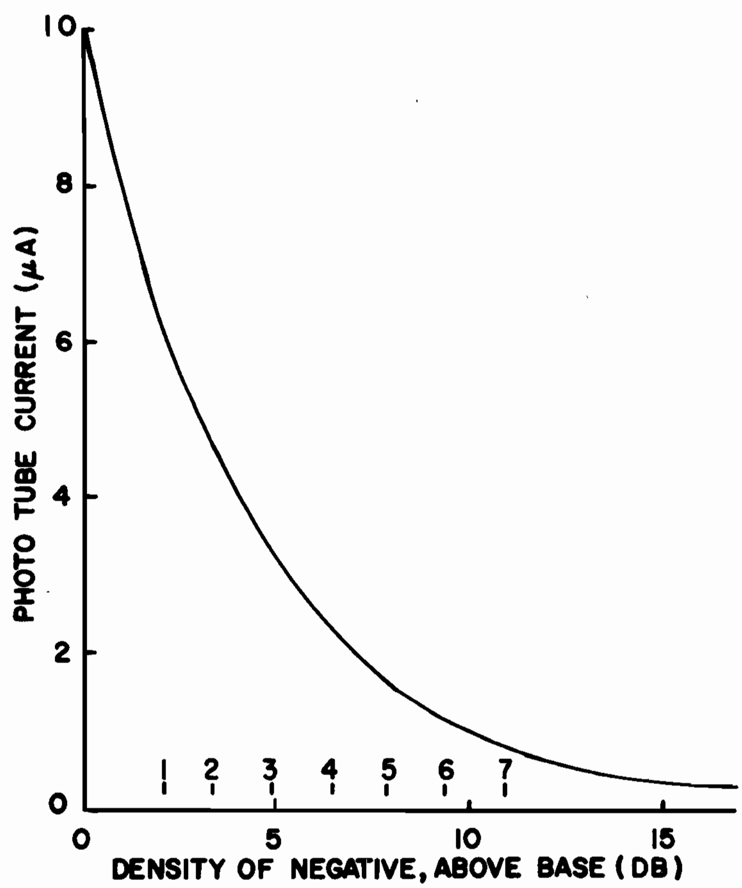


Fig. 4.3

decreases by 1.5 db. Fig. 4.3 is a plot of output current against the film density. The seven intensity levels are indicated along the abscissa.

The equal density steps leave two problems which are still unresolved. The first is the inconvenient crowding of the steps in the high echo intensities. The compression is objectionable particularly in our system, where the signal is stepped by a thresholding circuit. The difficulty has been almost eliminated by using a non-linear load at the output of the photomultiplier, as will be described later.

The second difficulty arises from the distortion which occurs if the spot has to average out spatial variations in density within the area of the spot. Since the signal depends on the average transmission coefficient (equation 4.6), the output will be biased towards low intensities if there are large variations within the area of the spot. The natural fluctuations in the received signal are partly averaged when they appear on film. A numerical check on the distribution of signals suggested that the bias error is not more than 2 db in received power, which is comparable to, or better than, the limiting instrumental accuracy of the system. Integration in range over two pulses before the first display helps in this respect by narrowing the distribution before displaying. Therefore, even though there is areal integration in writing the pattern on the CRT and then reading it with the scanner, the initial integration in range is useful to narrow the distribution and was therefore not eliminated when the scanning system was introduced.

The small scale variations in the film density, originating in the radar itself can lead to greater difficulties. The ripple pattern caused by a modulation of the spot position at a 60-cycle rate is still a serious unresolved defect in our grey scale displays. The beat pattern is noticeable in the peripheral test pattern where the line spacing is greatest. Since the thresholds are calibrated against the test pattern, the fact that its densities will appear smaller will result in an overestimate in the echo intensity. Defocussing the camera lens (ahead of the film) is a practical if not an elegant way of reducing the effect.

The considerations of the distortion of the intensity scale have led to the realization that the half-tone filter used to correct for the variable line spacing will lead to distortion if the individual dots can be resolved on film. Consider the following example: At one tenth of the CRT screen radius the areal brightness is ten times what it is at the edge of the screen. The filter at the short range is made to have 10% clear area and 90% opaque, resulting in the same average exposure at both radii. If the filter is in focus and resolvable on film, the exposure at 1/10 radius will consist of dark dots covering 10% of the area surrounded by 90% of clear base. The average density will be nearly the base density. Fig. 4.4 is a plot of the equivalent average density as a function of range for two values of density at the edge, 3 db and 6 db. At short range both values tend to be near base. Now the above example is extreme in that the pure half-tone pattern will not be reproduced on film, and some averaging will be caused by scattering and insufficient resolution. However, the case of a partly resolved filter can occur and, while the error will correspondingly be smaller, it is best to focus the camera judiciously and, if necessary, to move the filter away from the CRT

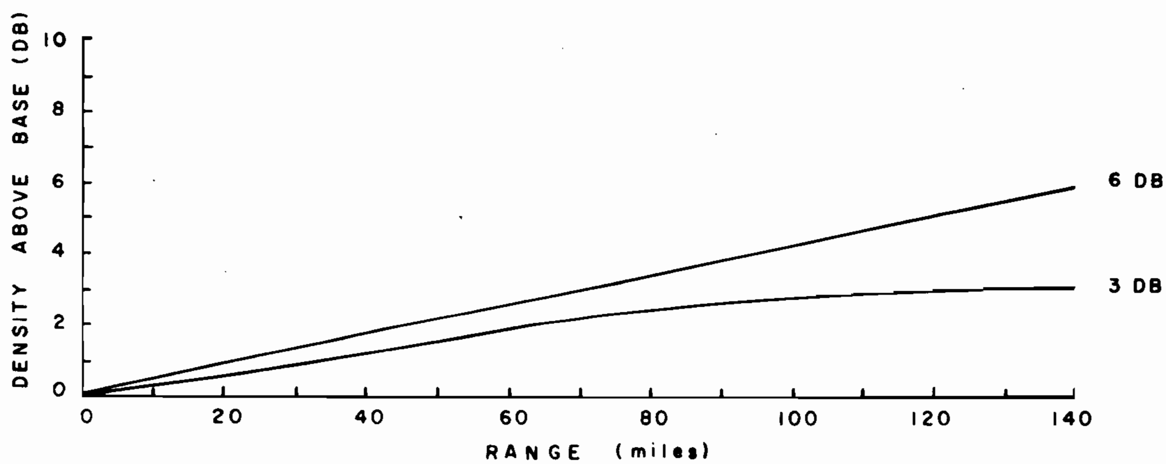


Fig. 4.4

until the circle of confusion for the given f/ number exceeds the dot spacing. In our case the dot spacing in the image plane of the camera is 0.03 mm. The corresponding depth of field for a 40-mm lens, set at f/2 is 3 mm. Thus, at the f/2 setting it is only necessary to focus the camera properly. At the f/4 lens opening used on our displays the thickness of the face-plate is just sufficient to eliminate the dot pattern on film if the object plane is set just behind the plane of the phosphor. Once the filter pattern has been lost, its function to correct the average exposure is completed. The negative can then be passed through further photographic processes (or through electro-optical scanning) without distortion of the grey scale.

4.6 Spot Size

We have assumed so far that the spot is a disc of uniform brightness. In actual fact the luminance varies over the area of the spot and is maximum at the centre. The distribution of electrons in the beam is gaussian. In the ideal case of no aberrations in the electron optics the charge distribution falls off exponentially with the square of the distance from the centre of the beam, leading to a similar light distribution in the spot (Soller et al, 1948). The gaussian region extends outwards to where the intensity is about 10 db below the peak intensity. Thus, if we define the luminance (per unit area) B (foot-lamberts) then

$$B = B_o \exp\left[-\frac{r^2}{1.44 r_o^2}\right] \qquad 4.8$$

B_o is the luminance at the centre of the spot and r_o is the radius at which the luminance is one half of the maximum. At 1.8 r_o the luminance is 10 db below the peak. The spot diameter normally quoted in the literature is 2 r_o.

The light flux is detected by a phototube which is sensitive to the total light reaching the photocathode. It is therefore of interest to consider contours containing a given fraction of the total intensity I_t. The fraction I_r/I_t can be found by integrating the function in equation 4.8.

$$\frac{I_r}{I_t} = \frac{\int_0^{2\pi} d\phi \int_0^{r} B\, r\, dr}{\int_0^{2\pi} d\phi \int_0^{\infty} B\, r\, dr} \qquad 4.9$$

The details will not be reproduced here but essentially the integral of the volume of revolution of a gaussian is simpler to evaluate than the more common area under the gaussian. The integral of equation 4.9 leads again to a gaussian and, in fact, the fraction of the total flux emerging from a circle of radius r, $\frac{I_r}{I_t}$ is given by

$$\frac{I_r}{I_t} = 1 - \exp\left[-\frac{r^2}{1.44\, r_o^2}\right] \qquad 4.10$$

Comparing equations 4.9 and 4.10, we see that at radius r_o the luminance is one half of the maximum (equation 4.9) and half of the total intensity is contained within the circle of radius r_o. Similarly at r = 1.8 r_o, B is 0.1 B_o and I_r/I_t = 0.9.

As the gaussian spot scans past an opaque straight edge, the

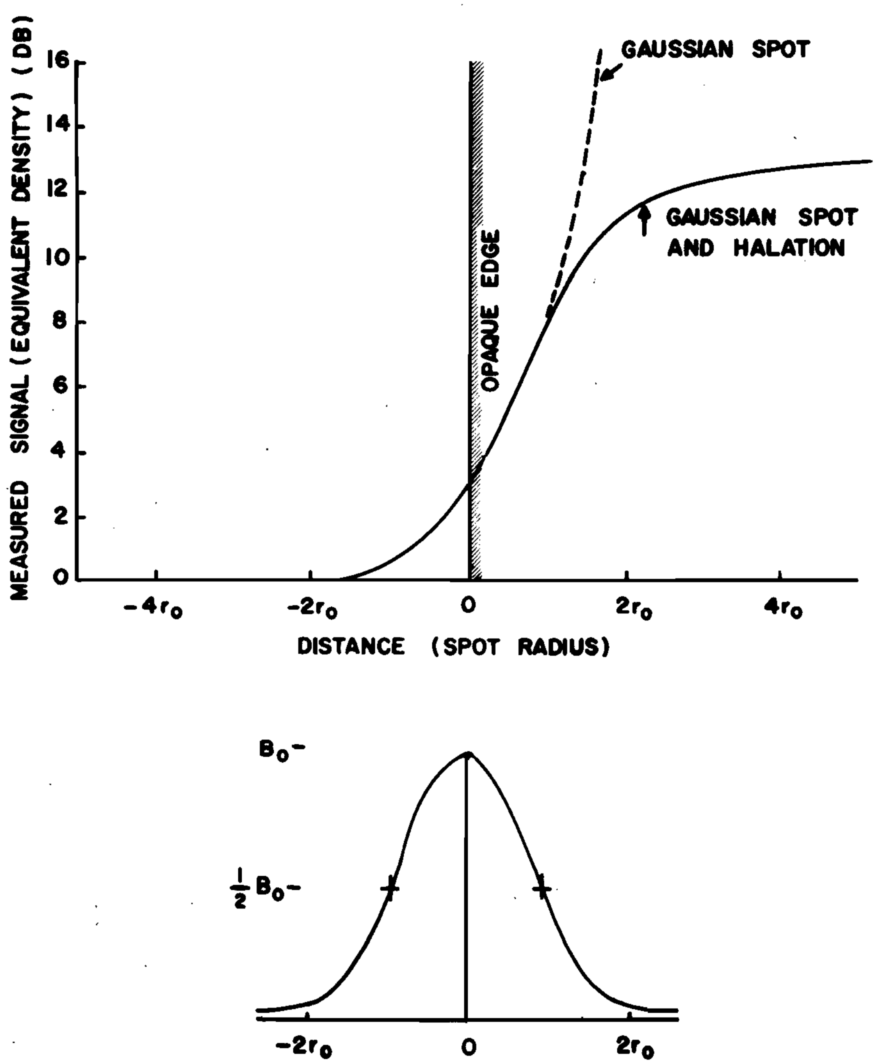


Fig. 4.5

signal decreases from the maximum through the full dynamic range in two half-intensity diameters. The waveform is shown in Fig. 4.5 (dashed curve) against a logarithmic ordinate. In actual fact, the signal levels off about 13 to 15 db below the maximum, due to scattered light and background light (solid curve). In the context of the present work where the dynamic range is about 10 db, the spot diameter measured at the -10 db level is of greater interest in determining the sharpness of edges after scanning, as shown in Fig. 4.5. The half-luminance diameter is more relevant to the averaging of the transmission coefficient by the spot: The information within the half-density diameter is weighted about equally, while beyond this diameter the contribution to the total signal is small, except possibly at the edge of a sharp transition.

The spot diameter on the flying spot CRT was measured by scanning a sharp edge of an opaque material placed in the scanner optical gate (a razor blade was actually used). The waveform from the photomultiplier output was displayed on a cathode ray oscilloscope and recorded as the spot emerged past the edge. The spot radius was measured by noting the time required for the intensity to change from $1/2\ I_t$ to I_t, and converting this time to distance on the face of the CRT. The half-luminance diameter turned out to be 0.2 mm or 0.5 miles on the scale of the transparency. The diameter at 10 db below the maximum luminance is about 0.4 mm, or 1 mile.

A more precise and a correspondingly more elaborate method has been outlined by White (1959). White's equipment is similar to a flying spot scanner except the optical system is arranged to produce a magnified image (x5) of the spot rather than a reduced image as in our scanner. With the image suitably enlarged it is possible to scan an aperture which is small in relation to the size of the image, and thus produce a detailed intensity profile of the spot.

One technique to measure spot size uses a TV-type raster which is slowly shrunk until the adjacent lines appear to merge. The intensity in the valley is the sum of contributions of two adjacent lines and appears to be equal to the peak intensity if each of the contributions is 3 db below the peak. The spot diameter is then equal to the height of the raster divided by the number of lines in the raster. The shrinking raster technique is known to yield diameters smaller than the diameter at the half-intensity. Another technique involves measuring the spot size with a microscope. It gives a considerably larger diameter because the eye observes the edge of the spot much lower on the intensity profile. Furthermore, the diameter measured this way also depends on the spot brightness and on the ambient light.

4.7 Halation

The contours containing a given fraction of the total emerging flux follow the gaussian relation of equation 4.9 out to the contour containing about 90 or 95% of the total. This gaussian region can conveniently be called the primary spot. The primary spot is surrounded by a halo extending over an area of several square centimeters and which contributes 5 to 10% of the total light reaching the phototube. A small echo on the film of say a density 10 db above base modulates the primary spot, resulting in a 10-db decrease in the flux in the primary spot. The halation component will reach the phototube unattenuated, or at most partly attenuated. Its contribution may then be comparable to the modulated primary spot. The halation effect is quite similar to lens flare, but is larger. A camera lens is capable of photographing an outside scene whose luminance range may reach 30 db. The contrast range of a CRT is 10 to 13 db (corresponding to a halation contribution of 10 to 5%).

The effect of the halation is to reduce the measured density from the actual density, as shown in Fig. 4.6. The curve for a 5% halation component is low by 2 db at the limit of the dynamic range (11 db above film base).* A fraction of the halation will also be

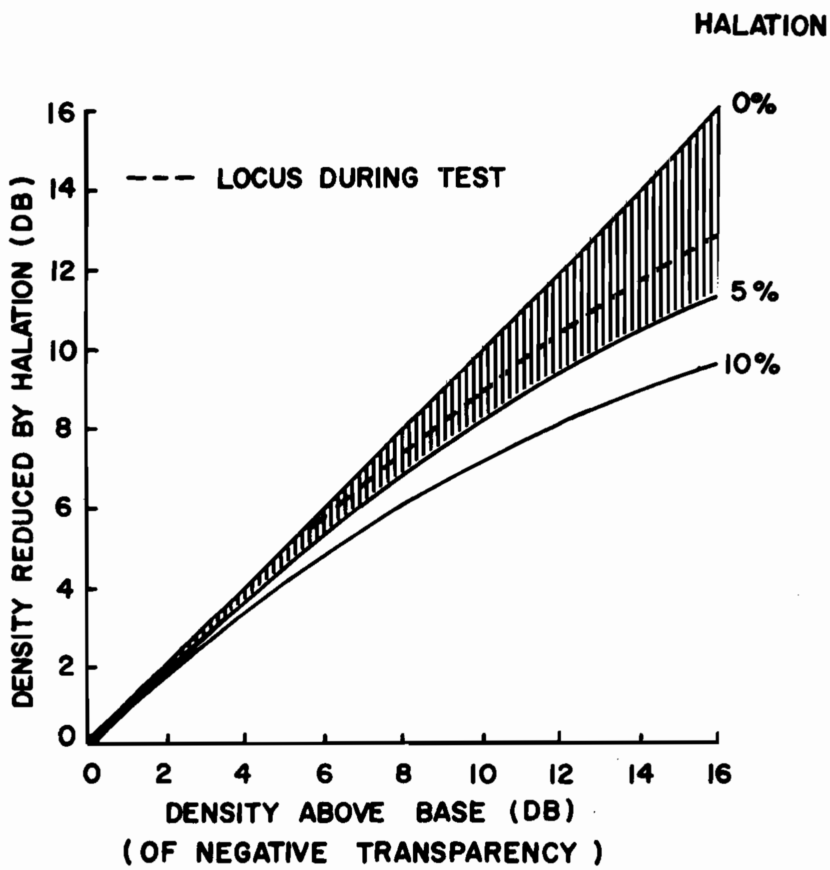


Fig. 4.6

*Because the film base attenuates the total flux equally, it is convenient to measure all densities above base.

reduced by some portion of the echo, the actual fraction depending on the type of echo. The echo from wide-spread precipitation will reduce the halation component more than small scattered echoes. As a result, the operating point is confined to the shaded region rather than remaining on the solid curve. The sensitivities of the seven thresholds in the modulator are adjusted when the spot scans the test pattern in which the 30-mile wide patches obscure a good portion of the halation. The dashed line in Fig. 4.6 represents a likely locus of operation while the test pattern is scanned. The actual weather pattern will therefore fall above or below the locus, depending on the areal extent of the echoes.

The total amount of halation in a flying spot scanner can be related to the contrast range of a television CRT. Once the relation is established, the information on the television contrast range, which is available in the literature, can be applied to the flying spot scanner. In television one defines the detail contrast in the following way: A bright raster covering the whole CRT is displayed, and in the centre a small area is electrically blanked. The detail contrast is the ratio of the maximum luminance of the raster to the luminance of the unexcited area (Law, 1939). As the spot paints the raster, the halation that the spot contributes at any instant to the test area depends on the relative distance of the spot. The raster is painted out rapidly and the measuring instrument integrates the total contribution of all the picture elements. The detail contrast is therefore directly equivalent to measuring the total halation of a stationary spot. The figures quoted for the detail contrast can thus be used directly as a measure of the dynamic range of the CRT when used as a flying spot scanner.

The results are also applicable to the shortcomings of the radial CRT display. On the display CRT the definition of detail contrast applies to the worst situation, seldom met in real precipitation. A more realistic figure is the contrast at the edge of a bright semi-infinite raster (for example the edge of shade 7 in our test pattern). This contrast is equivalent to totalling exactly half the halation of the stationary spot, and is therefore 3 db better than the total halation. On the display CRT the greatest halation effect is due to shades 6 and 7. The contribution of the halation, however, is only significant in comparison to the luminance of shade one. Halation associated with the highest shades also exposes the echo-free areas and so raises the fog level of the film. However, by increasing the density of the first shade and raising the first threshold (in the scanner), the picture on facsimile can be kept clean.

Extensive measurements of detail contrast were made by Law (1939). The values he obtained ranged from a factor 6 (8 db) to 25 (14 db). The method used by Law was to project images from the rear on a glass plate with the phosphor backing, instead of using a complete cathode ray tube.

The halation contribution on the scanner CRT was measured by inserting appropriate test frames into the scanning aperture. The frames consisted of an opaque disc, slightly bigger than the image of the primary spot, surrounded by an annular ring of clear base, and again opaque outside of the ring. The transmitted light was a measure of the halation component within the annular ring. Measurements with several rings were made to obtain some indication of the distribution with the distance from the primary spot. The results listed below place an upper limit on the probable values.

mm on CRT	Miles	Fraction of Flux
0 - 0.4	0 - 1	90%
0.4 - 4	1 - 10	5%
4 - 8	10 - 20	2%
8 - 20	20 - 50	2%
20	50	1%

The most suspect value is the 5% for the range from 1 to 10 miles. The difficulty was caused by the small size of the mask (0.05 mm). The physical explanation of the causes of halation indicates that close to the primary spot, where the measured contribution is 5%, there should be less than 1%. Also, of the total 10% from outside of the primary spot, 2% is due to scattered light in the optical system; (2% is high for an optical system; a properly mounted camera lens, instead of our enlarging lens, should reduce the flare to less than 0.5%). While the scattered light does not originate on the CRT, it is part of the system as used in normal operation, and so must be included in assessing its performance. Allowing for the 5% in the annular ring from 1 to 10 miles as being somewhat suspect, the halation contribution can be placed to be about 5%.

4.8 Cause of Halation

The halation surrounding the primary spot is caused by multiple reflections in the face-plate of the cathode ray tube. A fraction of the light is trapped in the face-plate and is thrown back at the phosphor. The specularly reflected components emerge in random directions and do not reach the lens. A portion of the light thrown back at the phosphor is diffusely reflected by the phosphor, and constitutes essentially an extended source, each element of which has a cosine distribution. The lens intercepts the flux from the extended source in the solid angle subtended by the lens opening, just as it does from the primary spot. The amount of halation is therefore the intensity of the extended source as a fraction of the total intensity of the primary spot. Surprisingly, in the older types of cathode ray tubes without an aluminized backing on the phosphor, half of the diffuse radiation emerges on the vacuum side and only half is thrown forward. The halation of an aluminized screen which reflects about 80% in the forward direction can therefore be expected to be considerably worse. (In other respects the aluminized screen is superior because of the increased luminance of the primary spot and because of the protection against ion burns.)

If the phosphor is in optical contact with the face-plate, the distribution of the flux in glass is a cosine distribution (top-left in Fig. 4.7). The flux beyond the critical angle is totally reflected at the front surface and is trapped in the face-plate. If the phosphor is not in contact the light is refracted upon entering the glass, so that essentially all the light is contained within the critical angle (top-right in Fig. 4.7).

Fig. 4.7 summarizes the two types of screen deposition, in optical contact on the left, and not in contact on the right. In all graphs the ordinate is related to the flux which arrives at glass-air interface (front) in a 2^{o}-differential cone, sketched at the top. In the upper left graph 58% of the flux is trapped in the glass (area

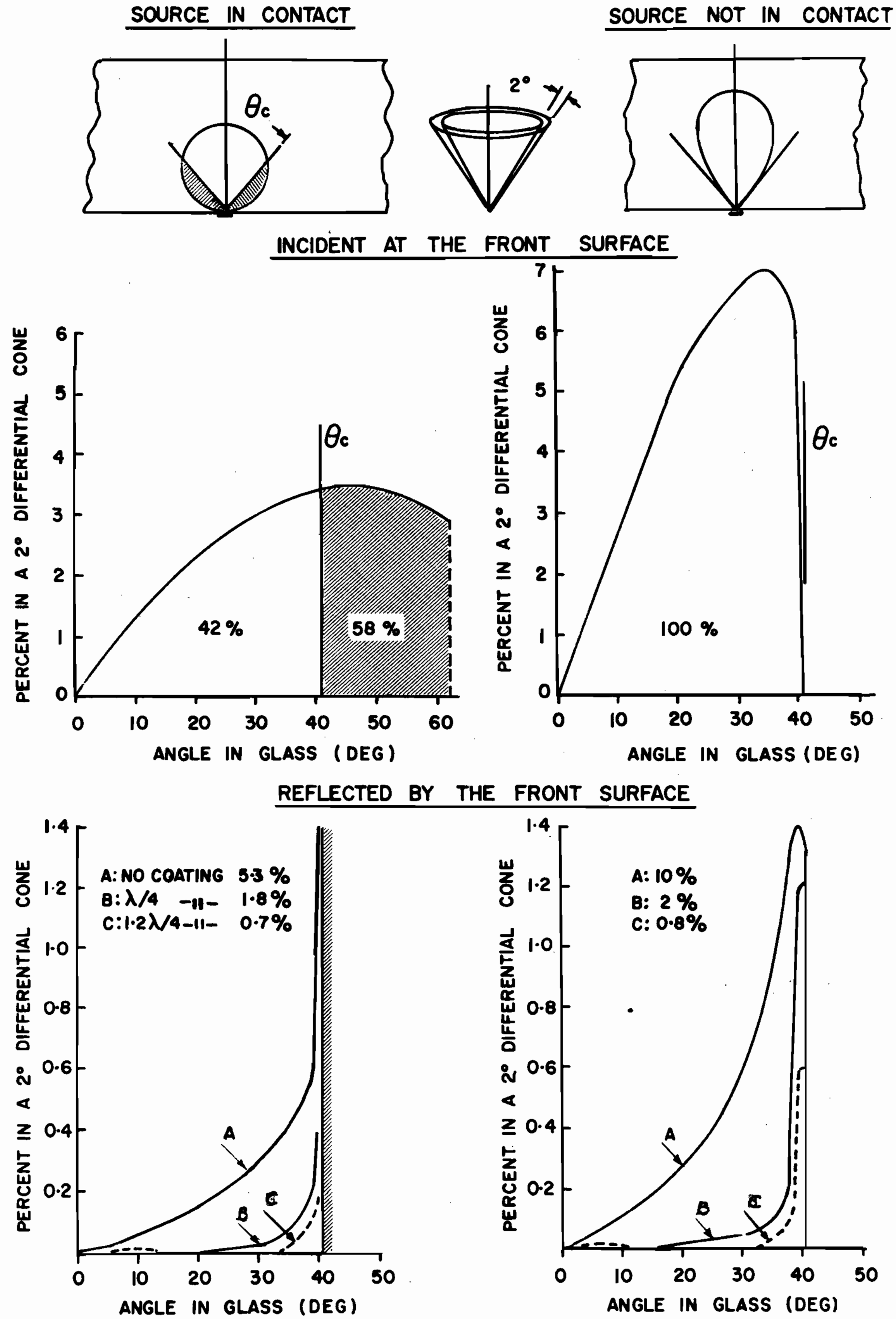

SOURCE IN CONTACT
SOURCE NOT IN CONTACT
θc
2°
INCIDENT AT THE FRONT SURFACE
PERCENT IN A 2° DIFFERENTIAL CONE
42 %
58 %
100 %
ANGLE IN GLASS (DEG)
REFLECTED BY THE FRONT SURFACE
A: NO COATING 5·3 %
B: λ/4 -ıı- 1·8 %
C: 1·2λ/4 -ıı- 0·7 %
A: 10 %
B: 2 %
C: 0·8 %
A
B
C

FIG. 4.7

under the curve).* Of the 42% within the critical angle another 5.3% is reflected (area under curve A, bottom left) so that only 37% emerges.

For the case of no optical contact between the screen and the face-plate, the flux reflected at the front surface is 10% (area under curve A, bottom right).

Normally one would expect a fraction (D) of the phosphor to be in contact and a fraction (1-D) not in contact, so that the total halation would be made up of the two components. Now, of the flux thrown back at the phosphor, only a fraction is diffusely scattered. The remainder is specularly reflected. (On reflection, the diffuse component is again D, while the specular component is 1-D.) For any fraction (D) between 20 and 80% one would expect to observe a set of concentric bright rings due to successive reflections. No rings were, however, observed, indicating that D must be close to unity. On the other hand, a high value of D would imply a halation component higher than 10%, yet measurement indicates that it is in fact less than 10%.

Attempts were made to devise a way of improving the contrast range of the scanner. Law (1939) has shown that halation can be significantly reduced by using a face-plate which absorbs a fraction of the light. The same observation was made by Haines (1953). In essence the advantage is taken of the fact that the parasitic light has a longer path-length in glass, due to the large angle off-normal, and has to traverse the path three times. Law calculated the detail contrast for a typical phosphor, as function of the absorption of the

*The fraction contained in a cone of angle θ is $\sin^2\theta$. For $\theta = 41^\circ$ the fraction is 0.58.

light in the face-plate for different fractions (D) of screen in optical contact. His graph is reproduced in Fig. 4.8.

In our case there was no possibility of adding such a face-plate to an existing CRT. There was, however, a possibility that an anti-reflection quarter-wavelength coating could make a considerable improvement. Returning to Fig. 4.7, curves (B) in the lower graphs are the calculated reflection components for a face-plate with a coating. In both cases there is a large improvement at angles, less than the critical angle. On the left, however, the coating has no effect on the radiation beyond the critical angle, which is by far the more significant fraction, while on the right the improvement is considerable: from 10% to 2%. (Calculations were also made for a somewhat thicker coating - $1.2\lambda/4$ - to allow for the peak in the flux distribution being near 30^{o}. A further improvement results, indicated by curves C in Fig. 4.7.)

A quarter-wavelength coating was evaporated on the scanner CRT and the spot characteristics were re-measured. There was no noticeable improvement, indicating that at least 30% of the phosphor must in fact be in optical contact. There remains therefore the conflict that

(1) Absence of concentric rings in the halo indicates a high value of D.

(2) Measurement of halation indicates a low value of D.

(3) Lack of improvement by an anti-reflection coating indicates a high value of D.

Although our system has a limited dynamic range and there is no direct way of increasing it with the existing CRT, it is reassuring that a special CRT with an absorbing face-plate could improve the contrast.

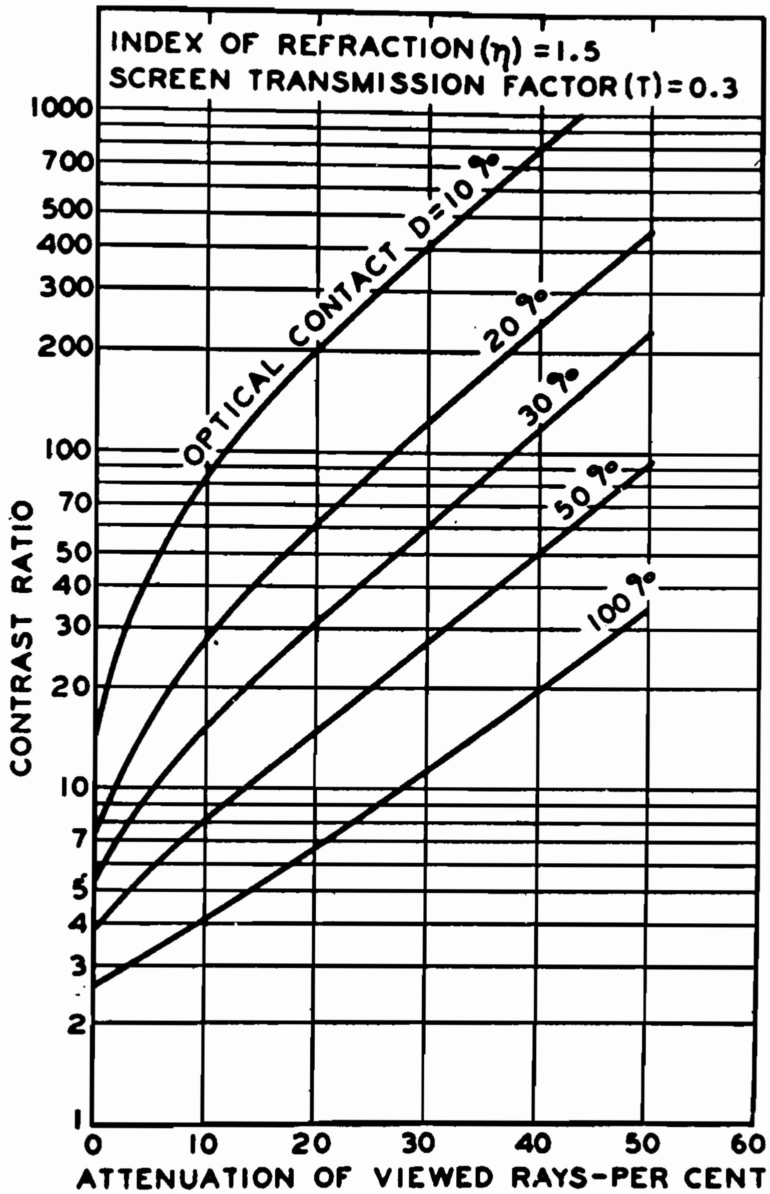

INDEX OF REFRACTION(η) = 1.5
SCREEN TRANSMISSION FACTOR (T) = 0.3
OPTICAL CONTACT D = 10 %
20 %
30 %
50 %
100 %
CONTRAST RATIO
ATTENUATION OF VIEWED RAYS-PER CENT
1000
700
500
400
300
200
100
70
50
40
30
20
10
7
5
4
3
2
1
0
10
20
30
40
50
60

Fig. 4.8

Such cathode ray tubes can be manufactured on request. At present, absorbent face-plates are being applied to the 23-inch television CRT's, both to increase the contrast and to provide an integral safety plate. (In the past the absorbing safety glass was mounted about one inch in front of the screen, leading to a loss of contrast instead of a gain.)

5. FLYING SPOT SCANNER CIRCUITS

5.1 Photomultiplier

The gain of a photomultiplier is a highly sensitive function of the operating voltage ($G \propto V^5$). To meet the stability requirement a well-regulated supply is used (John Fluke Co. Model 409A). The maximum anode current is limited to 10 µa for stable operation. The scanned material is a negative transparency with most of its area at base density. The 10 µa current is therefore maintained continuously in operation, minimizing the effect of dark adaptation of the photocathode. As the flying spot scans denser portions of the frame the current decreases from the maximum 10 µa to 0.8 µa, for a density of 11 db above base. Since the information on film is distributed uniformly on a (logarithmic) density scale, the seven intensity levels appear as equal factors in phototube current. The signal from the phototube is to be stepped in the subsequent circuits. The stepping circuit, which is essentially a voltage-sensing device with a sharp transition, must be a direct-coupled circuit due to the low frequency of the picture information. Because of inherent drifts of direct-coupled circuits, the seven intensity levels should preferably be distributed as equal increments in voltage at the input to the thresholds. The analogous requirement existed in the stepping amplifier used by Legg (1960) in the video stages of the radar. There the logarithmic receiver provided just the right form of signal for stepping.

A thyrite element at the output of the photomultiplier introduces a non-linearity in response to overcome the compression of the low signals (high density end of the scale). The thyrite element is a power-law device of index 0.45, rather than being a logarithmic

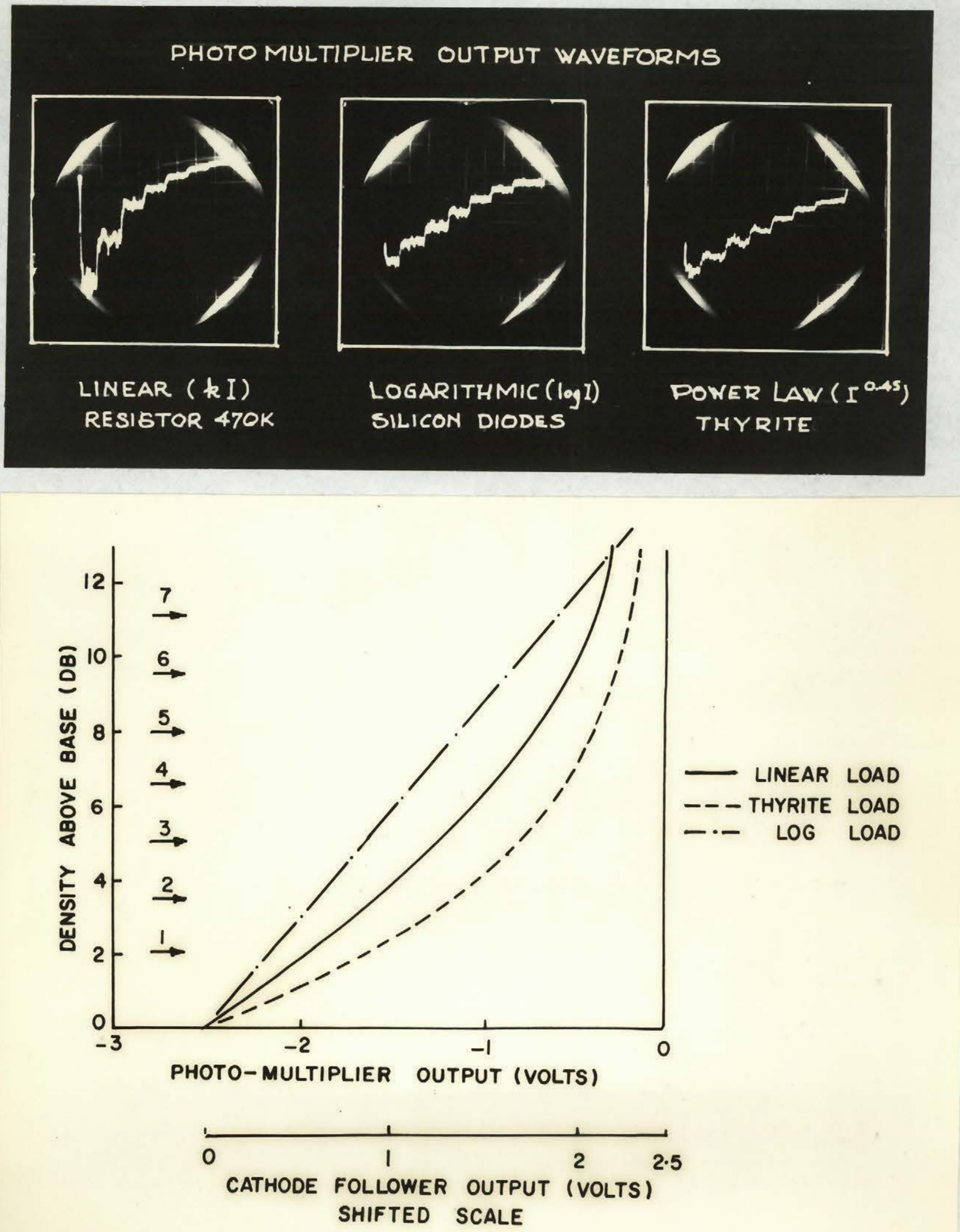


PHOTO MULTIPLIER OUTPUT WAVEFORMS
LINEAR (kI)
RESISTOR 470K
LOGARITHMIC (log I)
SILICON DIODES
POWER LAW ($I^{0.45}$)
THYRITE
DENSITY ABOVE BASE (DB)
PHOTO-MULTIPLIER OUTPUT (VOLTS)
CATHODE FOLLOWER OUTPUT (VOLTS)
SHIFTED SCALE
LINEAR LOAD
THYRITE LOAD
LOG LOAD

Fig. 5.1

transducer. The useful dynamic range is about 10 db; beyond 10 db the thyrite offers little advantage over a linear load. A circuit with a logarithmic response was tried experimentally. A string of three silicon diodes were used as the load for the photomultiplier. At low current levels the characteristic (I-V) for a silicon diode is nearly logarithmic. The results were encouraging but the signal-to-noise ratio was inadequate and the circuit was rejected.* Fig. 5.1 shows the transfer characteristic of the phototube with the thyrite load. The low power-law shaping is only partially successful. At higher densities the compression is still apparent, but is less serious than with a linear load (dashed curve). The waveforms at the top of Fig. 5.1 illustrate the improvement brought about by the shaping circuits. The calibration curve for the thyrite element was determined

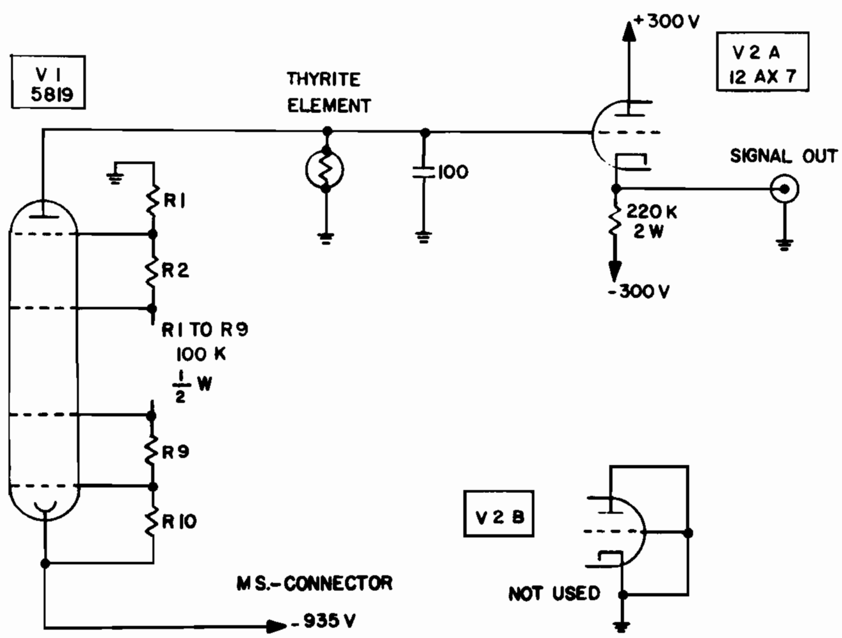


Fig. 5.2

*The current of 10 μa was too low. It is possible to use diodes as feedback elements in an amplifier (preferably solid state) to achieve a satisfactory logarithmic response and a good signal-to-noise ratio.

by means of gelatin neutral-density filters covering the dynamic range. The density values on the abscissa are the nominal values for diffuse density quoted by the maker, rather than the specular density actually measured.

The circuit diagram of the photomultiplier is shown in Fig. 5.2. The output from the anode of the phototube is passed through a cathode follower (12AX7) before it is sent to the equipment rack. The cathode follower introduces a shift in the voltage level, equal to the self-bias of the tube. When no light reaches the phototube, its output current is zero and the output cathode assumes a potential of +2.5 V necessary to bias the cathode follower to 1.5 mA plate current. As light reaches the photocathode the voltage decreases by the amplitude of the signal. The CRT brightness is so arranged that the light flux through the base density produces a signal of -2.5 V (upper scale in Fig. 5.1), making the cathode follower output exactly zero volts (lower scale in Fig. 5.1). Two limits of operation are established in this way.

(a) Maximum density (opaque): The cathode follower output is +2.5 V determined by the bias characteristic of the tube, which is quite stable.

(b) Clear base: The cathode follower output is zero volts. The ground potential is a convenient standard for comparison.

5.2 Signal Flow Diagram

The signal flow diagram is shown in Fig. 5.3. The response curves for three parts of the system are shown in graphs (1), (2) and (3), while the overall response is shown in graph (4). This convenient

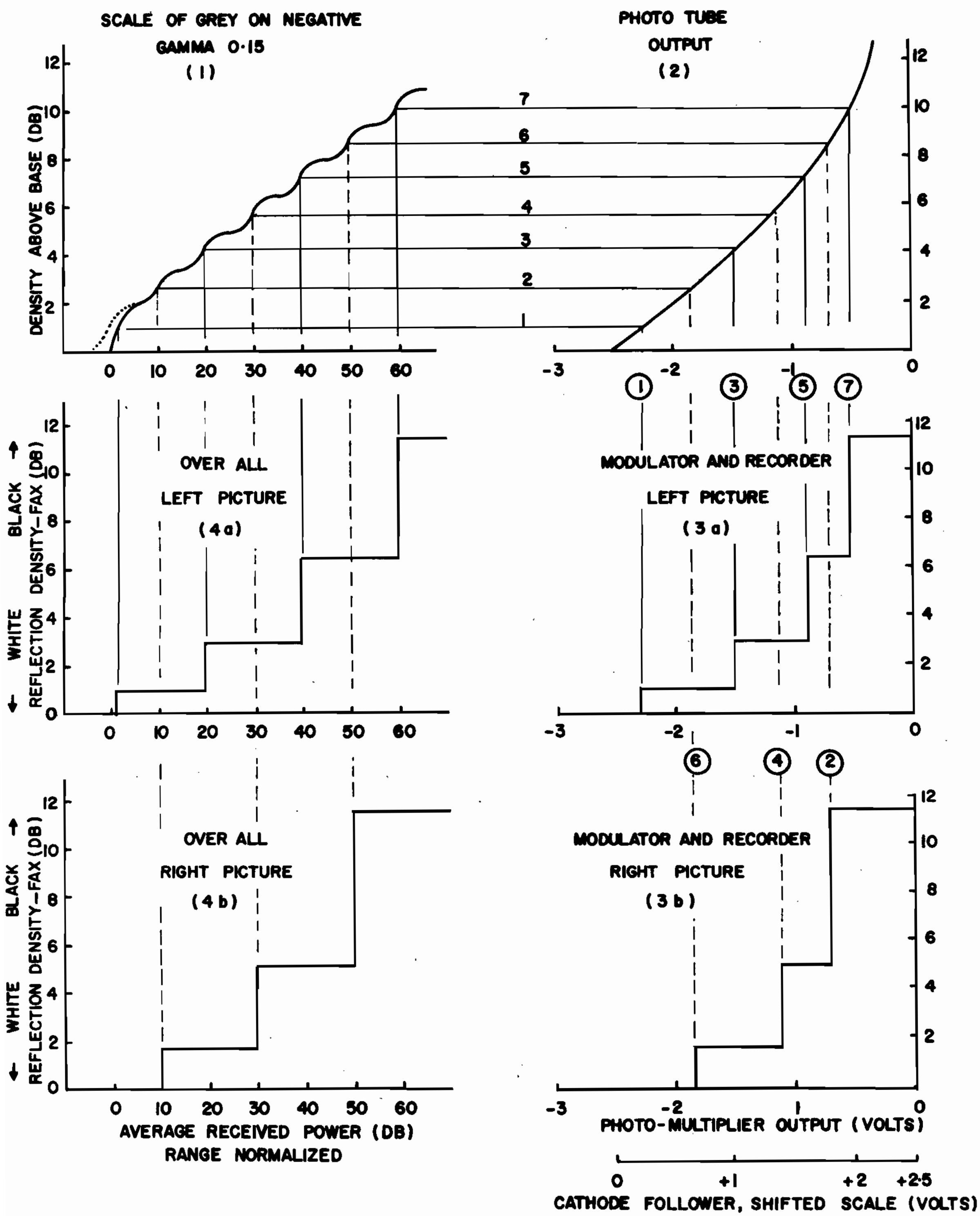

SCALE OF GREY ON NEGATIVE
GAMMA 0·15
(1)
PHOTO TUBE
OUTPUT
(2)
DENSITY ABOVE BASE (DB)
OVER ALL
LEFT PICTURE
(4a)
MODULATOR AND RECORDER
LEFT PICTURE
(3a)
OVER ALL
RIGHT PICTURE
(4b)
MODULATOR AND RECORDER
RIGHT PICTURE
(3b)
WHITE BLACK
REFLECTION DENSITY-FAX (DB)
AVERAGE RECEIVED POWER (DB)
RANGE NORMALIZED
PHOTO-MULTIPLIER OUTPUT (VOLTS)
CATHODE FOLLOWER, SHIFTED SCALE (VOLTS)

FIG. 5.3.

form is often used to describe several steps in a photographic process (see for example James and Higgins, 1961). Graph (1) shows the transfer characteristic of the radar receiver as modified by Legg (1960) to display the received signal on the density scale of the film. The gamma of the system is 0.15, compressing 60 db at the input to the receiver into 9 db on film (from 2 to 11 db above film base). As described in chapter 2, there is some evidence of stepping but the steps are not well defined. The actual characteristic, instead of being on the line of constant slope, is alternately above and below it. Over the range of the lowest 5 db in received power the actual curve (solid line) shows some distortion and differs from the expected one (dashed line). The distortion is caused by suppression of the trace on the PPI display in the absence of signal. The suppression was originally introduced by Barath (1961) to improve the appearance of the reproductions of the radial display when these were considered to be the final product from our radar. Now that the pictures are processed further in the scanning system, the aesthetic appearance of the picture on the first storage medium is not of great importance. Blanking the trace does offer a distinct advantage by keeping the background of the film at base density. The light flux through the clear base provides a reliable reference in the scanning process, and therefore at no time in the adjustment is one obliged to remove the film to establish a reference level. The distortion caused by the blanking will lead to a loss of sensitivity of about 1 db. The effect is kept small by making the step from base to the first shade 2 db (or more) compared to the other steps of 1.5 db. The loss of 1 db could be further reduced by increasing integration in range (e.g. by shortening the pulse-length before the signal is blanked and applied to the CRT).

The information on the negative transparency is next transformed into an electrical signal in the flying spot scanner. Curve (2) is the transfer characteristic of the photomultiplier, and is identical to that shown in Fig. 5.1. The signal from the phototube is stepped in the subsequent circuits. The seven lines denoting the boundaries between the 10-db intervals are carried through the diagrams. Stepping of the signals occurs twice in the system: Once in the video stages resulting in curve (1), and once again beyond the scanner. The two sets of steps should be related properly, in order that some benefit be derived from the first set. The system depends solely on the second set of steps to achieve well-defined contours on the final product. Each threshold after scanning should occur on the steepest ascent of curve (1), as indicated by the flow lines. A mismatch in the two sets of steps does not lead to any significant degradation of the contours because the fluctuations are adequately smoothed out on the transparency. A mismatch will however lead to significant variation of area of a given shade with small changes in the sensitivity of the second threshold. This is apparent in curve (1) if a flow line is displaced vertically and intercepts the transfer curve in the shallow region.

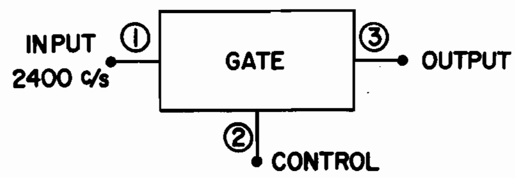
The third graph describes the rest of the system, from the stepped modulator through to the recorder output. The input variable is the (slow) video signal from the scanner and the output is the reflection density of the facsimile paper. Two paths are shown: One leads to the left picture with four active shades (curve 3a) and the other leads to the right picture with three active shades (curve 3b). The two pictures appear side by side on facsimile. The signals which produce the two pictures are transmitted in alternate intervals of 250 msec.

The steps in graph (3) have been drawn as being vertical, implying zero dynamic range of the transition region. The actual transition is of course finite but is made sufficiently small that the sharpness of the contour is far more dependent on bandwidth beyond the modulator and the surface characteristics of the recording paper. On the abscissa of curve (3) the width of the transition region is less than 4 mV out of the total 2.5 V, representing 60 db in P_r. If this value is carried back along the flow lines to the received power scale, it corresponds to 0.2 db in received power at the high intensity levels and 0.1 db at the low intensity levels. The difference is due to the compression of signals at the output of the phototube.

5.3 Stepped Modulator - Description

The modulator performs two functions in the system. (1) It introduces sharp steps in the areally averaged signal. (2) It provides at its output an amplitude modulated carrier suitable for transmission to the facsimile recorders. The output signal is at about 0 dbm level into a balanced 600-ohm line. The carrier frequency is 2400 c/s.* In principle, the modulator consists of seven transmission gates or switches. Each gate (top of Fig. 5.4) has three terminals: (1) Input (2) control

*The link at Montreal Airport is over private (McGill) lines. During trials various levels of transmission up to +10 dbm and carrier frequencies up to 4000 c/s were used experimentally. When the link to the University, using leased lines, is added the operation will be restricted to the parameters referred to throughout the text.



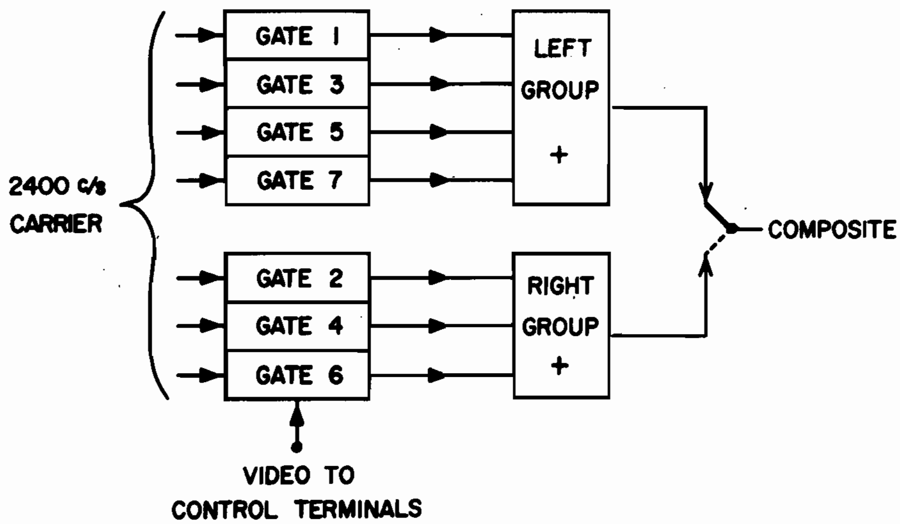


Fig. 5.4

(3) output. The gate can be compared to a standard "and" gate used in digital computers, with the exception that inputs to terminals (1) and (2) are not interchangeable. The 2400 c/s carrier is applied to the input terminal no. (1). The carrier will only appear at the output, depending on whether the control potential at the terminal no. (2) is above a pre-set threshold. The control voltage is the video signal from the scanner.* As soon as the control voltage crosses the threshold the gate changes its state. The controlling circuit used here is non-

*It is in the audio range, but the shape of the signal is peculiar to video: The direct-current component represents the average luminance of the picture, while a truly audio signal normally has no DC component.

regenerative: The transition range is narrow but an intermediate state is possible if the control voltage remains in the transition region. By making the transition region narrow it was not necessary to resort to regenerative circuits. In these the transition is initiated by the control signal but it proceeds to completion, driven by the regenerative feedback.

The video information is applied to all seven gates simultaneously, as shown in the lower part of Fig. 5.4. The outputs of the seven gates are then subdivided into two groups, one to be displayed in the left picture, the other in the right picture. Each group is added in a summing circuit. A high-speed telegraph relay samples the outputs, switching between the two terminals every 250 msec, in synchronism with the scanner line frequency. A conventional line-driving amplifier drives the 600-ohm audio line.

The individual outputs from the seven gates are also used in an experimental apparatus to derive areal coverage within radar range (chapter 6). To maintain flexibility and independence in the auxiliary system, switching between the two groups of intensities (left-right) is done at the output of the gates rather than at the input. Each gate is therefore operating during every line of the scanner, even though its output appears on facsimile only every other line. Having a meaningful output from the gate on each line is particularly helpful in observing the waveforms on a normal cathode ray oscilloscope. The eye can just observe the features in the waveforms at the repetition frequency of 4 sec^{-1} without a storage oscilloscope.

The circuit of the modulator is shown in Fig. 5.5 and 5.6. At the foot of Fig. 5.5 a block diagram indicates the sections shown on

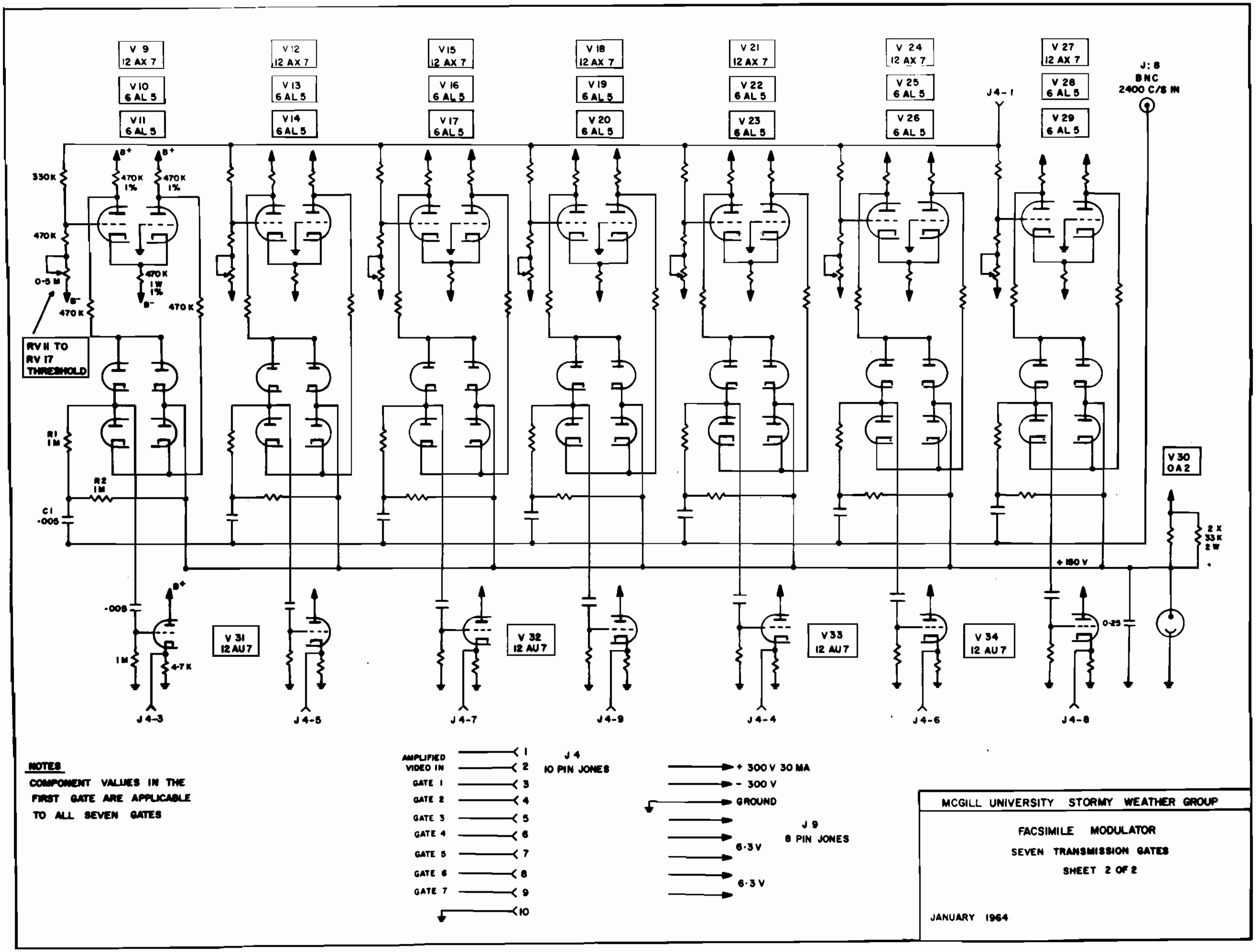
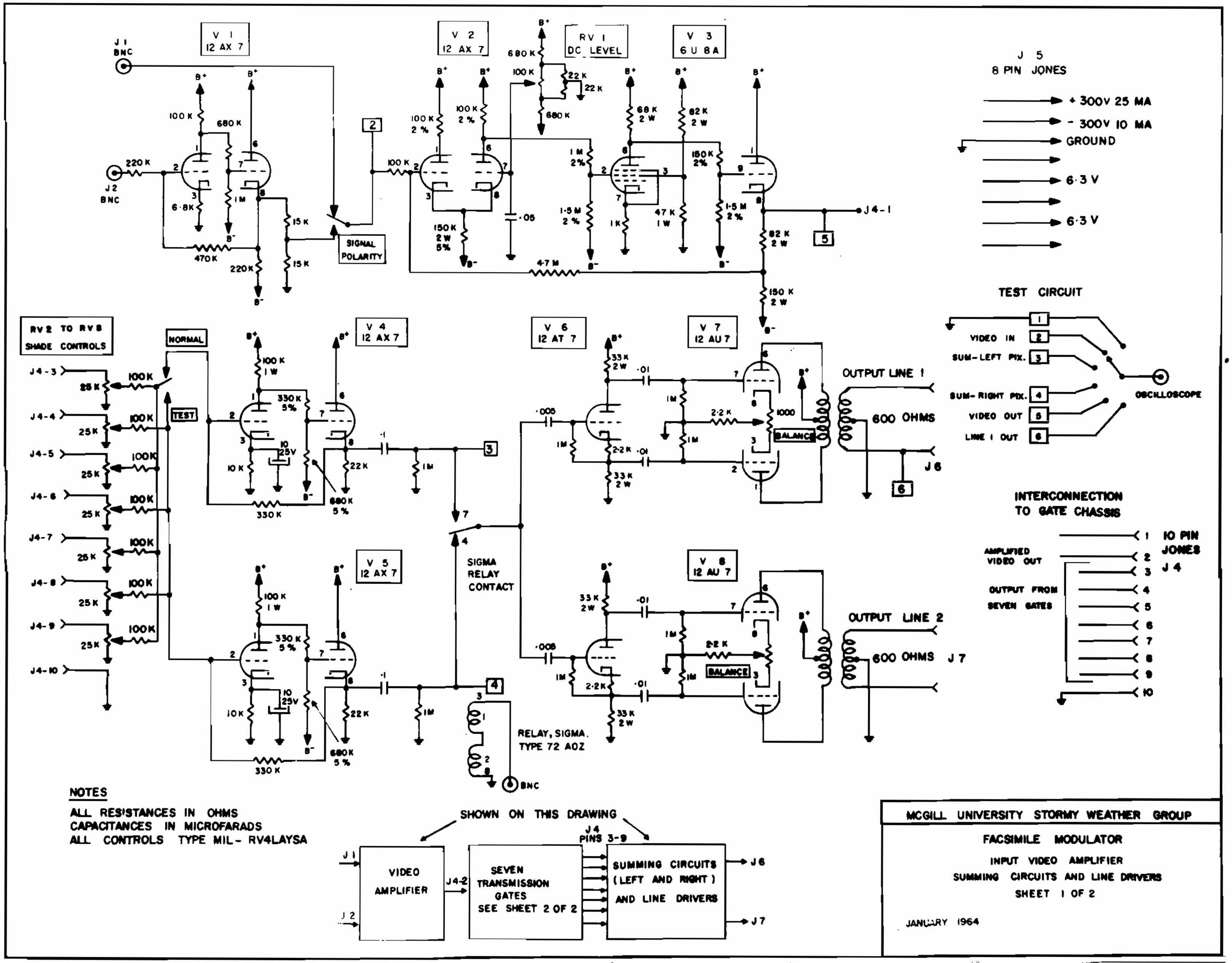

V 9 12 AX 7
V 10 6 AL 5
V 11 6 AL 5
V 12 12 AX 7
V 13 6 AL 5
V 14 6 AL 5
V 15 12 AX 7
V 16 6 AL 5
V 17 6 AL 5
V 18 12 AX 7
V 19 6 AL 5
V 20 6 AL 5
V 21 12 AX 7
V 22 6 AL 5
V 23 6 AL 5
V 24 12 AX 7
V 25 6 AL 5
V 26 6 AL 5
V 27 12 AX 7
V 28 6 AL 5
V 29 6 AL 5
J4-1
J: 8 BNC 2400 C/S IN
330K
470K 1%
470K
0-5 M
470K 1W 1%
RV II TO RV 17 THRESHOLD
R1 1M
R2 1M
C1 ·005
V 30 OA2
2 X 33K 2W
+ 150 V
·005
1M
4·7K
0·25
V 31 12 AU7
V 32 12 AU7
V 33 12 AU7
V 34 12 AU7
J 4-3
J 4-5
J 4-7
J 4-9
J 4-4
J 4-6
J 4-8
NOTES
COMPONENT VALUES IN THE FIRST GATE ARE APPLICABLE TO ALL SEVEN GATES
AMPLIFIED VIDEO IN
GATE 1
GATE 2
GATE 3
GATE 4
GATE 5
GATE 6
GATE 7
J 4
10 PIN JONES
+ 300 V 30 MA
- 300 V
GROUND
J 9
8 PIN JONES
6·3 V
6·3 V
MCGILL UNIVERSITY STORMY WEATHER GROUP
FACSIMILE MODULATOR
SEVEN TRANSMISSION GATES
SHEET 2 OF 2
JANUARY 1964

FIG. 5.6



V 1
12 AX 7
V 2
12 AX 7
RV 1
DC LEVEL
V 3
6 U 8 A
J 5
8 PIN JONES
+ 300V 25 MA
- 300V 10 MA
GROUND
6·3 V
6·3 V
J 1
BNC
J 2
BNC
SIGNAL
POLARITY
J4-1
TEST CIRCUIT
VIDEO IN
SUM-LEFT PIX.
SUM-RIGHT PIX.
VIDEO OUT
LINE 1 OUT
OSCILLOSCOPE
RV 2 TO RV 8
SHADE CONTROLS
NORMAL
TEST
V 4
12 AX 7
V 6
12 AT 7
V 7
12 AU 7
OUTPUT LINE 1
600 OHMS
BALANCE
J 6
INTERCONNECTION
TO GATE CHASSIS
10 PIN
JONES
J 4
AMPLIFIED
VIDEO OUT
OUTPUT FROM
SEVEN GATES
V 5
12 AX 7
SIGMA
RELAY
CONTACT
V 8
12 AU 7
OUTPUT LINE 2
600 OHMS J 7
RELAY, SIGMA,
TYPE 72 AOZ
BNC
NOTES
ALL RESISTANCES IN OHMS
CAPACITANCES IN MICROFARADS
ALL CONTROLS TYPE MIL- RV4LAYSA
SHOWN ON THIS DRAWING
J4
PINS 3-9
VIDEO
AMPLIFIER
J4-2
SEVEN
TRANSMISSION
GATES
SEE SHEET 2 OF 2
SUMMING CIRCUITS
(LEFT AND RIGHT)
AND LINE DRIVERS
MCGILL UNIVERSITY STORMY WEATHER GROUP
FACSIMILE MODULATOR
INPUT VIDEO AMPLIFIER
SUMMING CIRCUITS AND LINE DRIVERS
SHEET 1 OF 2
JANUARY 1964

FIG. 5.5

each sheet. The input video from the photomultiplier is connected for the normal modulation polarity to J1, by-passing the inverter V1. The video signal is amplified in the amplifier consisting of V2 and V3. The amplifier is direct-coupled and is stabilized by negative feedback. Its open-loop gain of 2000 is reduced to about 50 by feedback, resulting in a stable and linear operation. The video waveform, 2.2V in amplitude, is amplified to 110 volts before being applied via J4-2 to the control terminals of the seven gates, shown in Fig. 5.6.

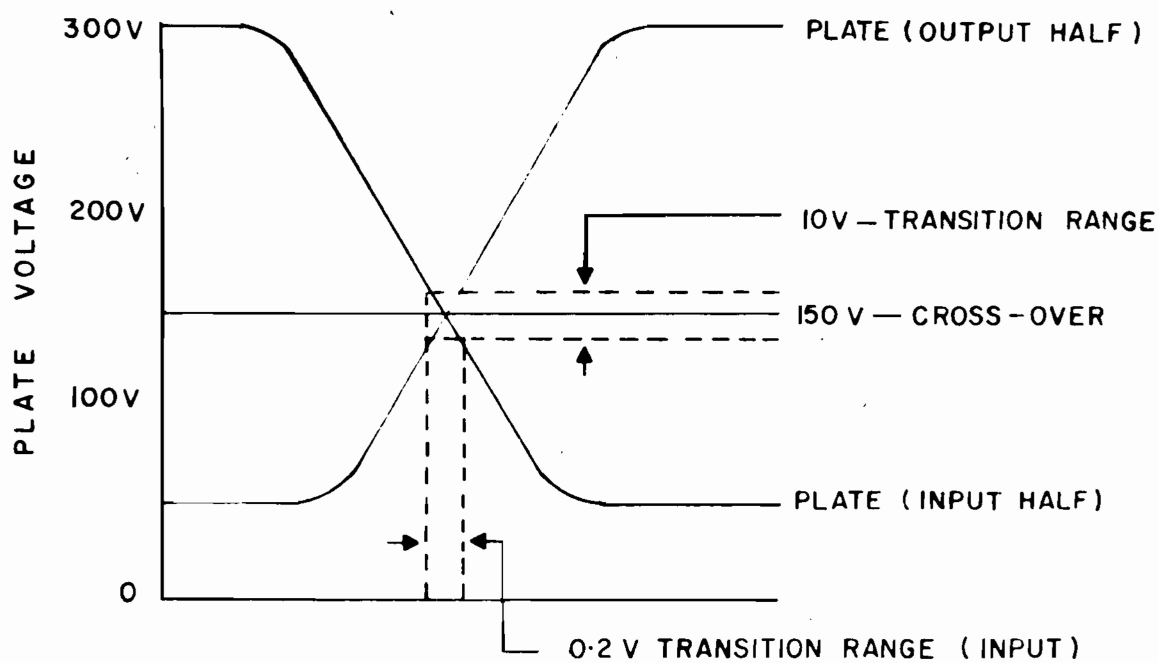
Each gate is a shunt-type gate: An active element shorts the carrier to a low impedance, allowing no signal to reach the output. Referring to the first gate, the carrier is applied to the gate through the capacitor C1. The secondary side of the capacitor is restored through R2 to the +150 V potential. The carrier passes through the series resistor R1 to the actual switch consisting of the four diodes.* Whether the carrier reaches the cathode follower V31 or not depends on the state of the four diodes. If the diodes conduct, the left plate-cathode junction is shorted to the junction on the right. The latter is connected to the low impedance source of 150 V. If, on the other hand, the diodes are cut off, the signal is not attenuated by the diodes and is passed through R1 to the cathode follower. The output side of the resistor R1 is thus either at a steady potential of 150 volts, or follows the carrier voltage, which itself is restored to 150 volts. There is no change in the quiescent point of the output and therefore the gate does not introduce a voltage pedestal. The gate can be

---

*A similar circuit is used as a synchronous clamp in colour television receivers. The demand for this circuit has led to the marketing of a tube 6JU8 containing four diodes connected to form such a switch.

considered to be a balanced modulator because the DC component (the pedestal) at video frequency is not introduced to the output.

The four diodes are controlled by the differential pair V9. The grid of the right tube is grounded, while the amplified video (control signal) is applied to the grid of the left tube. If the potential on the control grid is below zero, the left half is cut off and the right half is conducting 0.6 mA. The diodes are also conducting and the switch is open. As soon as the control grid crosses zero volts in the positive direction, the tubes reverse the states, cutting off the four diodes. The controlling video at J4-1 is 110 volts peak to peak (from 110 to 220 V). Controls RV11 to RV17 adjust the sensitivities of the seven gates, and are therefore the threshold controls. As the video voltage at the input to the differential amplifier V9



WAVEFORMS ON PLATES OF THE DIFFERENTIAL AMPLIFIER

Fig. 5.7

crosses zero volts, the two plates cross the 150-volt potential, but in the opposite direction. The waveforms are sketched in Fig. 5.7. The transition range at the plates of each differential amplifier is 10 volts. The necessary swing at the input grid is about 0.2 volts, out of a total range of 110 volts.

When the gate is closed the carrier is attenuated by a factor two in voltage amplitude. When the gate is open the attenuation results from shunting the 1 Mohm (R_1) resistor by essentially half the forward impedance of a 6AL5 diode, or about 100 ohms. The attenuation in the open state should theoretically be $\left(\frac{10^6}{100}\right)^2$, or 80 db. Leakage and pickup limit the attenuation to about 40 db (factor 100 in voltage amplitude). During the early part of the summer 1963 the on/off isolation was only 20 db. The leakage of the carrier occurred along the +150 V bus. The glow tube regulator (OA2) and the bypass capacitor now reduce the leakage to an acceptable limit.

The seven outputs from the gates are returned to the shade controls shown on sheet 1, Fig. 5.5. The shade controls, RV2 to RV8, adjust the signal amplitude and therefore determine the reflection density on the facsimile recorder. The weighted signals are added in the 100 Kohm summing resistors in conjunction with the two feedback summing circuits V4 and V5. The outputs of the summing circuits are sampled by the relay contact (Sigma type 72AOZ-TCP). The composite signals for the left and right pictures are applied to two identical line-driving amplifiers. A test circuit is included in this chassis which can be used to display on a monitor oscilloscope the important waveforms, as indicated on Fig. 5.5.

5.4 Stepped Modulator - Adjustment

The signal at the output of the photomultiplier ranges from -2.5 V (clear base) to -0.3 V (11 db above base). The cathode follower shifts the signal to the range 0 V to + 2.2 V. The level of 0 V serves as a reference for setting the CRT brightness. The CRT bias control is set until the cathode follower drops from +2.5 (beam off) to zero volts. The video signal is next amplified in the two stage amplifier. The DC level control RV 1 is set such that the clear

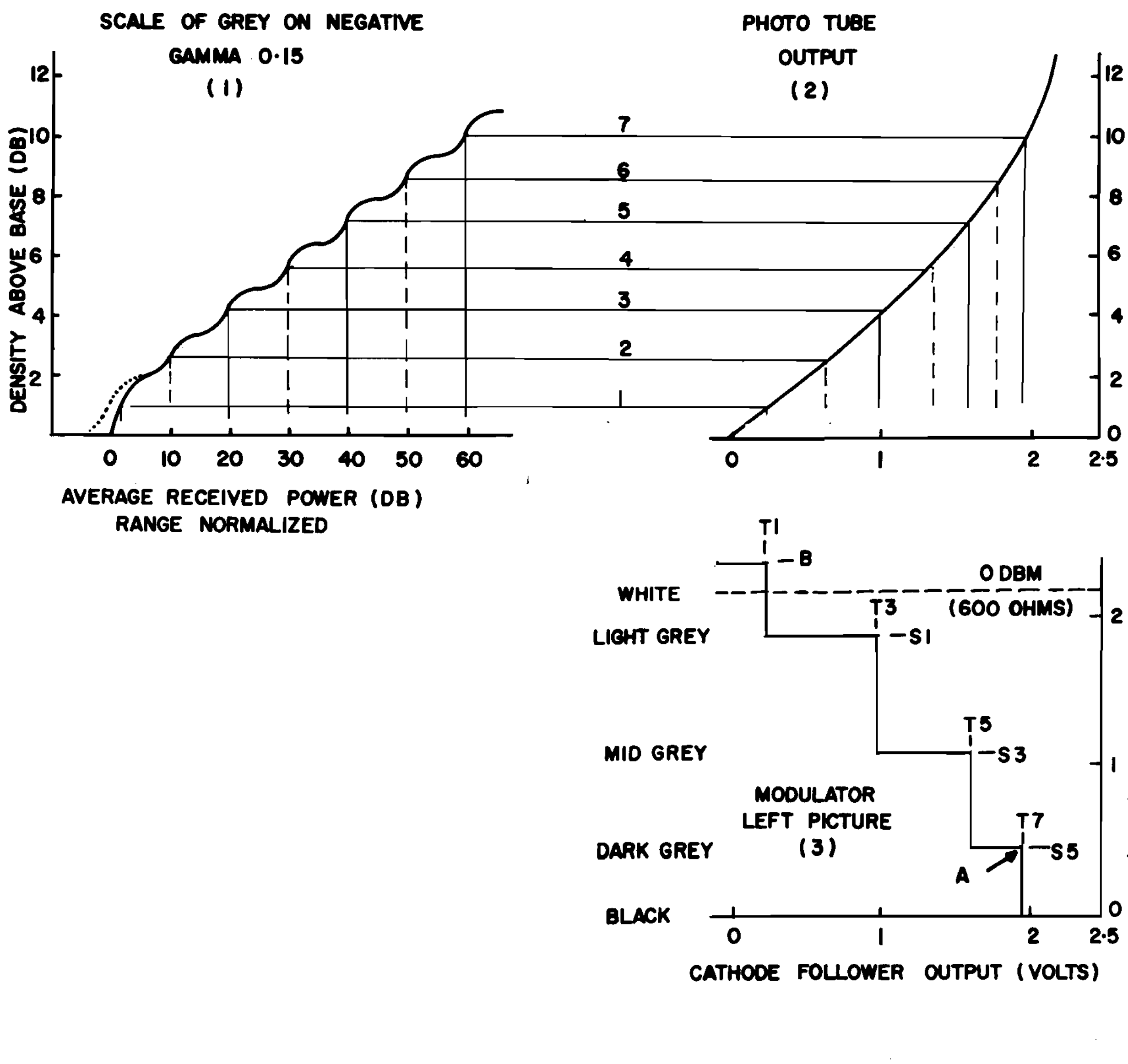


Fig. 5.8

base level after amplification occurs at +110 volts and the signal through the maximum density then is about +220 volts.

Before describing the setting of the gates the desired transfer characteristic for the modulator will be established. Fig. 5.8 shows the signal flow diagram through to the output of the modulator. The first two curves are the same as those in Fig. 5.3, described earlier. The third curve now shows the transfer characteristic of the modulator. For simplicity, the signal will be traced only to the left picture containing four active shades representing intensity levels 1, 3, 5 and 7. The abscissa of curve (3) is as before the output from the scanner. The ordinate is peak-to-peak carrier amplitude into the audio line. The modulation on the line is negative, such that the output is at its maximum in the absence of echo (clear base). The level of the output is just sufficient to produce no marking on the recorder, and therefore results in a clear white background. As the spot scans past an echo, the scanner output decreases, and as it crosses the thresholds the modulator output decreases in steps until for the seventh intensity all four gates are cut off.

Referring to point (A) in the third graph of Fig. 5.8, the location of the point (A) is determined by the two controls of gate <u>seven</u>. The threshold control (T7) locates the point (A) on the abscissa, and thus determines the sensitivity of the seventh intensity level. As soon as the video crosses the seventh threshold the gate is cut off and black is painted on the left picture. The output of the seventh gate, when it is turned on, determines the ordinate of point (A) and therefore establishes the shade of the <u>fifth</u> intensity level (S_5). In a similar way the sensitivity of each gate is controlled by <u>its</u>

threshold control. The output amplitude from the gate determines the next lighter shade. The signal from the first gate therefore serves only to provide sufficient output to cut off the marking amplifier in the recorder and produce no marking.

The third graph of Fig. 5.8 offers the key to an objective adjustment procedure of the modulator. The thresholds are first roughly distributed throughout the input range, but their order must not be interchanged, nor should two thresholds coincide. The shade controls are then adjusted, starting from the seventh, then the fifth etc. A convenient input signal to the modulator for the shade adjustment is a sawtooth waveform derived from the horizontal sweep generator. For the threshold adjustment the input signal is derived from the photomultiplier with the regular processed frame in the gate. In practice, while the adjustment proceeds the processor is in operation and a new frame enters the gate every 3 3/4 minutes. The scanning line on the

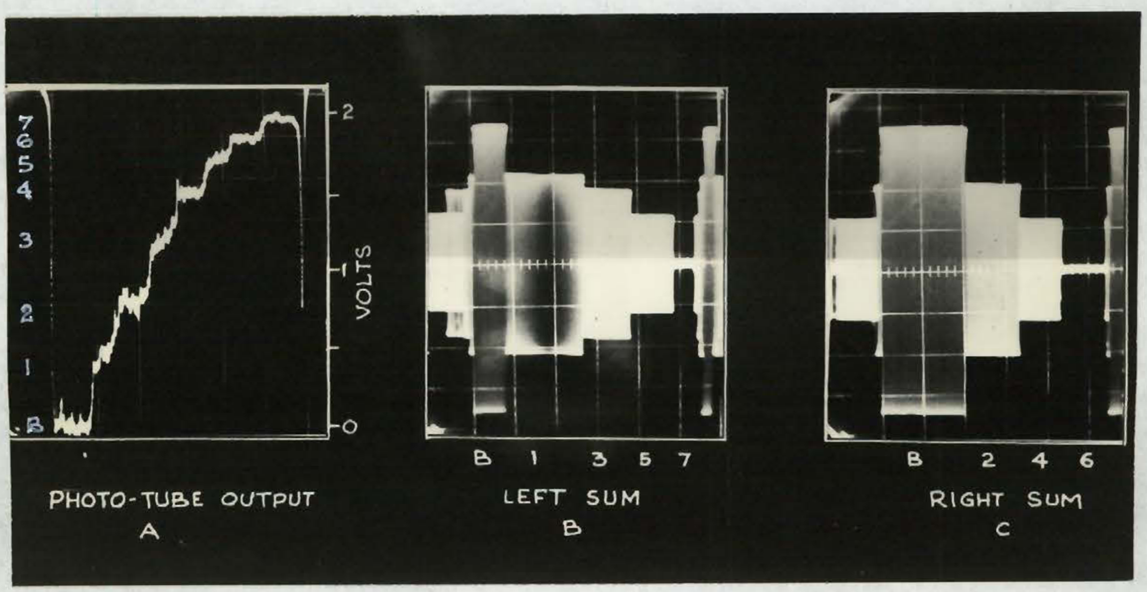


Fig. 5.9

scanner CRT is positioned in its "test" position and the north test pattern on film is scanned. The position of the test line was shown earlier in Fig. 4.2. The output from the scanner is displayed on a cathode ray oscilloscope, synchronized with the horizontal line frequency. Fig. 5.9 (a) shows typical waveforms. The horizontal position of each transition is marked on the face of the CRO. The output from the left group of intensities (Fig. 5.9b) is then displayed on the CRO by switching the selector switch of the test circuit in the modulator (circuit diagram in Fig. 5.6). As each threshold control is rotated, the horizontal position of the corresponding transition in the output waveform changes. The positions of the four transitions are set to occur at the appropriate positions, previously marked on the face of the CRO.

5.5 Stepped Modulator - Stability

In order to establish a stable operating system, precautions were taken wherever it was possible to eliminate sources of drift in the circuits. The processor and the scanner run unattended for periods of 20 hours or longer. The foremost requirement for an automatic operation is adequate freedom from drift. In the particular case of the modulator, the approach was taken to use as many tubes as required, but to operate each tube at a conservative performance level. One consequence of this is the fact that as many as 34 tubes were used. The tubes are used in configurations similar to those used in transistor circuits where drift is a known problem, and there precautions are taken to compensate the circuits for drift. The input video amplifier and the two summing circuits (left group and right group) are operational amplifiers with feedback. The gains of the amplifiers therefore depend on resistor ratios rather than on tube characteristics. In fact both the threshold settings and the output amplitude (or shade) settings are determined only by passive circuit elements. The output amplitudes have not had to be reset in three months of operation during the fall of 1963. The threshold settings are checked daily but the primary reason for drifts is a variation in the film processing. The performance of the processor is discussed in section 5.7.

5.6 Flying Spot Generator

The flying spot generator was constructed by modifying a high quality radar PPI display.* The basic feature of the display that made it suitable for conversion was a fixed-coil deflection system, with deflection amplifiers direct-coupled from the input through to the deflection coils. In the R-θ operation the necessary waveforms to the X and Y deflecting units are sawtooth waveforms whose amplitude varies respectively as the cosine and sine of the azimuth angle. To produce the rectangular raster on the display the resolved R-θ sweep waveforms were replaced by suitable horizontal and vertical sweep voltages. The direct-coupled amplifiers could maintain a linear sweep over the full 212-second frame time. The voltage-to-current conversion circuits necessary for the deflection coils were part of the display. The electrical conversion was relatively straightforward; only mechanical construction was necessary to mount the cathode ray tube in the right position in the optical system. The mounting was made quite rugged to maintain the optical alignment and to avoid jitter in the picture due to vibration of the CRT.

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*A spare display unit for the Kelvin-Hughes Rapid Processor Projector.

The basic display unit will not be described here beyond stating the useful feature of the unit: The power supplies and the circuits are built to tight specifications necessary for a stable operation, particularly since direct-coupled circuits are used throughout. Only one additional chassis was constructed: The horizontal and vertical sweep generator chassis. Also the CRT biasing circuit was simplified. Advantage was taken of the fact that the scanner CRT is not brightness-modulated, nor is blanking of the spot brightness during retrace necessary.* The biasing voltage on the grid is now derived directly from a glow tube regulator (OG3/5651). The well stabilized bias, combined with good power supply regulation, has resulted in a brightness stability better than 1/4 db ($\pm$1/8 db). The one other factor which has equally contributed to the brightness stability was the regulation of the 6.3 V AC heater supply, particularly the supply to the CRT itself. The stability was measured by removing film from the optical gate and recording the output of the photomultiplier over a period of 18 hours. The quoted figure therefore includes the stability of the photomultiplier circuit.

The circuit generating the necessary horizontal and vertical sweeps is shown in Fig. 5.10. In addition to the generation of sweep voltages, the chassis supplies the necessary driving pulses to the high speed relay to interlace the signals for the left and right pictures. Also, a shaped rectangular pulse is generated in this chassis and supplied to the transmitter for generation of the synchronizing signal necessary to start the facsimile recorders.

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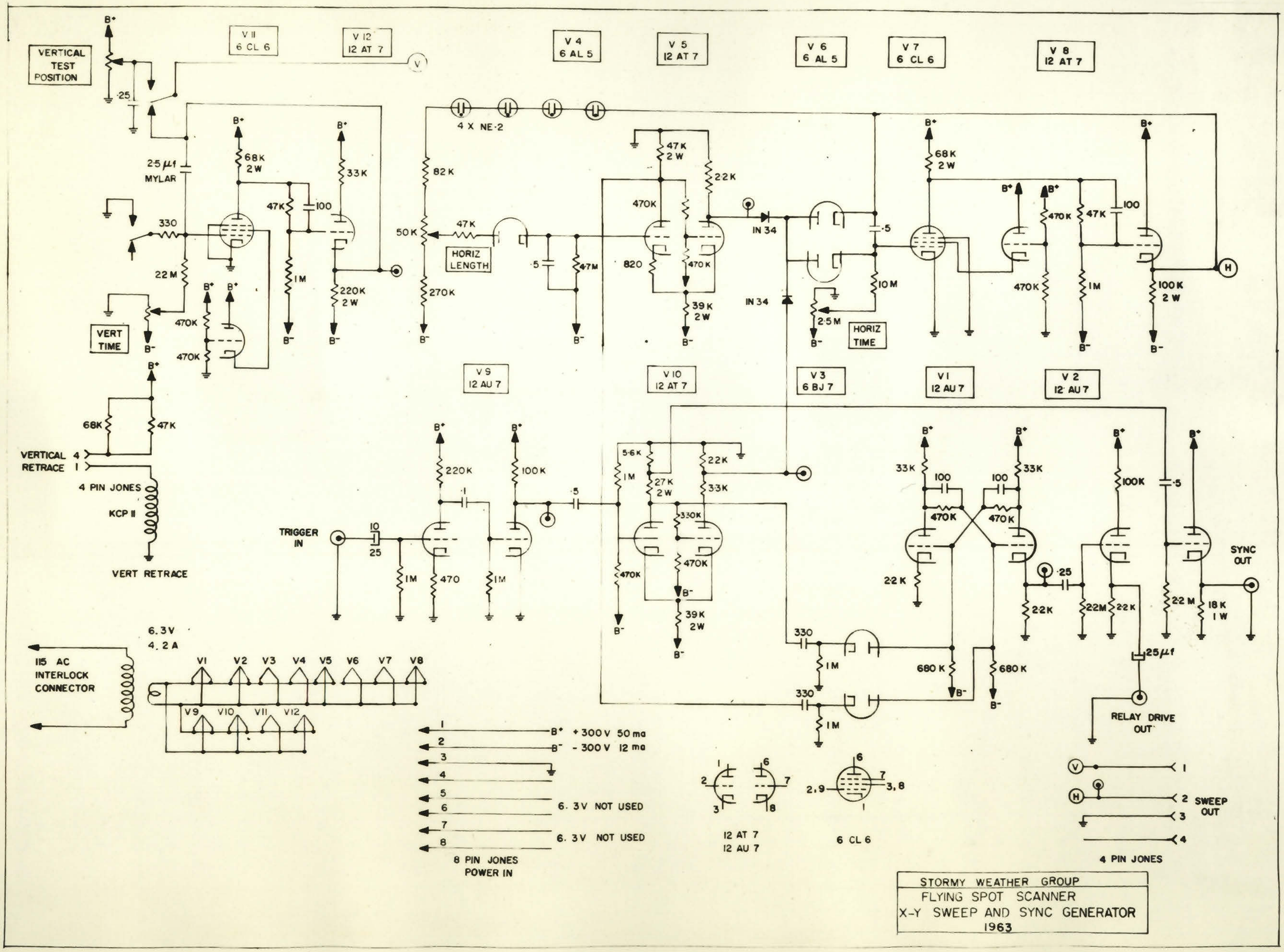
*This is only true in the case of scanning for facsimile where the writing spot has essentially zero retrace time.



VERTICAL TEST POSITION
V 11 6 CL 6
V 12 12 AT 7
V 4 6 AL 5
V 5 12 AT 7
V 6 6 AL 5
V 7 6 CL 6
V 8 12 AT 7
4 X NE-2
2.5 µf MYLAR
HORIZ LENGTH
IN 34
IN 34
HORIZ TIME
VERT TIME
V 9 12 AU 7
V 10 12 AT 7
V 3 6 BJ 7
V 1 12 AU 7
V 2 12 AU 7
VERTICAL RETRACE
4 PIN JONES
KCP II
VERT RETRACE
TRIGGER IN
SYNC OUT
RELAY DRIVE OUT
115 AC INTERLOCK CONNECTOR
6.3V 4.2 A
B+ +300V 50 ma
B- -300V 12 ma
6. 3V NOT USED
6. 3V NOT USED
8 PIN JONES POWER IN
12 AT 7
12 AU 7
6 CL 6
SWEEP OUT
4 PIN JONES
STORMY WEATHER GROUP
FLYING SPOT SCANNER
X-Y SWEEP AND SYNC GENERATOR
1963

FIG. 5.10

The horizontal sweep is produced in the Miller run-up circuit of V7 and V8B cathode follower. A sweep is produced whenever the disconnect switch diodes V6 are cut off. Conversely, the retrace occurs when the diodes conduct, shorting the timing capacitor. The synchronizing signal is used to retrace the sweep rather than to start the sweep, resulting in a simplification of the circuit. There are two alternate paths through which disconnect diodes can be turned on to cause retrace. One path comes from the recorder supplying the synchronizing pulse after every line on facsimile. The other path is from the output of the sweep generator to cause a self-initiated retrace. The two paths are combined in the matrix diodes at the input to the switch, V6. In normal operation the retrace pulses arrive at the switch alternately: Over the first path at the beginning of a facsimile line, and over the second path in the middle of the line coincident with the boundary between the two adjacent pictures. The self-retrace path is direct-coupled through the four neon glow-lamps to eliminate any possibility of stopping of the sweep if the trigger from the recorder fails. The protection is necessary to prevent burning of the CRT screen.

The synchronizing pulse at the beginning of the line is derived from the recorder and after amplification in the amplifier (V9) is applied to the input of the Schmitt trigger (V10). The plate of V10 starts the retrace by cutting off the disconnect diodes. The self-retrace occurs when the sweep reaches the threshold level of the other Schmitt trigger (V5). The sweep length can be varied by changing the voltage level of the fed-back sweep. The circuit has then two independent controls: the sweep length and the sweep time. The sweep length sets the length of the raster on the scanner CRT. The sweep-time control equalizes the width of the two pictures on facsimile. If the sweep is too slow it reaches the middle retrace too late. The second sweep is then not completed by the time the next pulse from the recorder arrives. By adjusting the sweep-time control the two pictures are made almost equal. The sweep starting in the middle of the facsimile line is made about 10 msec slow, so that its termination is caused by the external pulse just before the internal feedback path would terminate it. The right picture is therefore about 1/8" narrower than the left picture.

The alternate pulses from the two Schmitt circuits V5 and V10 drive a binary stage V1. The two stable states of the binary correspond to the left and right pictures. The output from the second half of the binary is differentiated to produce trigger pulses of alternate polarity. These pulses are used to drive the high-speed relay in the modulator.

The vertical sweep is generated in the Miller integrator V11 and V12. It is quite similar to the horizontal generator, except the time constant is greater. The sweep is started by a pair of relay contacts. One of the contacts substitutes a set DC voltage to the output to position the scanning line across the test pattern. The sweep is adequately linear, even though the 212-second sweep time approaches the upper limit for a Miller circuit, partly because a capacitor with low leakage (mylar dielectric) was used as the timing element. The sweep was experimentally operated over a 7 1/2-minute frame time to produce pictures 9 inches by 11 inches. The sweep was acceptable for the few pictures that were produced, but it is unlikely that it could be maintained operationally.

5.7 Rapid Processor

The rapid processor used in the scanning system was originally built to provide a projected picture of a surveillance radar. As manufactured, the unit comprises the PPI display, the rapid film processor and a projector. In its normal operation a picture is photographed during one antenna rotation, is processed during the following rotation and is then projected on a screen (rear or front) for direct observation. A fresh picture enters the projector after every antenna rotation, a period which may be as short as 6 seconds.

After the picture has been exposed, the film (Ilford, type BU) moves to the processing aperture (22 mm in diameter) where it is processed by sprayed chemicals. The available time of one rotation is divided into four sectors during which the film is sprayed in succession by the developer (Ilford ID-85), rapid fixer (Ilford IF-18) and a wash solution, and in the fourth sector is dried by a stream of hot air. The chemicals are sprayed by compressed and heated air in a unit consisting of three jets. The chemicals that have passed through the processor are drained to a waste storage after being used once only. In designing the processor the major effort was expended in achieving the shortest possible processing time. Control of sensitometric characteristics was not of first importance in producing a two-tone display of a conventional search radar. In normal operation the compressed air (30 psi) is heated to about 65 C. The temperature of the developer in the processing pot is raised by the compressed air from room temperature by about seven degrees to about 27 C. The final temperature was found to depend to a large extent on the initial temperature of the developer. When used in the original form, the processor has a rate of consumption of one 18-oz bottle of each of the chemicals in about 6 hours. The ratio of the rates for the developer and fixer depends on the fraction of the total processing time each occupies.

Several modifications were necessary to adapt the unit to the relatively long (3.75 min) CAPPI cycle. The controlling unit for the processing was modified to allow its program to be stopped during a large part of the CAPPI cycle. During antenna descent the processing cycle is started and it proceeds at an internally controlled rate, instead of following the antenna rotation. The processing time was lengthened towards improving the stability of the product, and is not completed at the end of the next rotation (which is devoted to recovery of the antenna to zero elevation). The processing continues for most of the following two rotations. Since the exposing of the next picture and the scanning of the preceding picture have already commenced, the film cannot be advanced upon completion of the processing cycle. The processed frame is kept in the processing aperture until the beginning of the following CAPPI cycle. Therefore, the frame in the gate of the scanner starts being transmitted 7.5 minutes after its exposure began and 3.75 minutes after the exposure ended. (Considerable saving in supplies of course results from converting the unit to CAPPI operation. A bottle of each of the chemicals now lasts typically three days. The film consumption is correspondingly low: 1000 feet/month.* The normal

*The spacing between useful frames is two inches as compared to one inch on our archival records. In the summer months of 1963 about 5000 photographs were taken monthly.

duty cycle is typically 1:2, or about 350 hours/month.)

Additional changes in the equipment were necessary to improve the stability of the product. As built, the process controller includes a safety feature that turns on the hot drying air, unless one of the three liquids is being sprayed. In the original scheme this amounted to 3 seconds every 12-second cycle, so that the processing pot was not appreciably heated by the air and an equilibrium temperature of about 27 C was established. After the long interruption was introduced into the cycle, the hot air, blowing for 200 seconds, established a much higher equilibrium temperature in the vicinity of 60-65 C. The high temperature led to evaporation of the developer and particularly the fixer, resulting in a precipitate being formed in the jet unit. In 24 to 36 hours blockage of the jets caused a rapid deterioration of the product. The dynamic range on film dropped from 10 db to less than 5 db (Fig. 5.11 upper part). After a thorough cleaning and washing one could proceed through a similar cycle.

The controller was modified to interrupt the air supply after the usual air-dry period of 5 seconds. The problem of the precipitate forming in the pot was substantially reduced but the decay of the film gamma tended to persist. Apparently the rate of chemical consumption was too slow, so that the developer deteriorated while it waited in the warm pipes leading from the bottle to the processor. A considerable improvement in the long-term stability resulted from disconnecting the air heater. The developer is now at room temperature rather than the former temperature of 27 C. The processing time is correspondingly longer, about 23 seconds* for the required film gamma. Fig. 5.12 is a

*Until August 1963 the process time was 39 seconds for a maximum density of 1.5 (including base).

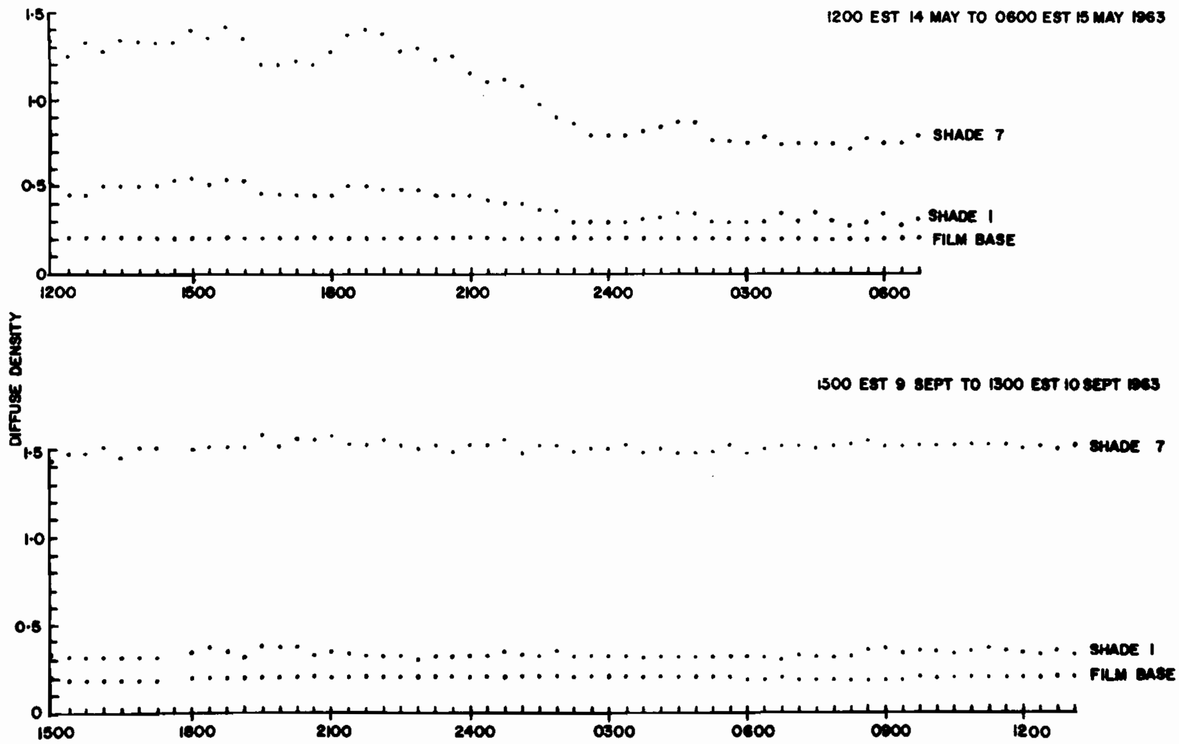


Fig. 5.11

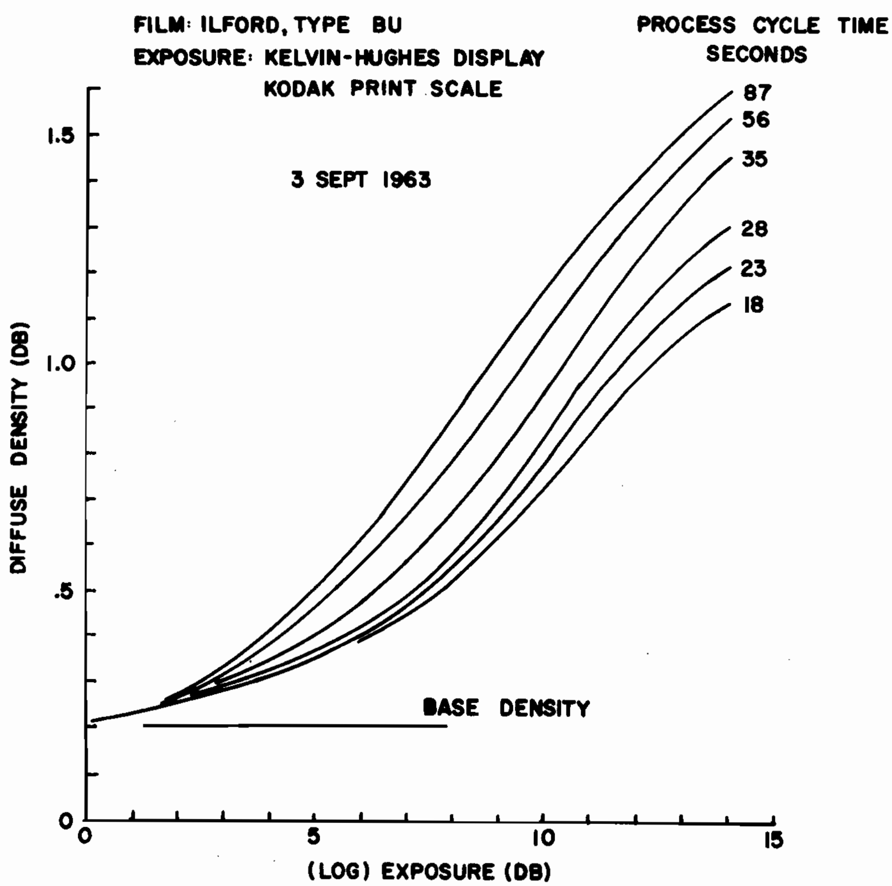


Fig. 5.12

plot of film characteristics for various processing times, ranging from 18 seconds to 87 seconds. In all cases the air heater is inoperative. The characteristics were obtained by photographing the CRT display with the trace brightness turned up somewhat higher than the seventh intensity. A grey test wedge (Kodak Print Test Wedge) was then placed on the face of the CRT. The trace provided the back illumination for the test. After the above changes were introduced, the decay in gamma was eliminated. The lower part of Fig. 5.11 shows the variation in density over the last 20 hours of a 44-hour period of operation. Measurements were made on every sixth picture occurring at 22.5-minute intervals.

The processing unit needs to be cleaned about once every week or 10 days, and can run unattended for up to three days between chemical replenishing. The process is, however, interrupted daily to clean the optical apertures because cleanliness is particularly important in a negative process where a speck of dust would appear as a grey echo on the facsimile picture.

Three problems remain. The lower part of Fig. 5.11 shows a random fluctuation of about 1 db in density. It is not likely that much improvement can be made with the spray type processor to bring these random variations signficantly below one db.

The second difficulty arises from a complete lack of temperature control within the processing unit. The stability of the processing depends entirely on maintaining a stable room temperature. This has proved to be difficult in winter. During the summer, air-conditioning is necessary because of the heat dissipated by the electronic chassis. The thermostatted air conditioner has provided an adequately stable room temperature. Tight control of the room temperature as a way of controlling the processing is not a happy solution. However, modifications to the processor to include temperature stabilization appear to be difficult due to the integration in one compartment of electronic chassis, control circuits and the chemical storage.

The third difficulty is related to the transfer characteristics of the film. The Ilford film, type BU, processed in the rapid processor is significantly different from a normal negative film, for example the Kodak Tri-X film (No. 5233) that we use to photograph other displays. The usual characteristics of the Tri-X film have an extended portion at constant gamma which starts as near as 1 db from base. The characteristic curve of the BU film shown in Fig. 5.12 (for example the curve for the 23-second development time that we currently use) starts at a reasonable slope, but beyond a density 0.5 the gamma is nearly unity. The slopes in this region do not differ significantly from curve to curve, which is quite unusual for negative film. As a result of the high slope, the required range of density of 9 db for shades 1 to 7 is obtained from an uncomfortably narrow input range (range of luminance on the CRT). With a narrow range, and hence small steps in luminance, the display non-uniformities become a serious problem. For example the half-tone filter used to correct for variable line-spacing is under-correcting by 1.5 db at one-tenth radius. While on our CPS-9 displays the 1.5-db error is less than the 2-db steps in luminance, on the display in the rapid processor the error just exceeds the size of the step. The undesirable film characteristic is not necessarily common to all rapid-access photography. It is rather caused by over-processing to get a sufficient sensitivity with the BU film. The BU film is estimated to be only half as sensitive as the Kodak Panatomic X, which is advertised as ASA 40. The comparison was made by measuring the luminance of level 1 on the CRT by means of a cadmium sulphide photocell and comparing it to the luminance of our CPS-9 displays.

5.8 Modifications to Processor PPI Display

The PPI display in the rapid processor was first modified to CAPPI and grey-scale operation in much the same way as the displays in the CPS-9 were modified by East (1958) and Legg (1960). The modifications involved changes in the range-gating circuits and video circuits. In the processor display these circuits included useful features such as sweep failure protection and centre blanking, which, however, degraded the waveforms below acceptable standards. Of the original circuits, only the video amplifier was retained.

The CAPPI gate waveform was at first fed to the display in the same way as it is to the CPS-9 displays: A 60-volt pulse at a high impedance, directly to the grid of the CRT. The capacitive loading of the cable is not serious in the CPS-9 displays, where the cable lengths are about 15 feet. The cable length to the processor display is in excess of 75 feet. The capacitive loading stretched the CAPPI gate waveforms, particularly the trailing edge (when the cable-driving tube is cut off) causing overlaps of adjacent CAPPI annular rings. The range-gating unit (video switch) in the CAPPI system was then modified to drive the gating pulse at a 2-volt amplitude and at an impedance level of 75 ohms. With the cable now properly terminated, the shape of the gate is preserved. The pulse is amplified at the display before being fed to the grid of the CRT.

A new circuit was constructed to bias the CRT correctly and to supply the gating pulse. The experience gained in stabilizing the scanner CRT was applied to the CAPPI display. In the scanner, luminance stability of better than 1/4 db (compared to 1 to 2 db on the CPS-9 displays) resulted from using reliable reference points for the grid and cathode bias of the CRT.

The CRT control circuit is shown in Fig. 5.13. Referring to the biasing circuit in the upper half of the diagram, the restoring voltage, which controls the CRT beam current, is derived from the two reference glow-tubes OG3/5651. The coarse and fine brightness controls make the brightness setting straightforward. As on the other displays in the CPS-9, the proper luminance level is established by monitoring the shade-one cathode current on the CRT (Barath, 1961). The box galvanometer is inserted into the circuit by throwing the switch to the test position, as indicated in Fig. 5.13.

The gating amplifier is shown in the lower part of the figure. The stable reference for the CRT grid is established at the plate of the pentode 6CL6. The gating pulse is applied after amplification to the grid of the 6CL6 pentode. The CRT conducts whenever the pentode is cut off. Now the top of the plate load of the 6CL6 is at ground potential, so that when no plate current flows the CRT grid is also at the ground potential. The only necessary precaution is to ensure that the pentode is properly cut off during the desired CAPPI interval.

The two relay contacts at the input to the gating channel are used to blank three of the peripheral test patterns on the processor display. During the test pattern rotation (antenna descent), the relay CR-1 opens, removing the gating pulse from the amplifier input.

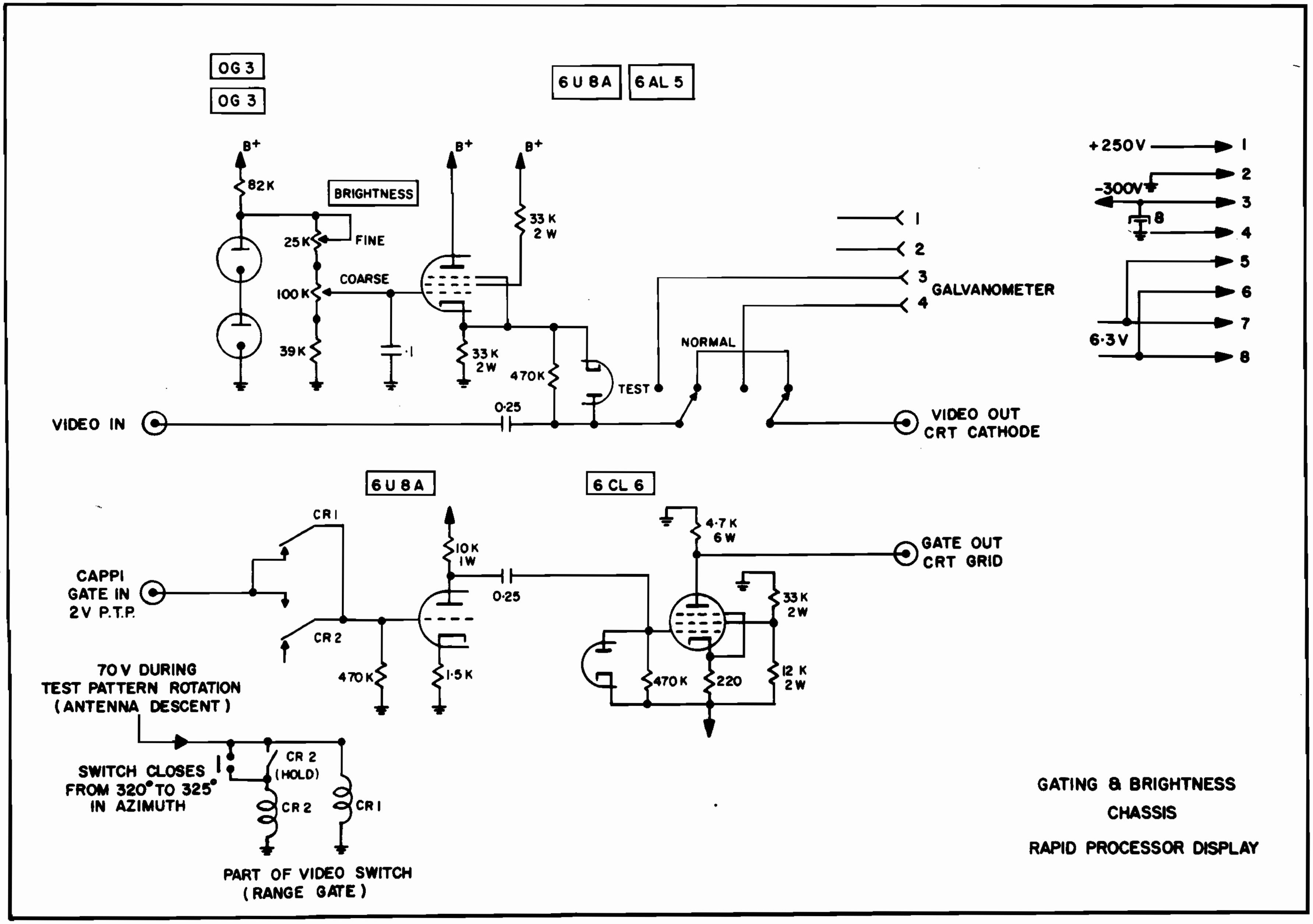

OG 3
OG 3
6U8A
6AL5
B+
82K
BRIGHTNESS
25K
FINE
100K
COARSE
39K
.1
33K 2W
470K
TEST
NORMAL
1
2
3
4
GALVANOMETER
VIDEO IN
0.25
VIDEO OUT CRT CATHODE
+250V
-300V
6.3V
8
6U8A
6CL6
CR1
CR2
CAPPI GATE IN 2V P.T.P.
10K 1W
0.25
1.5K
4.7K 6W
GATE OUT CRT GRID
33K 2W
12K 2W
470K
220
70V DURING TEST PATTERN ROTATION (ANTENNA DESCENT)
SWITCH CLOSES FROM 320° TO 325° IN AZIMUTH
CR2 (HOLD)
PART OF VIDEO SWITCH (RANGE GATE)
GATING & BRIGHTNESS CHASSIS
RAPID PROCESSOR DISPLAY

FIG. 5.13

At the azimuth of 320° a contact in the CAPPI triggering unit operates relay CR-2, allowing the north test pattern (last of four) to be displayed. The relay CR-2 is held closed for the rest of the rotation by a self-holding contact.

The biasing circuit has improved the stability of the CRT luminance to the same level as that of the scanner CRT. The display was photographed for a 20-hour period to produce the plot of density of shades one and seven in the lower half of Fig. 5.11. The variations in the densities are an indication not only of processor stability, but also of the CRT itself. In particular, the variation in shade-one density is indicative of the CRT performance because the lowest density is affected least by variations in processing and most by drifts in CRT luminance.

6. EVALUATION

6.1 The System in Operation

The McGill Weather Radar is operated by the Stormy Weather Group (a) in order to develop suitable forms of displays, (b) to collect precipitation records for research use, and (c) to offer weather radar services to the Montreal Weather Office. This unique combination offers invaluable opportunities to try out the new display techniques under operational conditions to evaluate their usefulness. The main user of the facsimile display is the Aviation Briefing Office, with a smaller use made by the Public Forecast Office.

Our past experience in trying out various alternative forms of display indicated that the only basis on which a service would seriously be considered by the users is a continuous, around-the-clock operation. A scheme was therefore evolved to make the facsimile display available on such a basis.

The general experience has been that once the display was accepted as a part of the routine, the users requested service when precipitation was within radar range, but also during extended periods of air-mass instability, when there was only a small chance of precipitation. Similarly, the radar and the processor were usually left operating overnight when the technicians were not on duty. The users could start the facsimile recorders when necessary. The decision when to start the recorder is at present somewhat precarious. However, in 1964 an automatic recorder will be used, with which it will be possible to display only a low-level picture, say every 45 minutes, when frontal precipitation is expected. During periods of unstable air mass it is still desirable to receive pictures continuously because of the rapid development that can occur.

It was soon discovered that it took about one hour to start the processor, replenish chemicals, etc. until usable frames would emerge from the processor and a stability of processing would be attained. The most practical solution was found to operate the processor almost continuously, with a daily interruption for cleaning of the optical gates (10 minutes) and a weekly interruption to wash through the chemical system.

To make the operating procedures as simple as possible, the azimuth positioning transmitter was modified. The original system is shown in the upper part of Fig. 6.1. Here the synchro-transmitter supplies the positioning information to the antenna. The antenna in turn transmits its actual position to the displays. The CAPPI program controller (Barath, 1961) is also driven from the information returning from the antenna. The problem was the necessary stoppage of the whole program when the antenna was stopped. This was particularly inconvenient in the processor if the stoppage occurred during the antenna recovery part of the CAPPI cycle, during which the film was being processed.

The new system is shown in the lower part of Fig. 6.1. The programmer and the sweep of the processor display are both controlled by a new positioning transmitter. The new transmitter is driven by a synchronous motor resulting in exactly 16 frames per hour. The program now proceeds uninterrupted, even when the antenna is stopped. There is a slight loss in positioning accuracy if the antenna lags the command information while the trace does not, but in a rotation at a constant rate the error is not noticeable. The advantage is gained

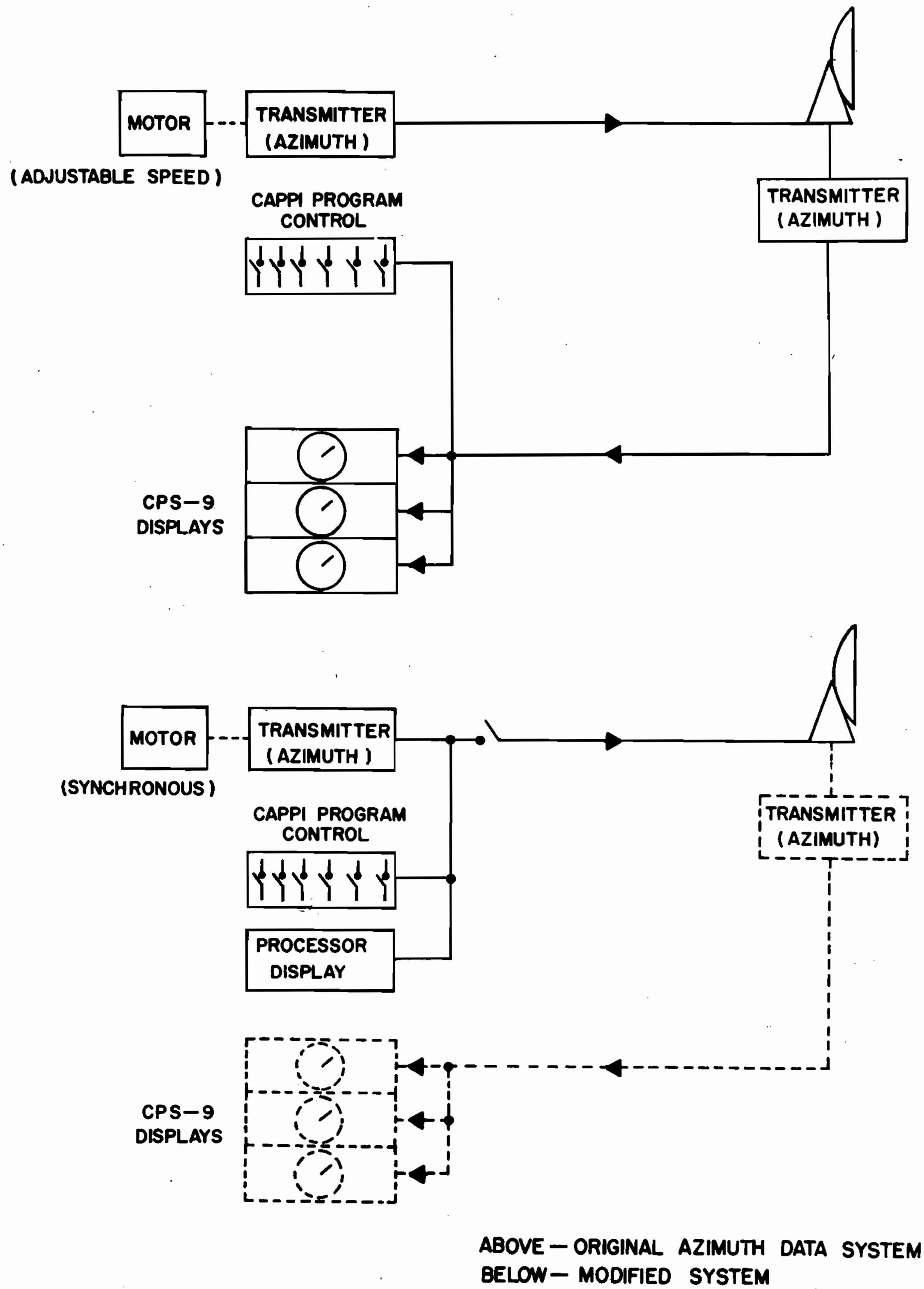

MOTOR
TRANSMITTER (AZIMUTH)
(ADJUSTABLE SPEED)
CAPPI PROGRAM CONTROL
TRANSMITTER (AZIMUTH)
CPS—9 DISPLAYS
MOTOR
TRANSMITTER (AZIMUTH)
(SYNCHRONOUS)
CAPPI PROGRAM CONTROL
TRANSMITTER (AZIMUTH)
PROCESSOR DISPLAY
CPS—9 DISPLAYS
ABOVE — ORIGINAL AZIMUTH DATA SYSTEM
BELOW — MODIFIED SYSTEM

FIG. 6.1

in being able to process normal frames with the regular test pattern when the radar transmitter (and the antenna drive system) is turned off. The system can then be put "on the air" by merely starting the magnetron radiation - a task that can easily be handled by relatively inexperienced personnel when the radar technician is not on duty.

In the summer months of 1963 the radar and the scanning system were operated for about 1300 hours, during which about 21,000 frames were processed. Useful records of precipitation were obtained on facsimile for about 550 hours.

6.2 Scan Conversion

A memory is a necessary part of any scan conversion system from polar (radar) to rectangular coordinates. Two factors peculiar to weather radar make film a most useful form of memory. One is the large number of elements that must be stored. The wide dynamic range, combined with about 10^5 areal elements, leads to nearly 10^6 elements. The theoretical limit on the capacity of one frame on 35-mm film is at least an order of magnitude better.

The other factor that makes the solution, using film, attractive is the need for averaging of the fluctuating signals. Writing the information on the storage surface in analog form has resulted in areal averaging, the extent of which is readily controllable.

Rapid-access photography has proven to be a relatively trouble-free and practicable part of the scan-converter. Certainly the availability of a permanent record on film at an intermediate point in the system proved to be invaluable in experimenting with the scanner and modulator circuits. A direct comparison of the product with the original was possible as changes and improvements were being made. The operating costs of the processor have turned out reasonable - $120 per month. For comparison, pictures for operations taken on a Polaroid Land Camera that we had been using in the past summers (Marshall and Gunn, 1961) had cost $1000 monthly.

6.3 Facsimile Display

The experience gained during the summer of 1963 has established the practicality of such a display. Facsimile in general is an integral part of the weather office. The traditional use of facsimile has been the reception of synoptic maps. More recently, recorders for special functions have come into use, as for example in conjunction with ceilometers and for the reception of satellite cloud cover pictures.

The radar pictures were used for briefing air crews before take-off. The crew could be presented with the current terminal weather as well as the development in the preceding few hours. The 5.5-inch wide pictures proved to be about as small as one could tolerate. Our past experience with pictures from a Polaroid Land Camera indicated that the smaller photographs were acceptable, mainly because of the better resolution than facsimile.

By far the greatest use was made of the left picture. The finer intensity resolution provided by the right picture was used occasionally, only when the highest intensity was level six. Similarly, of the six heights, the map at 5000 feet was analysed, while the sequence was scanned to locate the echo tops. We found that hand-out copies of the facsimile pictures would have been well received, had they been available. Since the crew is briefed one hour before take-off, the copy could usefully be the latest one, delivered at the ramp.

At present, the last contact the crew has with the weather office is one hour before take-off. Any information they receive after that is third-hand, through the Area Traffic Control. The possibility of extending the service to the Area Traffic Control is an interesting one, but there a facsimile recorder is not likely a suitable display. Because of the pressures of the activity in the ATC, a slow-scan television display (receiving the same signals) is more suitable for current pictures.

The format of two pictures side-by-side was chosen to some extent by necessity, to make the best use of the available recorders. As it turned out, the display gave more than adequate intensity resolution for operations, and at the same time it provided records for research in a more suitable form than our "un-integrated" film records of the CPS-9 displays.

The objection to the presentation scheme for operational use is the unnecessary waste it makes of the communication channel. The number of shades is limited to four on facsimile paper, not on the transmission line where the 32-db dynamic range is more than adequate for simultaneous transmission of seven intensity levels. On the short-haul lines used for weather radar, the waste of the channel space is not really a strong argument.

A more valid objection can be raised against the choice of the intensities represented by the different shades. In particular, in the left picture, half the dynamic range on paper is devoted to the step from dark grey to black to ensure that the echo is recognized when it occurs. Rates of precipitation exceeding 400 mm hr^{-1} (intensity 7) occur so rarely that a better use of the darkest shade would be made if the highest intensity were about 100 mm hr^{-1}.

6.4 Future Displays

Instead of using a single display with the fine intensity resolution, both for operations and for research data, it would be advantageous to separate the two functions. The best approach is to use a common radar and scan converter and provide separate, but compatible, displays suited for each user.

For operational use, a narrower recorder with a single picture is envisaged, rotating at 240 rpm instead of the present 120 rpm. The number of shades would depend on the size of the picture; four for a 5-inch wide picture, or five on a 9-inch picture. The latter size has the added advantage of being compatible with the format used for transmission of satellite pictures. The use of a single recorder for both functions appears economically attractive, particularly in television stations for presentation on the air.

For research use, the two maps side-by-side on facsimile, are somewhat inconvenient. The facsimile paper is not archival. Also, because the intensity levels are separated into two pictures, further work is necessary to combine them.* A better medium is a photograph of a slow-scan television, compatible with the operational display (same scanning rates), but with all seven intensities super-imposed. A positive transparency is preferable to a paper print because of the increased range of contrast. Whether the output is a print or a transparency, the photographic material introduces only the fine grain of the film, much less objectionable than the texture of the facsimile paper. Pictures of the slow-scan television display would replace the CAPPI photographs as the records of precipitation for research use.

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*Combining stepped-gain pictures from a conventional radar presents a similar problem.

The slow-scan TV pictures were produced experimentally to demonstrate the effect of areal integration without the distraction of the coarse texture of the facsimile paper. One such photograph is shown in Fig. 1.7; another pair is shown in Fig. 6.2 and 6.3. (For comparison the same echo is shown on facsimile in Fig. 6.4.)

6.5 Shortcomings of the Present System

(a) Dynamic Range

The total dynamic range in the scanner is limited by the contribution of halation on the screen of the CRT and by light scattered in the optical system. At the same time the smallest useful step in density is limited by non-uniformities and drifts in scanner luminance.

The halation component could usefully be reduced by using a cathode ray tube with a light-absorbing face-plate. At the same time, the optical system would also have to be modified to decrease the contribution of the objective lens and its mount. It is reasonable to expect that a range of 15 to 17 db can be realized. The wider dynamic range should, however, be used to improve the fidelity of the scanner, rather than to increase the range of densities on film much beyond the present 11 db. There is no indication that a wider range on film would offer any real advantage. On the contrary, a density range of, say, 17 db could make the (small) high intensity echoes susceptible to small changes in the optical system, such as the presence of dust on the objective lens. The source of the difficulty is the modulation polarity: For maximum echo intensity the transmission through the film is minimum.

It is important, however, that the 11-decibel range be obtained, through a photographic process at a gamma less than unity, from as wide

Fold out, twice.

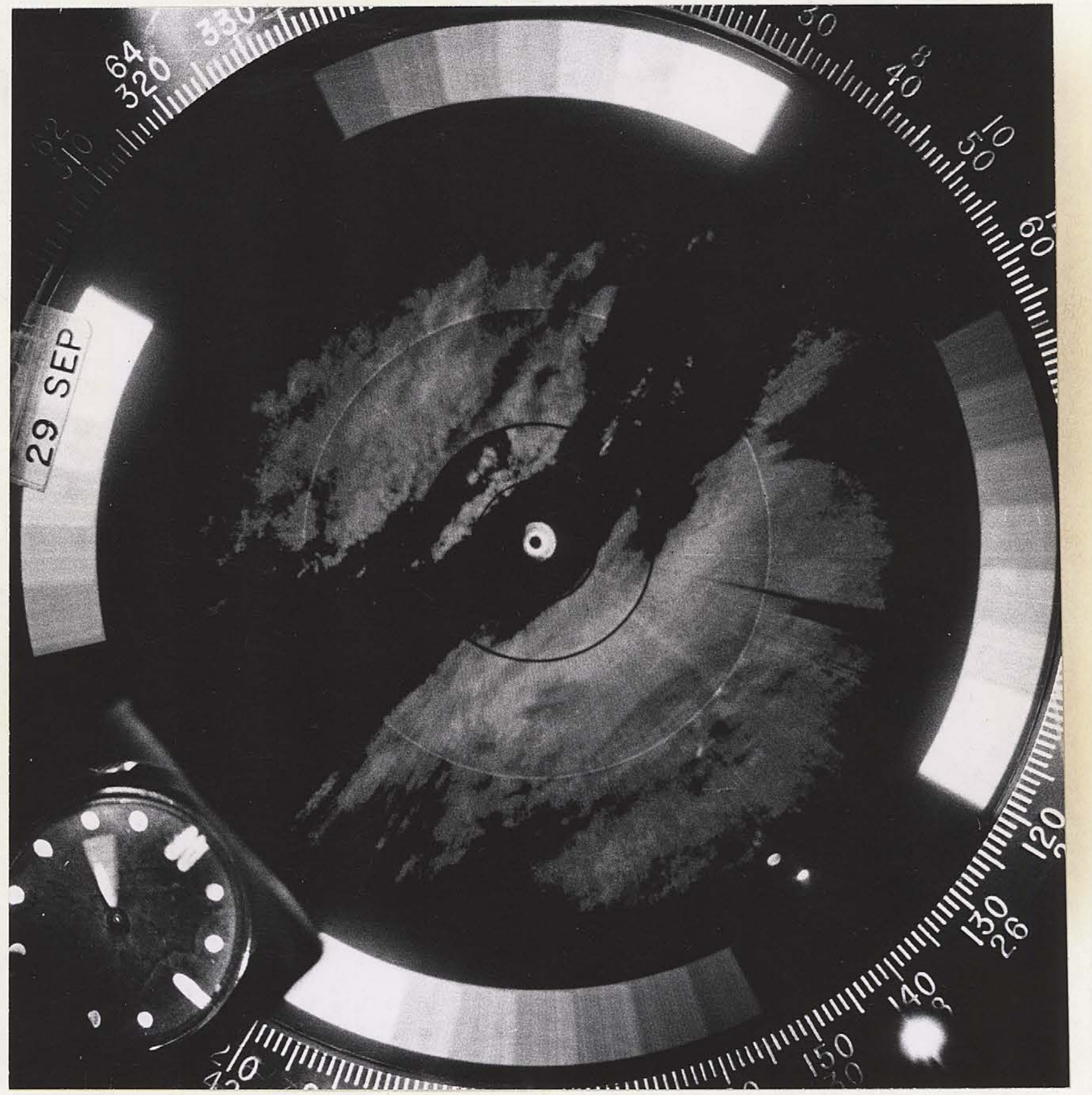


Fig. 6.2

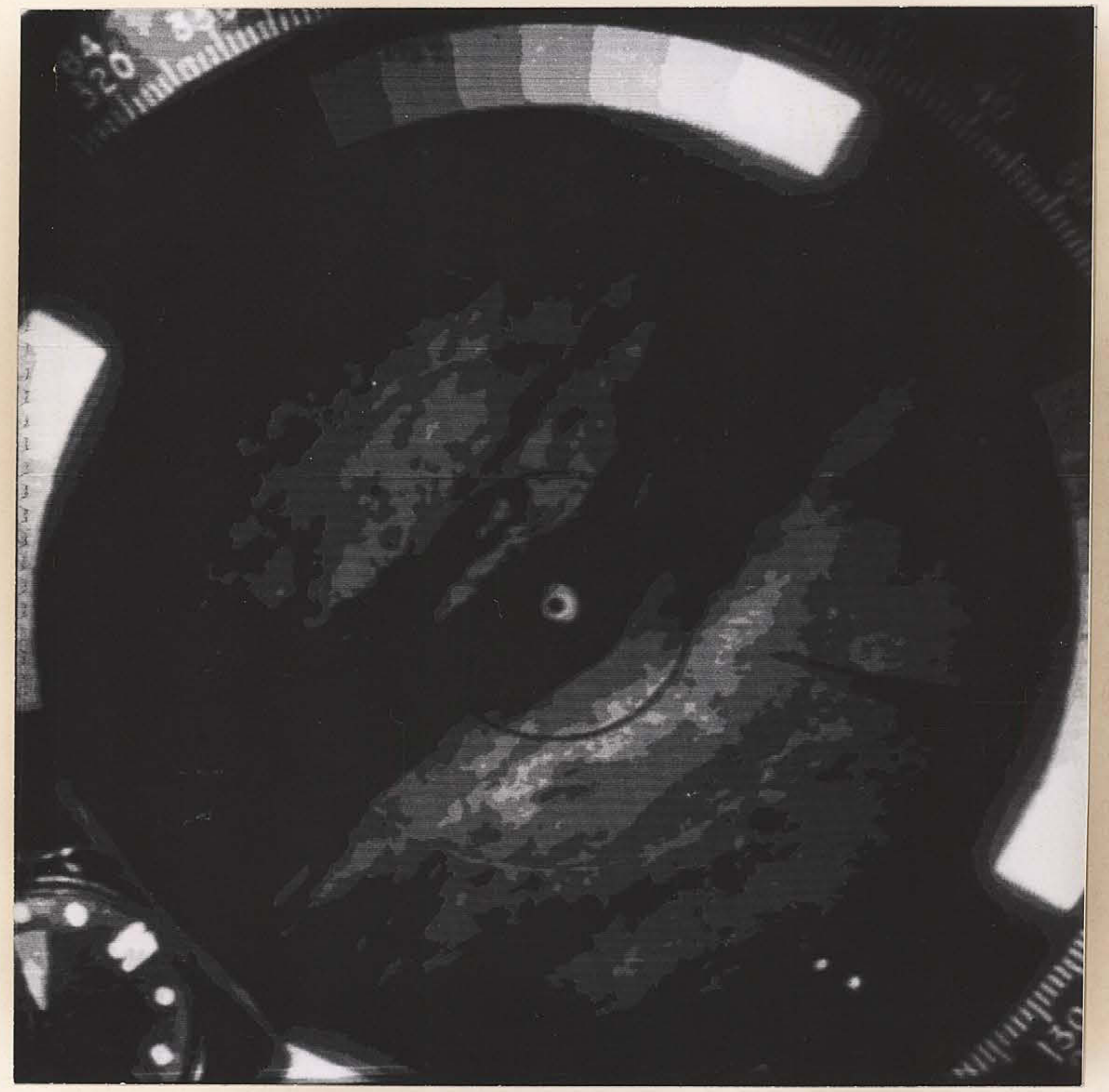


Fig. 6.3

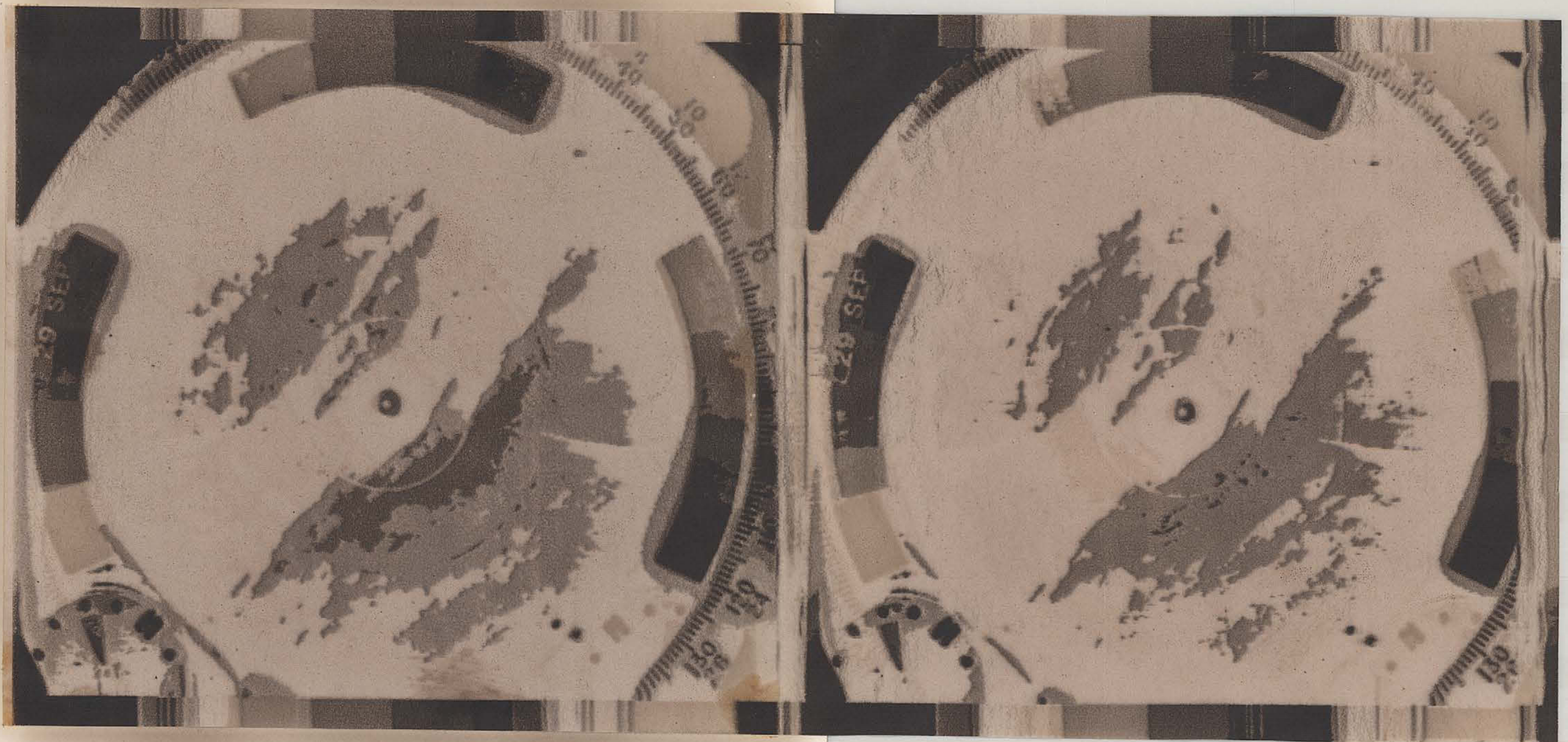


Fig. 6.4

a range in luminance on the first CRT as possible. The (first) display CRT should also have an anti-halation face-plate. The modulation polarity here is positive (maximum echo - maximum luminance), and therefore there is less danger in using a wide dynamic range than in the scanner. The need for a wide dynamic luminance range is caused by the difficulty in producing a radial display with a uniformity much better than 1 db.

(b) Signal Shaping

The grey scale display developed by Legg has been used as the starting point in the scan conversion. The changes in the existing circuits were kept to a minimum until the best form of input could be established. Since the steps, which are so necessary to the presentation on the final display, must be inserted after integration, the first set of steps in the video stages becomes of secondary importance. The main function of Legg's shaping amplifier is just that: shaping the signal so as to distribute the intensity information uniformly over the dynamic range. Having two sets of steps only improves the product if the steps are matched, as shown in the flow diagram of Fig. 5.3. Under these conditions, the sharpness of a step on facsimile is least affected by the grain in the screen of the scanner CRT. Similarly, small drift in the second threshold does not affect the picture. In both cases, the sharper the first step (by virtue of increased pre-threshold integration), the better the effect. The advantage of the two sets of steps is rapidly lost, however, if a mismatch exceeding one half of a step is allowed to occur.

A practical and less dangerous alternative is to use a continuous scale of grey on film. Then the effect of drift is just proportional to its amount. Legg's shaping amplifier was developed to offer the alternative of a continuous output. However, a straightforward procedure for aligning and maintaining the continuous scale has not been evolved. The partially-stepped scale we now use points towards the best choice. By making the transition range of each step about 3 to 4 db of the total 10 db, all presence of stepping in the echo will be removed. The transitions can be monitored in the same way as now, to maintain calibration, because the test pattern could be preserved in its present, stepped form.

(c) Test Pattern

The peripheral test pattern on film was modified by Barath (1961) from Legg's original form. The modified pattern was to serve two purposes. The first one was to provide seven roughly equal patches of grey, corresponding to the seven intensities in the echo. The second purpose was to use the position in azimuth of each transition between two shades to monitor the sensitivity of the threshold. The latter function has not been used in practice, and now that the signals are further processed in the scan converter, the test pattern would be more useful if the transitions occurred at fixed positions.

The peripheral test pattern is circular, and during the test it is scanned by a stationary line. It is not easily known where the line is in relation to the test pattern, and on several occasions the shades on facsimile were moved by one step, especially if the test pattern was slightly shifted on film. A fixed test pattern would help and it could easily be produced by timing circuits.

A more difficult change, but possible in the case of a fixed coil radial display, is to produce the north test pattern with the inner boundary straight from east to west, parallel to the scanning line (see Fig. 4.2) instead of the present boundary along the 140-mile range. With the present test pattern, the length of the pattern must be closely controlled to make sure that the scanning line can intercept all seven shades.

6.6 Auxiliary Displays

A set of plots against height, of rainfall exceeding each of the seven thresholds and totalled over the area within range, is a useful summary of the precipitation within range. Such profiles have been derived directly from the video stages of the radar by Hamilton (1963), who is studying the usefulness of the profiles. Hamilton used an experimental apparatus which cannot be easily adapted for routine operation.

The scan converter offers a practical way of deriving the profile information as a by-product. While a frame is being scanned, the signals at the outputs of the seven modulator gates give a measure of the areal coverage. Because the scan is rectangular with a uniform density of scanning lines, the duration for which the carrier is turned off by a given gate, is proportional to the areal coverage of precipitation exceeding the corresponding level. A direct way to derive the profiles then is to use seven digital counters, one for each gate to count the pulses of the audio carrier. A trial run with a digital counter indicated that the technique would yield values, as accurate as the rest of the system would permit.

The difficulty with the direct method of counting in synchronism with the facsimile scan is that the 2.4 Kc/s counting rate is too fast for mechanical counters. Electronic counters, even the simplest ones, on the other hand are capable of counting rates one or two orders of magnitude greater. No further simplification, and therefore a saving in cost is realized by specifying a counting rate as low as 2.4 Kc/s.

The direct approach of using seven counters is therefore not economically attractive. An alternative approach, as yet untried, is to scan each frame several times rapidly (1.5-second frame time) to derive the total coverage, exceeding each intensity, in succession. Seven rapid scans could be reasonably inserted in the 12.5-second interval now used to display the test pattern on facsimile. A single counter could give the seven totals in succession and the counting rate would be 50 Kc/s.

APPENDIX

Additional Samples of

Areally-Integrated Precipitation Maps

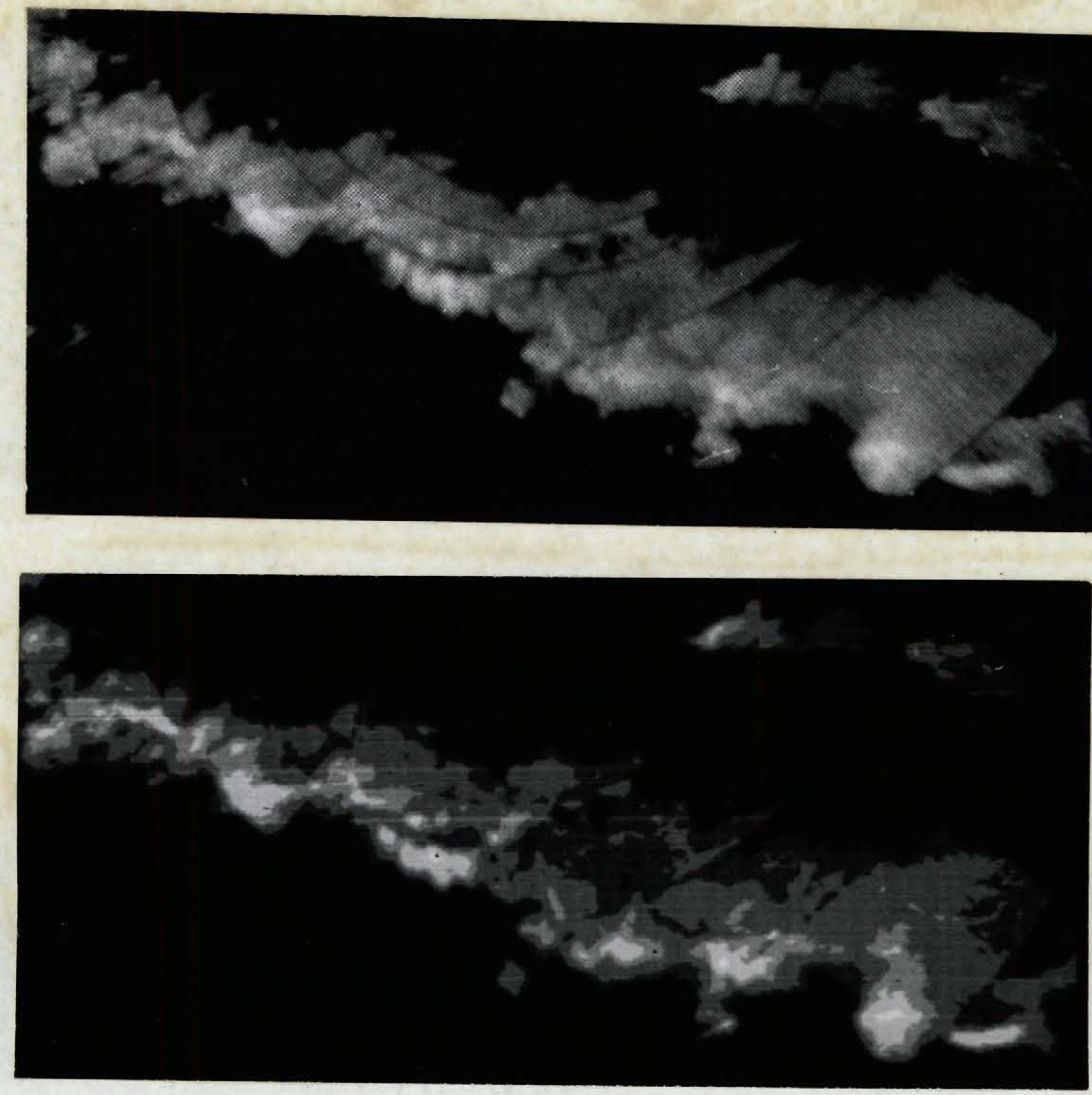


Fig. A1 - At the top is a section from a 10,000-ft CAPPI, 20 August 1962 to a scale of 25 miles per inch. Below is the same section after being scanned and displayed on an intensity-modulated rectangular raster. The maximum intensity (level 5, white) in this line of thunderstorms can be determined by counting the five readily resolved steps up the grey scale.

Fig. A2 - A low level map from 17 June 1963. At that time grey echoes were displayed on a black background, with intensity levels 1, 3, 5 in the left picture and 2, 4, 6 in the right picture. There is no echo of level 6; the white cores in the left picture are level 5. Aging of the facsimile paper has darkened the darkest grey shade so that the first step from background is almost lost.

This, and all subsequent facsimile pictures in this Appendix are on a scale of 50 miles per inch.

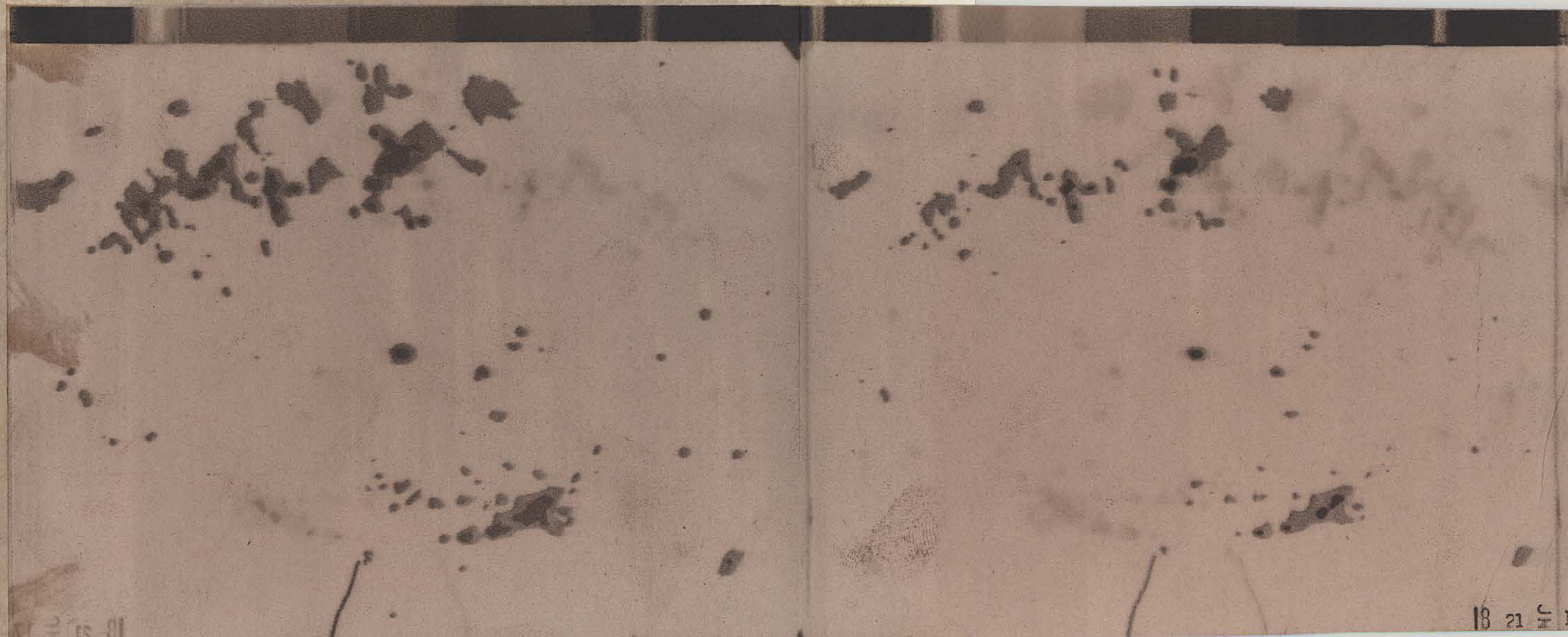


Fig. A3 - The film of 17 June 1963 (Fig. A2) was re-scanned some months later with grey echoes on a white background. In the left picture black has been reserved for level 7.

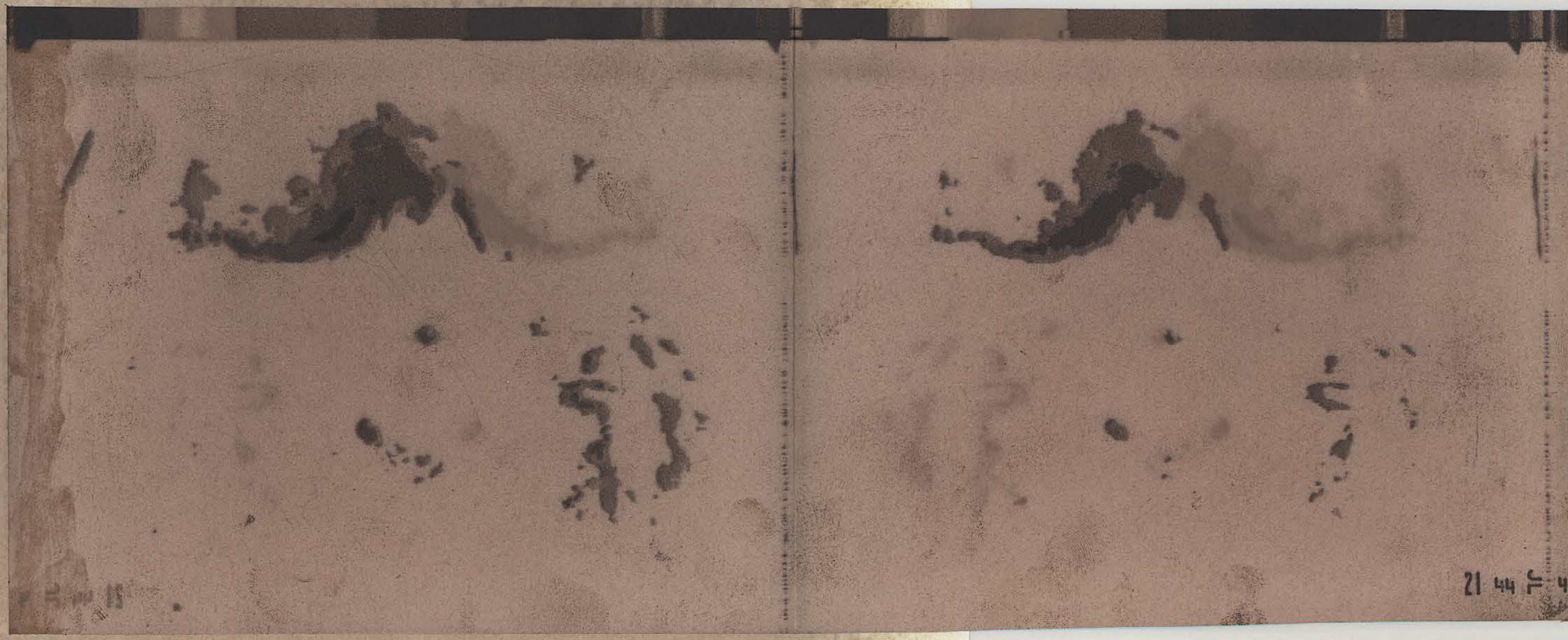


Fig. A4 - On 4 July 1963, this squall line with highest intensity 5 moved in from the North-West at an unusually high speed of 50 knots.

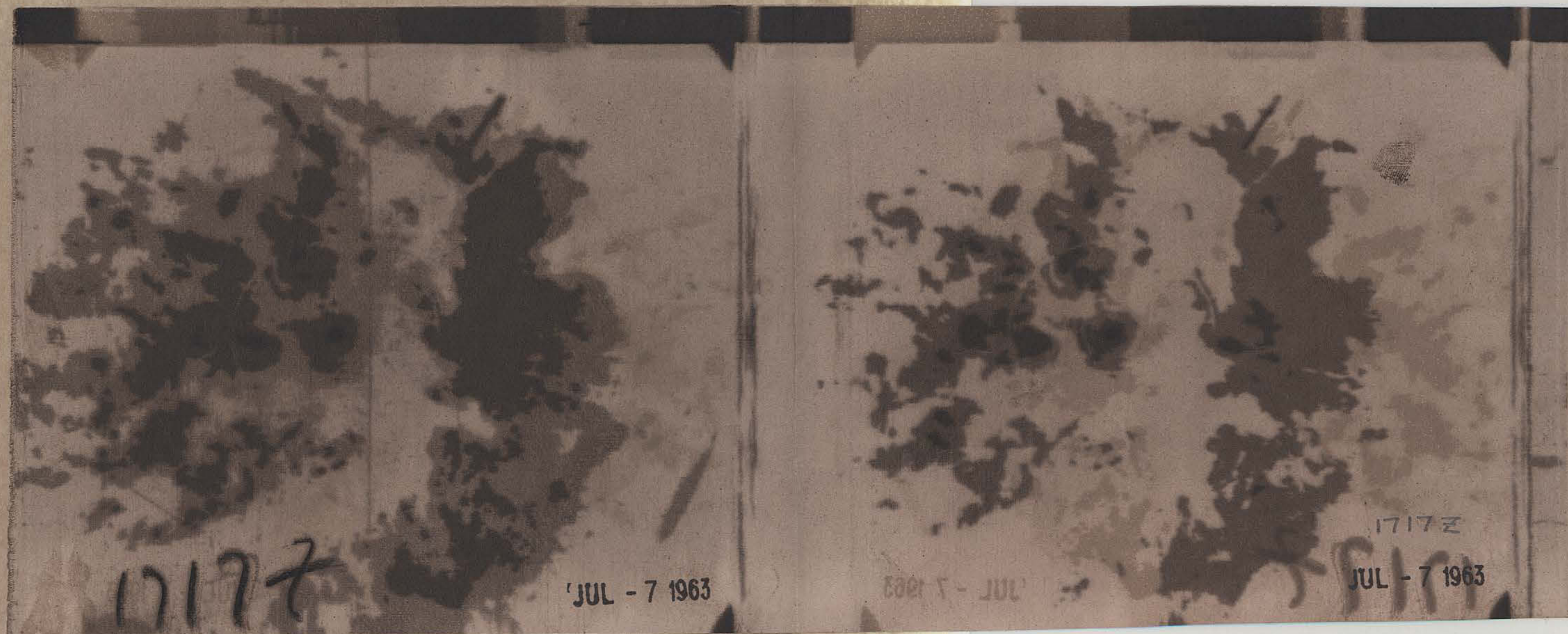


Fig. A5 - Warm-frontal precipitation on 7 July 1963 as seen on a 5000-ft map. The small spots of level 6 are probably not real and may well be due to the excessively large density range on the film at that time and the consequent distortion caused by halation.

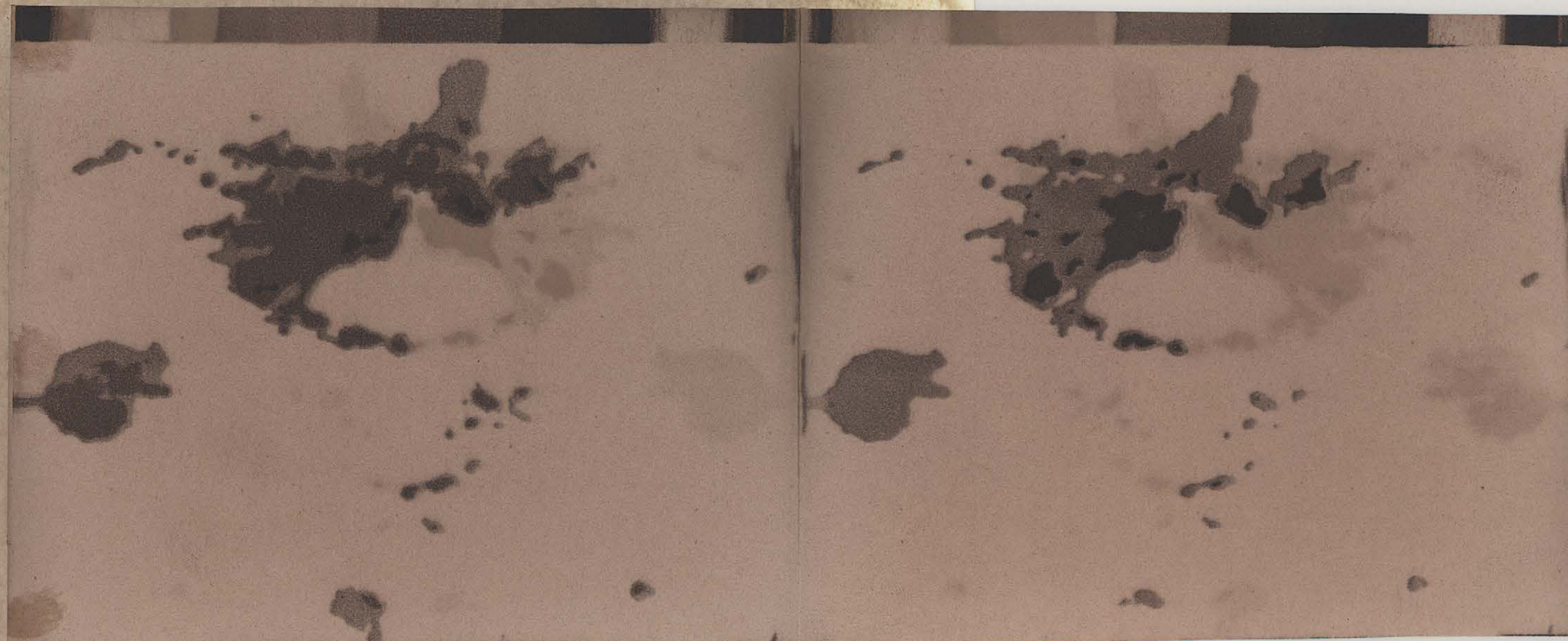


Fig. A6 - A map at 20,000 ft. showing the plume associated with a narrow line of thunderstorms on 7 August 1963.

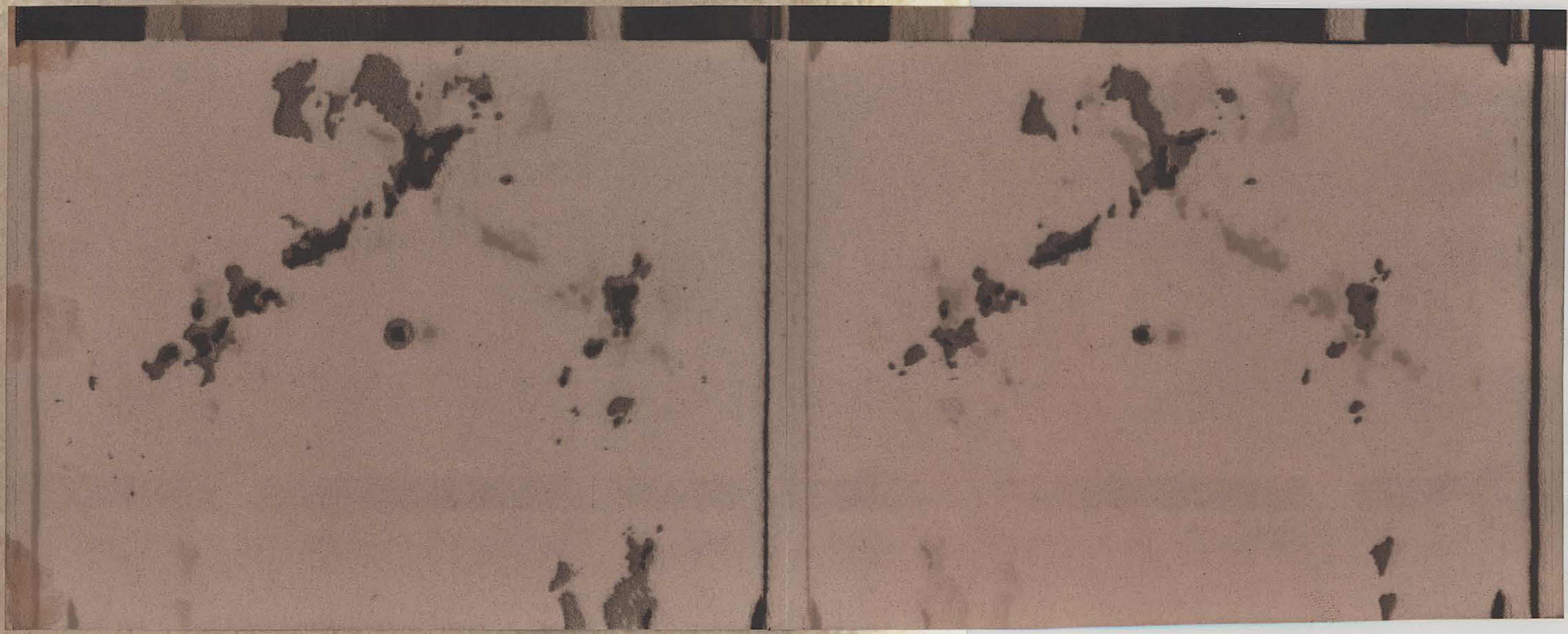


Fig. A7 - A squall line ahead of a cold front in late September 1963. The reddish tint in this picture is due to aging. This picture looks more dramatic than the preceding one (Fig. A6) because here almost all the dynamic range was used to display intensities 1 to 5.

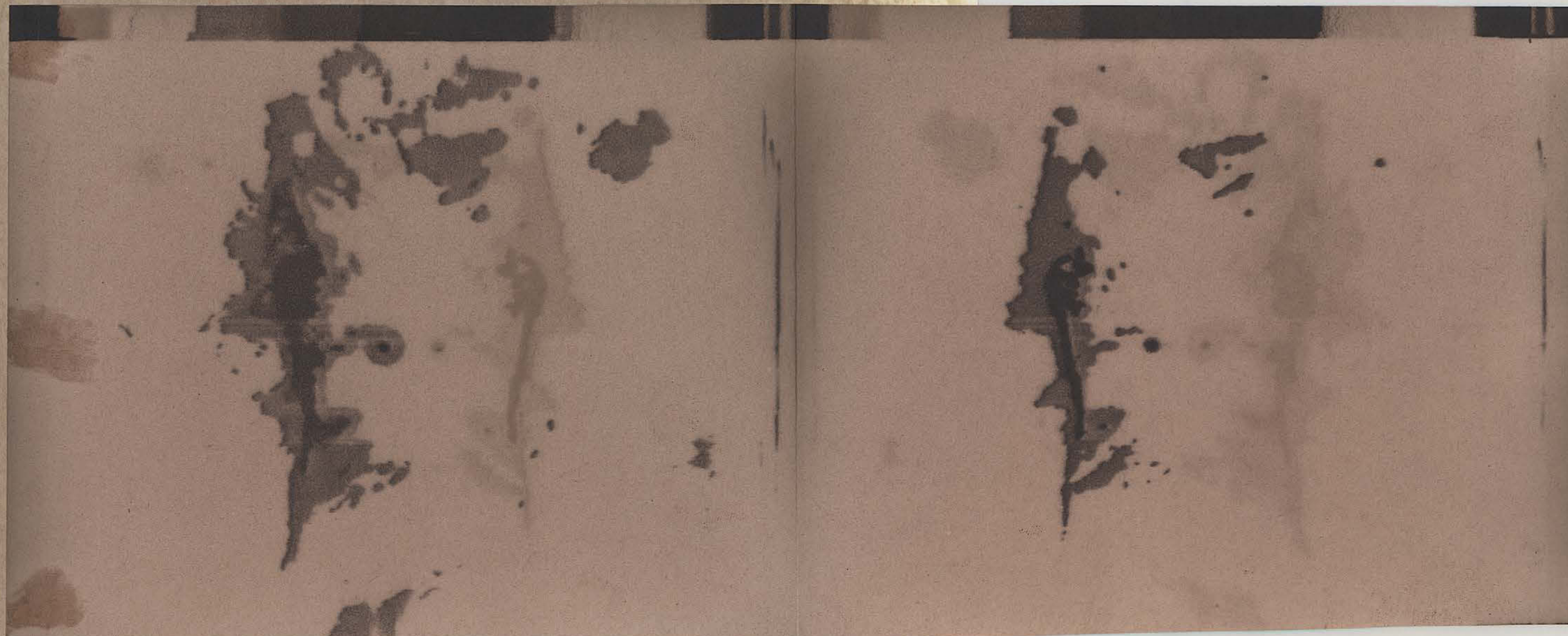


Fig. 8A - On 5 March 1964 this unseasonal line of echo produced heavy rain at Montreal with wind gusts over 100 knots.

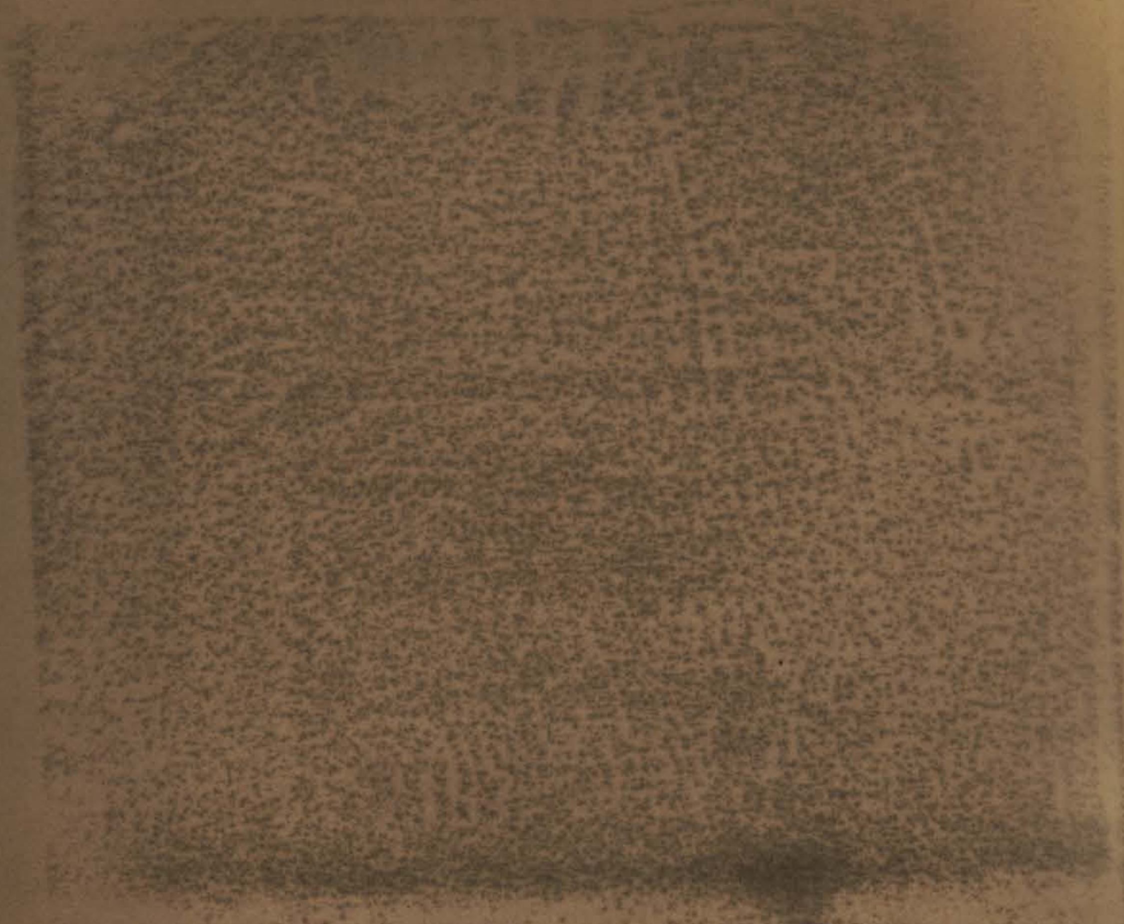
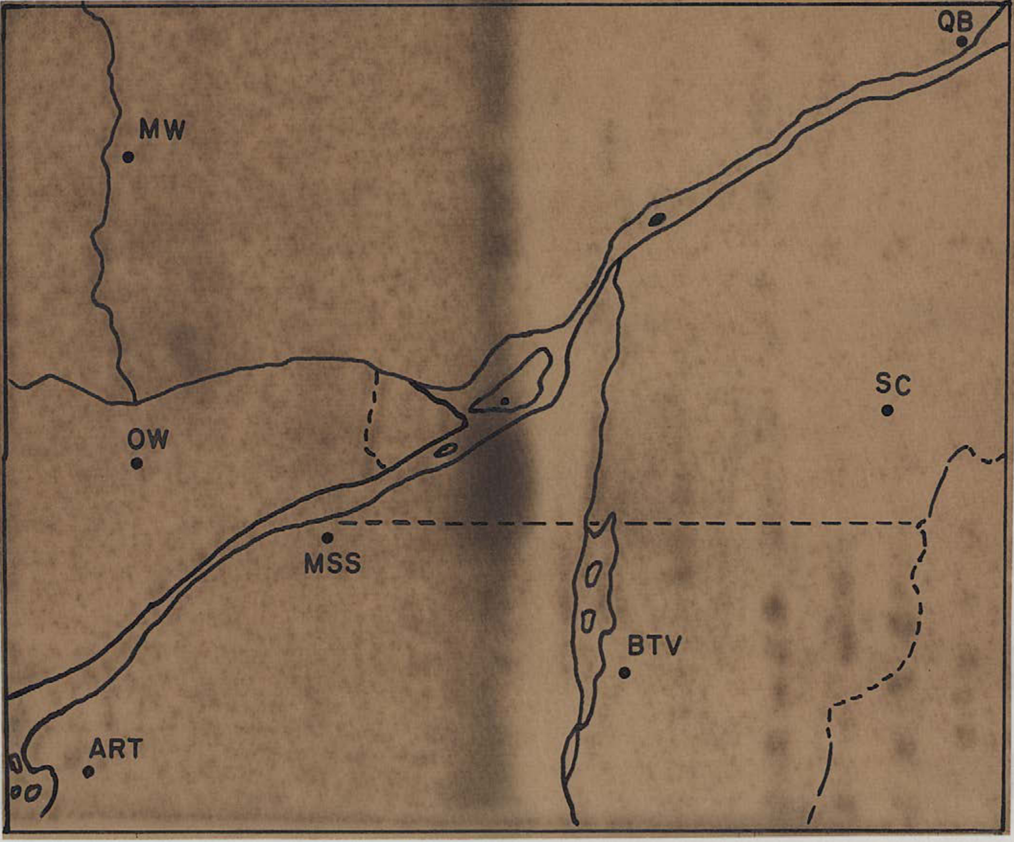


Fig. A9 - A six-height sequence of radar precipitation maps, on facsimile, on 30 August 1963. The six heights portrayed are 5, 10, 15, 20, 30 and 40 thousand feet. On the left picture provision is made to display intensity levels 1, 3, 5 and 7 and on the right 2, 4 and 6. On this occasion there was no 6 or 7. A small patch of echo in the south-east reaches up to 40,000 ft. Sequences such as this emerge routinely on the recorder in the Aviation Briefing Room one mile from the radar console. In that office, the time and date is stamped on each picture by an automatic time clock (as in Fig. A3). A transparent geographic outline similar to that used by the forecasters and briefers is enclosed.

Aug 30 1963
1700


QB
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BTV
ART

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