A VIDEOMAGNETOGRAPH STUDY OF DIFFUSION OF SOLAR MAGNETIC FIELDS IN WEAK PLAGE REGIONS

Thesis By

Robert Carroll Smithson

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ABSTRACT

A new instrument for use in astronomical research has been developed. This is the differential video photometer, a device for detecting differences in light intensity between two television pictures. With a suitable source of video, the device is capable of detecting intensity differences of the order of one part in one thousand. It should be useful in many applications, such as colorimetry, polarimetry, motion detection, and doppler shift measurements. It has been used thus far primarily as a videomagnetograph which measures the line-of-sight component of the solar magnetic field in the photosphere. Sensitivity to magnetic field strength is on the order of 5 to 10 gauss.

A study has been made of the characteristics of magnetic flux diffusion in weak plage regions. Points of enhanced magnetic field have been found to exist which have lifetimes of about 3 to 4 days, and which move in a random walk with a step time short compared to 24 hours. The random walk of these points considered as discrete entities is not, however, responsible for much of the flux diffusion in the weak plage regions. The R.M.S. displacement of the points is about 7800 km in 24 hours. A second form of flux transport has been found in which in a period of a few hours, a previously stable point will become unstable, and either shoot out a tongue of flux, or begin to move as a unit. This process can move flux over distances of the order of 10,000 km at apparent velocities of 1 to 2 km/sec. This process may be responsible for most of the flux transport in weak plage regions.

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INTRODUCTION

This thesis concerns the development of a new instrument for solar research and the first studies of the sun using the new instrument. The instrument is a "differential video photometer", a device for displaying, in near-real-time, light intensity differences between two television pictures on the order of one part in one thousand. The first application of the device in solar research has been as a magnetograph, although it could equally well be used for Doppler subtractions or the study of solar structures in weak lines, to name only two of its possible uses. The instrument has already been used to produce pictures of the sun in the D-3 line of helium.

Since the development of the magnetograph by Babcock (1953), it has been possible to measure solar magnetic fields as weak as a few gauss. This degree of sensitivity greatly advanced knowledge of the role of the solar magnetic field in solar activity. It had long been known (Hale, 1908) that magnetic fields were associated with sun-spots, but the magnetograph enabled the monitoring of solar magnetic fields for extended periods of time covering the entire history of an active region, and eventually led to a model of the solar cycle (Babcock,1961) which explained many of the features of the solar cycle.

Several years after the development of the magnetograph, Leighton (1959) developed a technique for displaying magnetic fields by the use of a photographic subtraction technique involving the subtraction of two spectroheliograms to produce a magnetic difference picture. (This technique is discussed in detail in the first part of this thesis.) The photographic subtraction method was only about 1/10 as sensitive as the Babcock magnetograph, but photographic subtraction offered the advantages of higher spatial resolution and higher time resolution. The knowledge gained by this technique led to further refinements in the understanding of the solar cycle, and of the process involved in the transport of solar magnetic fields (Leighton, 1964, 1969).

Although the photographic subtraction technique makes it possible to make measurements of solar magnetic fields with high time resolution, the complexity of the data reduction process makes the production of time-lapse magnetograms difficult at best. Also, those who are concerned with the prediction of solar flares would like a system for monitoring the solar fields in real time. Finally, a higher degree of sensitivity to magnetic fields would be useful in a system which retains the high spatial resolution of the photographic method.

The differential videophotometer described in this thesis is an attempt to construct a system which overcomes the disadvantages of the photographic technique. The attempt has been largely successful, with the exception, at present, of the desired increase in sensitivity. The instrument is considerably more sensitive than film to light intensity differences, but so far it has been necessary to use it in a optical system using a birefringent filter, which does not easily permit the attainment of sensitivities much better than those obtained from spectroheliograms. This is primarily due to the better signal-to-noise ratio obtainable in magnetic difference signals produced by spectrographic techniques.

This thesis is divided into two major parts. The first part deals with the differential video photometer as an instrument, with particular emphasis on its use as a magnetograph. Appendix I discusses the detailed circuit design of the instrument, and will be of primary concern to those who may need to trouble-shoot the instrument or design new peripheral equipment for it. Appendix II is of more general interest, since it describes the instrumental parameters of the differential video photometer in some detail. Appendices III, IV, and V constitute a manual on the operation of the instrument for those who may be concerned with the operation of the particular instrument described in this thesis.

The second part of the thesis describes a study of some of the detailed characteristics of the solar magnetic network in plage regions. This study is presented both as work which is of some interest in its own right, and as an indication of the type of problem to which the differential video photometer may be applied in its configuration as a video magnetograph.

The detailed motion and lifetime of certain structures in the enhanced magnetic network have been studied. The major result of that study is that there exist bright points of relatively strong magnetic field which have relatively long lifetimes (about 3-4 days). These bright "vertex points" move about in a random walk, but this random motion of the points as discrete entities is not responsible for all of the diffusion of magnetic flux in the enhanced magnetic network. Another phenomenon has been discovered which is probably responsible for most of the flux transport in weak plages. Occasionally, a discrete point of flux will suddenly squirt out a tongue of flux, which forms a new bright point some distance from the original point. This process takes place in a few hours and involves the transport of flux over distances of the order of 10,000 to 20,000 km.

The study described was derived for the most part from daily surveys of the entire solar activity zone made using the videomagnetograph at Downs Laboratory at the California Institute of Technology in Pasadena. Some of the observations were made at Big Bear Solar Observatory.

It is hoped that the observations described here represent the first in a series which will shed more light on the detailed processes responsible for magnetic flux transport on the sun.

PART I - THE DIFFERENTIAL VIDEO PHOTOMETER

INTRODUCTION

It is possible to divide instruments for the measurement of solar magnetic fields into two categories. The first group includes those devices which use photographic techniques to produce a map of the solar fields. Photographic methods generally produce magnetograms with high spatial resolution, but low field strength sensitivity. Although much of the processing of photographic data can be automated, the procedure remains complicated enough to require several days. This complexity discourages the preparation of large numbers of magnetograms for time-lapse movies, and makes real-time evaluation of results difficult.

The second group of instruments includes those which use a photomultiplier tube or similar device as the light sensitive element (Babcock, 1953). The aperture of the photomultiplier tube is mechanically scanned across the solar image in a raster pattern to produce a two dimensional field map. The mechanical raster scan tends to be slow, making high time resolution difficult to obtain. The spatial resolution of magnetograms produced in this way is limited, since the scanning aperture must be large enough so that the entire field of interest can be scanned in a reasonable time. Field sensitivity is high -- at least ten times as sensitive as the photographic methods. The disadvantages of low time and space resolution have been partly overcome by the use of multichannel instruments using many photomultipliers (Livingston, 1968), but at a cost in system complexity and cost.

The rapid development of television technology in the last few years has made it possible to consider a third type of instrument, which uses a video image tube as the light sensing element. Since television raster scanning can be exceedingly rapid compared to mechanical scanning, both time and spatial resolution can be as good as that obtained by photographic techniques. Data processing can be done electronically and the finished magnetograms displayed in real time. At present, true real time display using commercial television cameras would be limited to about the same field strength sensitivity as the photographic methods, but the development of rapid access video disc recorders has made it possible to average several magnetograms to increase the effective signal-to-noise ratio of the video signal, and thus the field strength sensitivity. Potentially, television offers a system with the time and spatial resolution of film, the sensitivity of photomultipliers, and real-time or near-real-time display of the processed magnetograms.

Of the older methods used for making solar magnetograms, the one most resembling the present video system -- and which in fact inspired it -- is the photographic subtraction method (Leighton, 1959). This method involves a photographic subtraction of two monochromatic images to produce a picture of the sun in which the line-of-sight component of the solar magnetic field appears as various shades of gray. In a magnetogram made by this method, zero field strength appears as neutral gray, while magnetic fields of one polarity or the other appear as lighter or darker areas, respectively.

The photographic subtraction method consists of using a beamsplitter and spectroheliograph (or filter) to make two simultaneous monochromatic pictures of the sun, one of the pictures being made in right-hand circularly polarized light and the other in left-hand circularly polarized light. Both pictures are taken in the same wavelength, a wavelength that falls in the wing of a solar line susceptible to the Zeeman effect and having a simple triplet Zeeman pattern. (The Zeeman splitting need not be simple triplet in form for the technique to work, but the analysis of the results is, at least in theory, simpler.) In the presence of a magnetic field, one component of the triplet shifts above the zero field frequency, and another shifts an equal amount below it, and these outer components are oppositely circularly polarized if the field is directed toward or away from the observer. If the frequency at which the two pictures are taken is in the wing of the absorption line where intensity is varying rapidly as a function of frequency, a small shift in the line frequency will be translated into a difference in intensity between the two pictures (See Figure 1).

Once the two pictures have been made, a unit contrast, positive copy is made of one of them in such a way that if it is superimposed upon its own negative, a uniform gray results. This positive is then superimposed upon the other negative, producing a picture in which all intensity variations common to both original pictures are cancelled, leaving only the difference between the two images as the final magnetogram (See Figure 2).

The differential video photometer described here is the result of an attempt to adapt television technology to the task of producing an electronic equivalent of the photographic subtraction technique. Although the sensitivity of the present video system to light intensity differences is more than ten times better than that of film, the sensitivity to magnetic field strength is about the same as that of film. The relatively poor sensitivity is due to a lack of a narrow band filter with a bandpass as narrow as that of a spectroheliograph. Since the two monochromatic images required for the subtraction process are taken sequentially rather than simultaneously, image motion due to seeing and guiding errors tends to

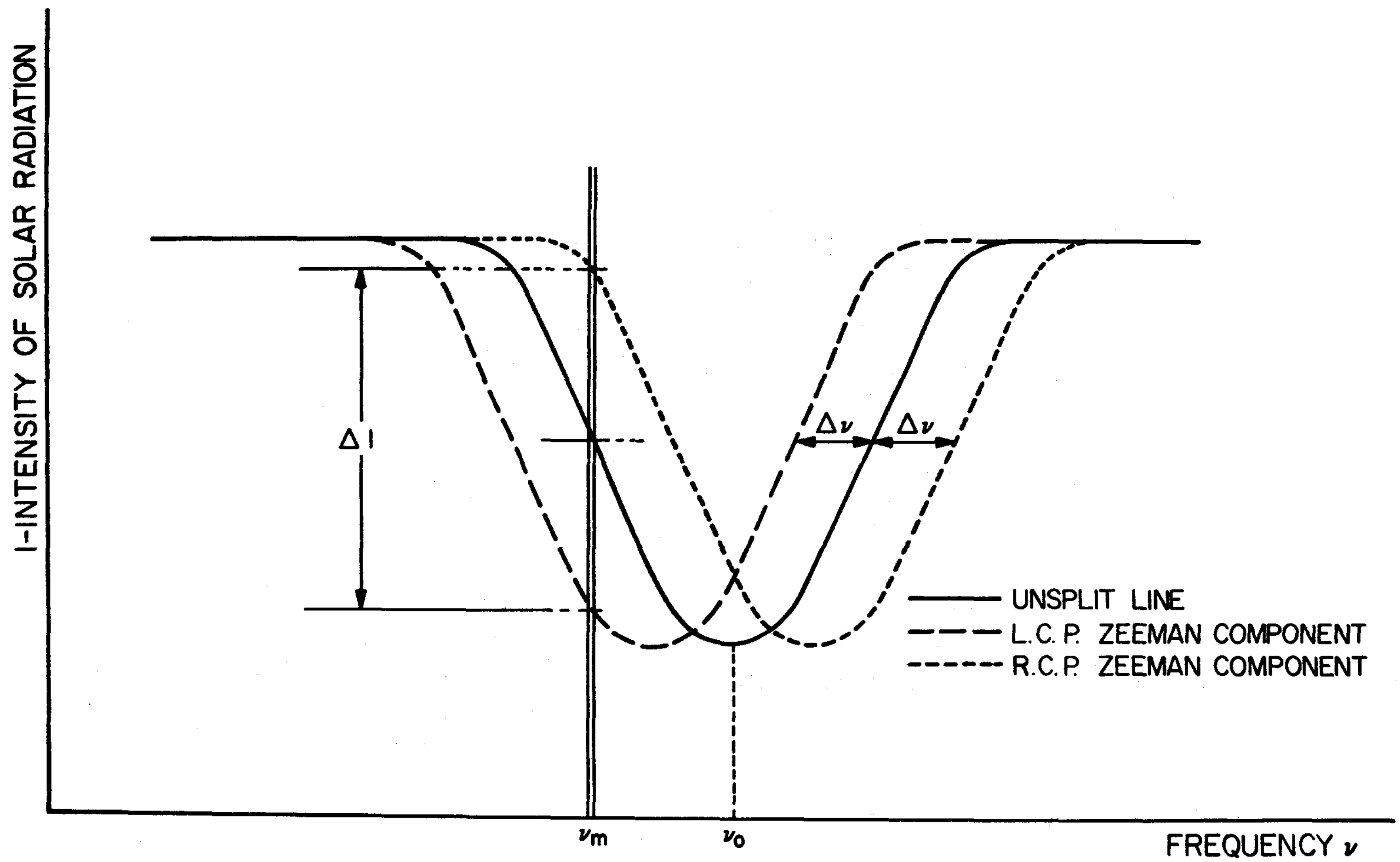


Figure 1. A split absorption line is translated into an intensity difference by placing the bandpass of the monochromator at ν_m on the wing of the line.

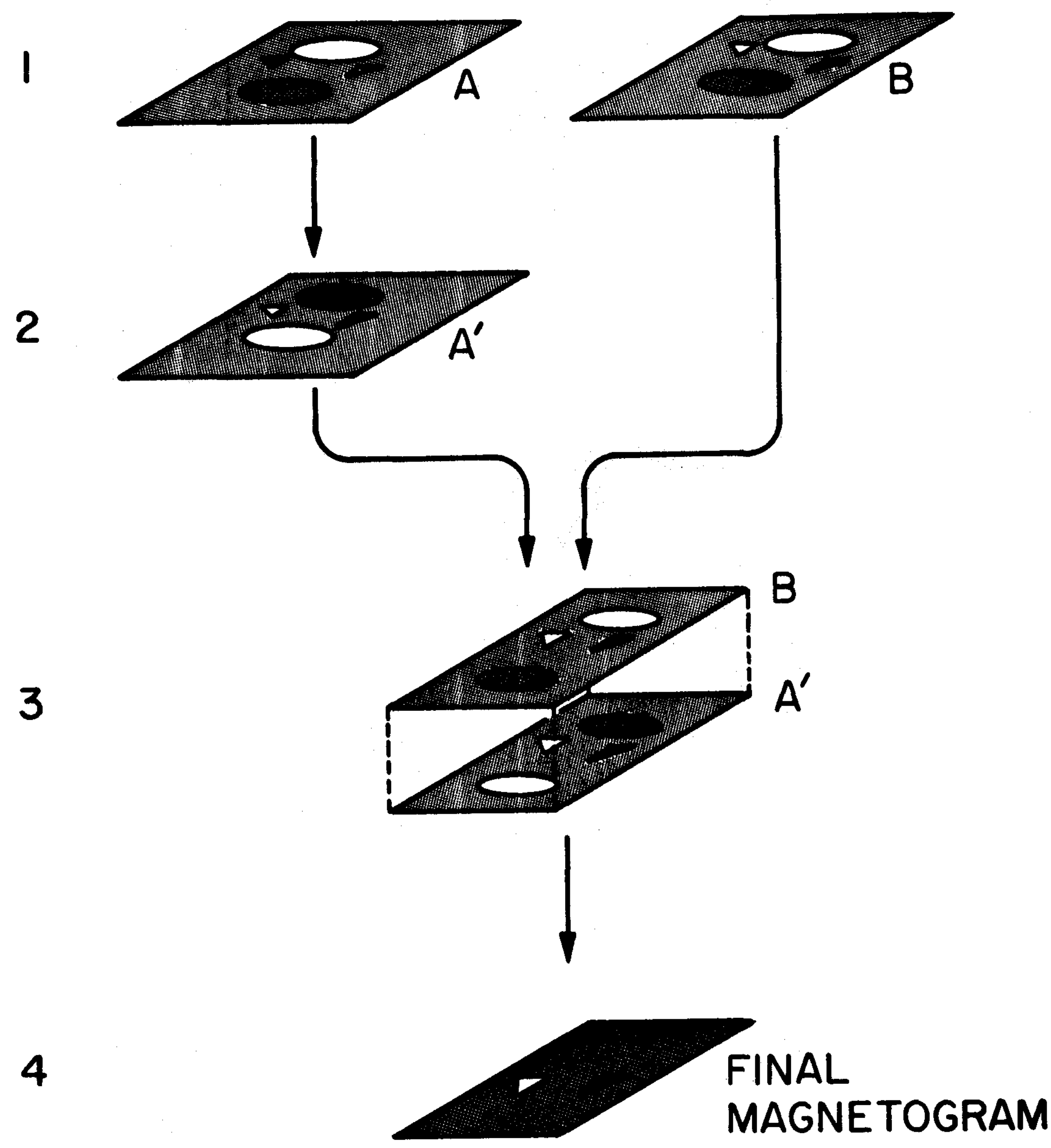


Figure 2. A diagrammatic representation of the photographic subtraction method. The triangles represent a magnetic signal, the circles a non-magnetic brightness variation.

cause misregistration errors in the subtracted magnetogram. Nevertheless, since the videomagnetograph is capable of displaying a finished magnetogram approximately one minute after the required television pictures are recorded, it is possible to employ a selected frame technique to produce magnetograms of high quality. Under conditions of good seeing at Big Bear Solar Observatory only about half of the magnetograms have to be rejected. Poor registration has been found to be due almost entirely to guider errors, which have the opportunity to become quite large in the ten second interval between the recording of the right-hand circularly polarized and the left-hand circularly polarized pictures. A modification of the system soon to be installed will reduce this interval to about a tenth of a second, a short enough time so that virtually no magnetograms should have to be rejected due to guider error.

Improvements in data processing techniques have recently shown that even using the present narrow band filter, the system is capable of sensitivity to magnetic field strength an order of magnitude better than the sensitivity of film, and a modification in the system control circuitry now under way will enable us to take advantage of this mode of operation.

The videomagnetograph has already produced several months of useful data in the form of daily surveys of the solar magnetic fields, as well as two excellent high resolution time-lapse movies taken at Big Bear. An extensive program of observation is planned at Big Bear during the summer of 1971. Figure 3 shows a typical magnetogram made at Big Bear using the videomagnetograph.

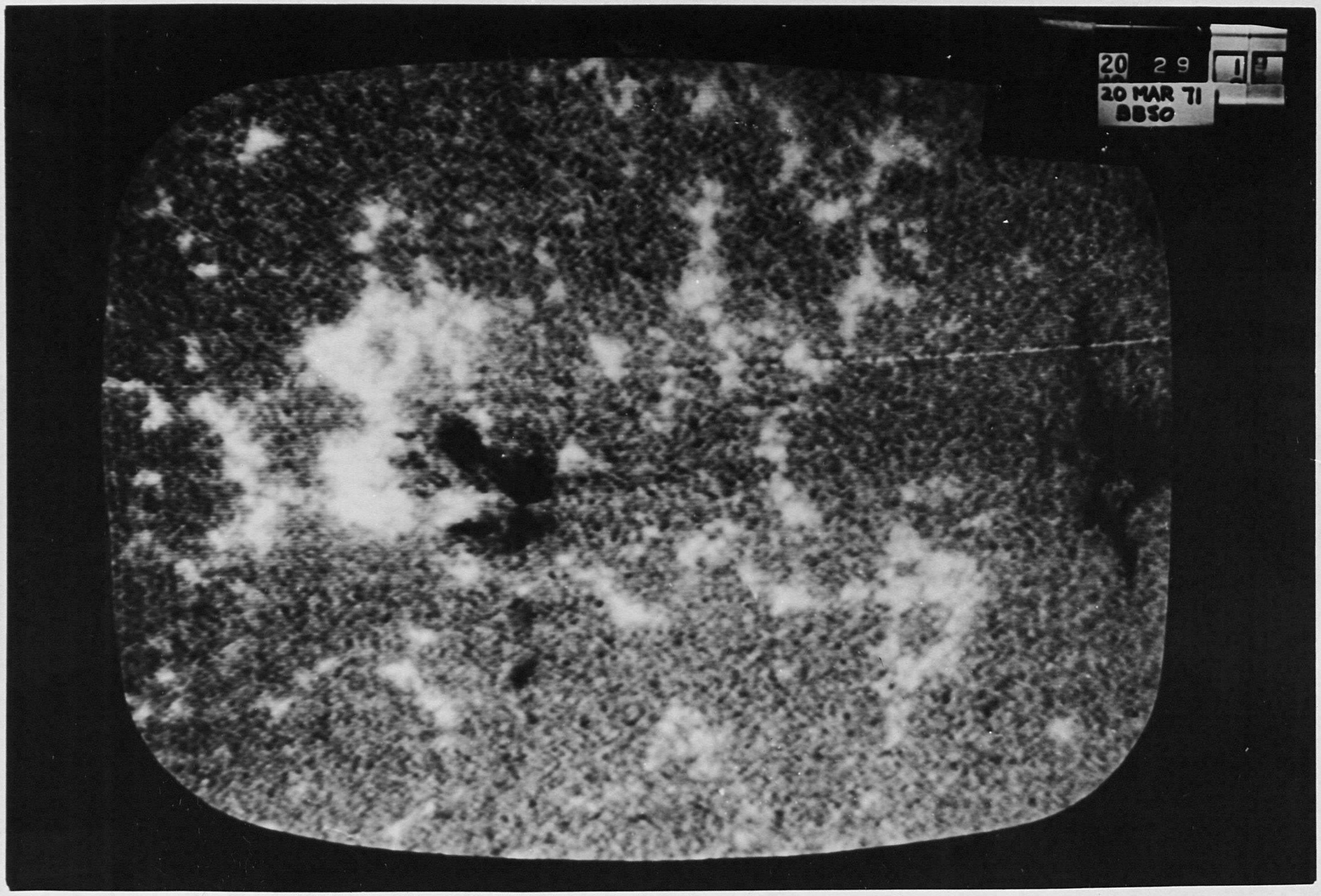


Figure 3. A videomagnetogram made at Big Bear Solar Observatory by Dr. S. Schoolman.

THE DIFFERENTIAL VIDEO PHOTOMETER - A GENERAL DESCRIPTION

For the purposes of this discussion it is probably best to think of the videomagnetograph as a differential video photometer - a device for the detection and measurement of small differences of light intensity between two similar scenes as viewed by a television camera. Although the instrument has thus far been used primarily as a magnetograph, it has many other potential uses. It has, for example, already been used to subtract photographic images, and as a lunar polarimeter.

The photometer is designed to detect intensity differences of the order of 0.1%. The best sensitivity obtained thus far is about 0.03% using a 256 picture averaging technique. The system can be used to subtract television images which are either obtained sequentially from a single television camera, or simultaneously from two cameras.

The heart of the photometer is a video disc recorder (Data Disc, Inc.), and an analog subtraction circuit. The entire system is controlled by a patchcord programmable controller which provides considerable flexibility in adapting the system to the requirements of a particular experiment. It was decided to build the system using standard 525 line commercial television because of the considerable price advantages afforded.

The primary problem to be overcome in the construction of the system was the lack of sufficiently high signal-to-noise ratios in commercially available equipment to attain 1:1000 subtraction accuracy. The signal-to-RMS-noise ratio inherent in the video disc recorder is about 100:1, and differences in the response characteristics of different recording heads add systematic noise which is at least 1% of the signal level, and can be much worse, depending on the specific head concerned.

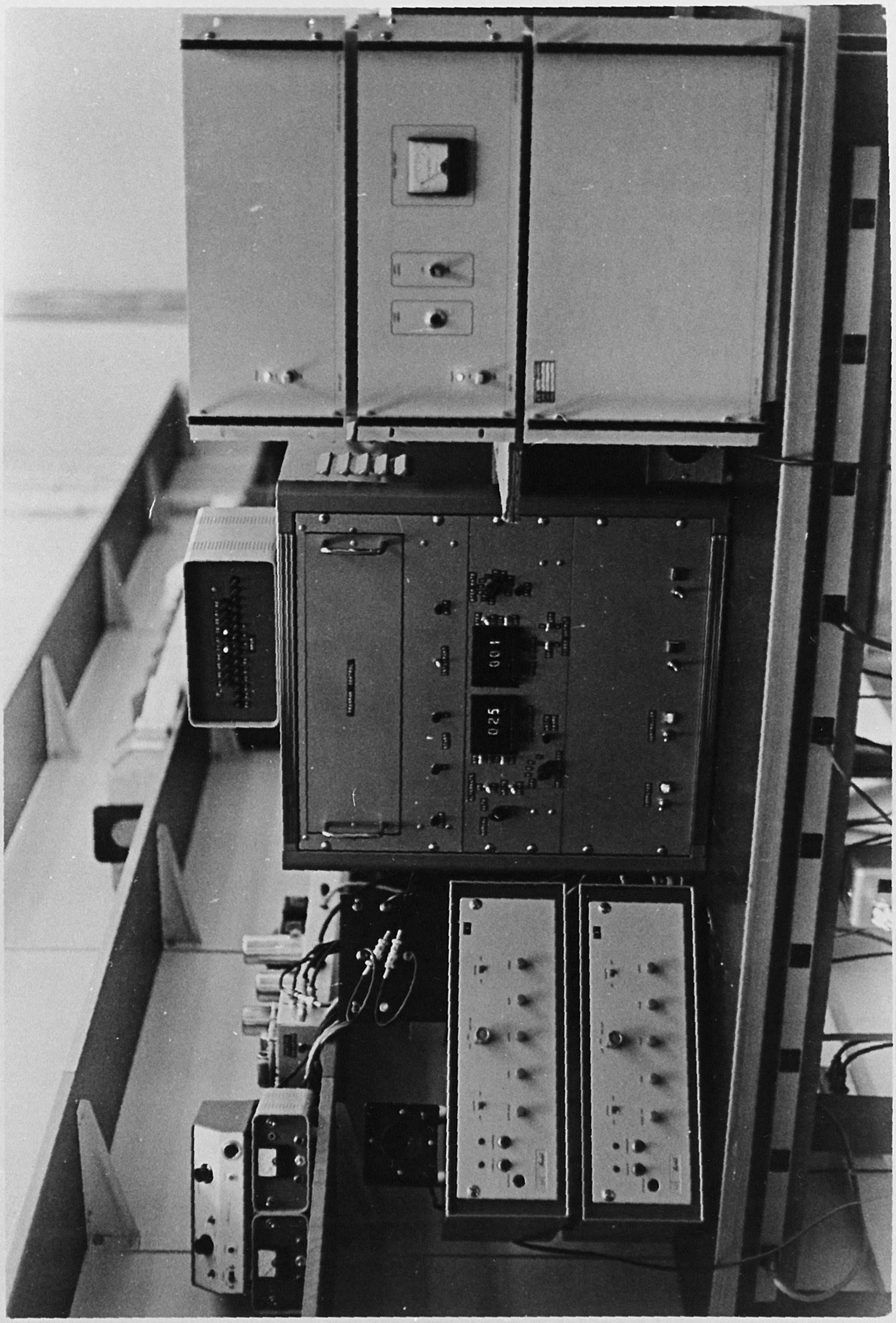


Figure 4. The differential video photometer.

A good television camera of moderate price may have RMS Johnson noise of 50 db below the signal. Systematic differences between the response of two cameras due to scan errors, nonuniform image tube faceplates, and other such effects can be greater than 100% with some vidicon cameras.

The videophotometer avoids these problems by use of a high accuracy subtraction and averaging circuit which removes systematic noise by electronic cancellation, and removes random noise by averaging a sufficient number of pictures to bring the signal-to-noise ratio to an acceptable level. Pictures are stored before and after processing on the video disc recorder.

In the present configuration, a permanent record of the difference pictures is produced by photographing the face of a Conrac monitor using an automatic 16 mm movie camera under control of the automatic system controller. The resulting 16 mm movies can be shown directly as time-lapse movies, or used as negatives for still pictures. The monitor is usually photographed with a 35 mm still camera if high quality negatives are desired for enlargement.

In a 256-picture averaging sequence up to 50 finished difference pictures can be stored on the disc recorder for immediate viewing as a time-lapse sequence. (This has not yet actually been done, however.) In addition, the system automatically displays each difference picture as it is produced -- both for purposes of monitor photography and for direct viewing.

The system is diagrammed in Figure 5. Processing of the video information is handled by the unit labeled "analog multiplexing, subtraction,

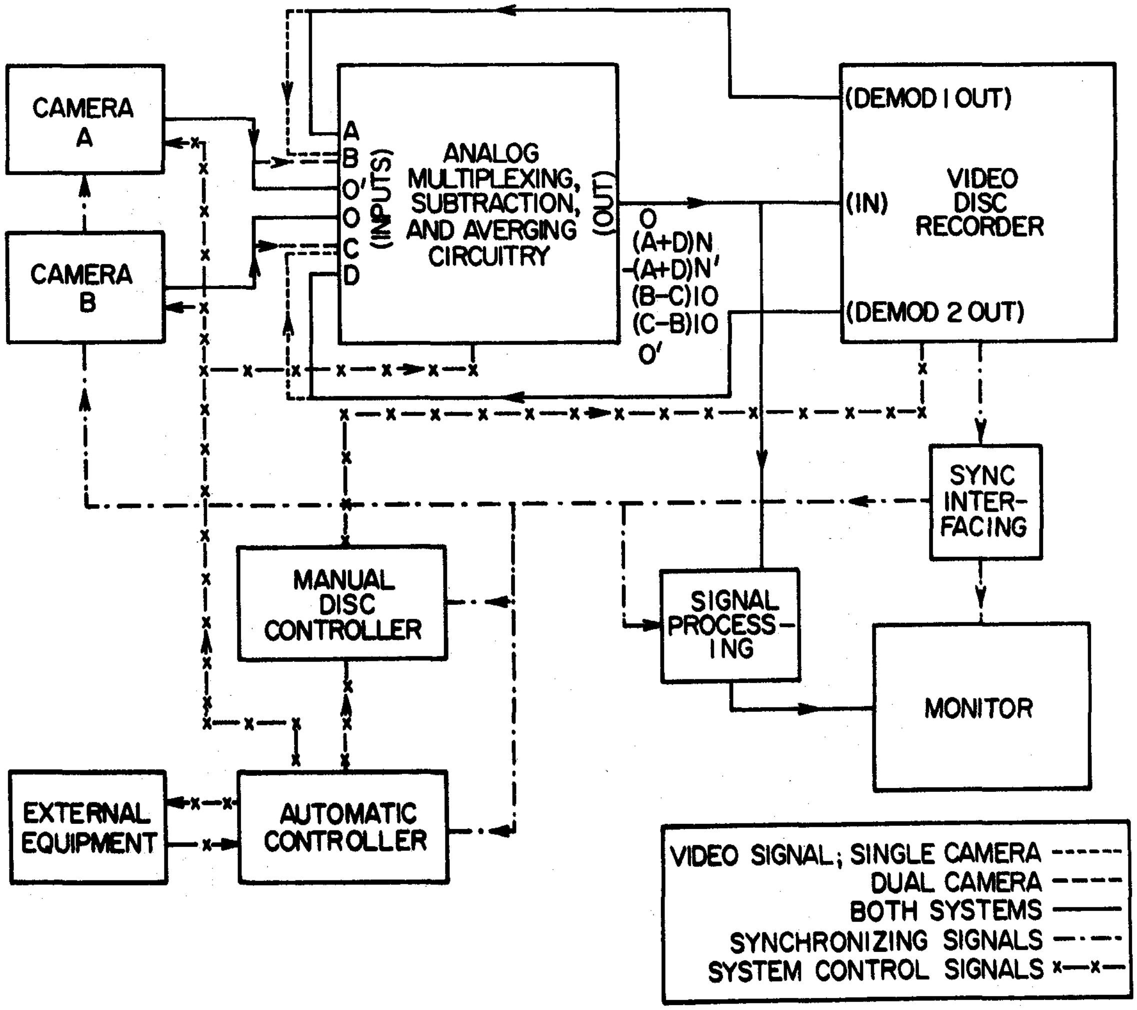


Figure 5. A block diagram of the system.

and averaging circuitry". This unit has six video inputs, labeled A, B, C, D, O, and O'. (N and N' are manually adjustable gain factors.) The desired output is selected by a binary code supplied by the automatic system controller. The output is connected to the input of the disc recorder and to the television monitor.

The video disc recorder has four video recording and playback heads. Two of these (Nos. 1 and 2) are movable, and may be positioned on any of 153 tracks per head. The other two (Nos. 3 and 4) are fixed on a single track. The recorder has one video input which may be switched to any one of the video heads. It is not possible to record on two heads simultaneously. There are two video outputs, one of which may be switched between head 1 and head 3, and the other of which may be switched between head 2 and head 4. These two outputs may be used simultaneously, and it is possible to read and record simultaneously (but not with the same head). The capability to read with two heads and write with a third simultaneously allows the subtraction and averaging of pictures recorded on the disc. The two major processing techniques are described below.

Single Camera (Sequential) Subtraction System

The operation of the system is best shown by an example. Suppose we want to look at differences in intensity between two views of the same scene, one seen in light linearly polarized "vertically", the other in light polarized at 90^{o} to the first or "horizontally". These two pictures might be produced by a television camera equipped with a polarizing filter mounted so that it can be rotated by 90^{o} to obtain one or the other of the two images, henceforth designated as "H" and "V". The required output is a picture representing 10(H-V).

The steps required to produce this output are:

(1) H is recorded on head 1, track 1

(2) H is recorded on head 2, track 1

(3) filter is rotated

(4) V is recorded on head 1, track 2

(5) V is recorded on head 2, track 2

(6) 10 ((head 1, track 1)-(head 2, track 2)) is recorded on head 3

(7) 10 ((head 2, track 1)-(head 1, track 2)) is recorded on head 4

(8) 1/2 (head 3 + head 4) is displayed as the final result.

The signal-to-noise ratio of this difference picture would be about 200:1 since it represents an average of four pictures with signal-to-noise ratios of 100:1. This represents a subtraction program having a minimum of complexity. Notice that the picture represents an average of two difference pictures, one of the form (head 1 - head 2) and the other of the form (head 2 - head 1). This means that differences in gain and response between the two heads are subtracted out since each head appears in the composite average twice -- once with a plus sign and once with a minus sign. This is not true of heads 3 and 4, but these can be held matched to a part in 100, which is adequate for cancellation to an accuracy of a part in 1000 when the ten times enhancement in the difference is taken into account. Step (8) could have recorded the result of this level of averaging on head 1 or 2, and after a number of such pictures were recorded, they could be averaged for a further improvement in S/N (signal-to-noise ratio). In practice, 64 such pictures are usually averaged for a S/N of 1000:1.

The ten-times enhancement of the difference signal serves a second important purpose. In the process of reading pictures from two tracks and recording an average or difference on a third track, a certain amount of transfer noise (n_T) is introduced in the reading and recording circuitry. This noise has a certain absolute value, and represents the minimum noise level obtainable by averaging a large number of pictures. Specifically, if 2^N pictures are averaged:

$$R_N = (\sqrt{2})^N R_I \sqrt{1 + \frac{(2A^2)^N - 1}{(2A^2)^N (2A^2 - 1)} \frac{n_T^2}{n_I^2}}$$

R_N = S/N ratio of the composite average

n_T = system transfer noise

n_I = initial noise level in a single picture

A = gain of averaging amplifier, i.e., $P_{AV} = A(P_1 + P_2)$

R_I = S/N ratio of initial pictures

In a system with no transfer noise, averaging two pictures gives an improvement of $\sqrt{2}$ in the S/N ratio. If transfer noise is present the improvement is reduced according to the above equation. It is apparent that since n_T is a fixed function of the system electronics (about .05 volts peak-to-peak), n_I should be as large as possible without saturating the amplifiers. Thus the ten times enhancement increases n_I so that the improvement in the signal-to-noise ratio in the averaging process approaches the improvement obtainable in a noiseless system. Also, it is advantageous to use a value of A larger than 1/2 (the value required for a simple average). If $A = 1/\sqrt{2}$, the noise level remains approximately constant with each level of averaging, but the signal level increases. This allows the efficiency of noise reduction to remain constant rather than decreasing as the S/N ratio increases. Of course this process can only be carried out so long as the difference signals themselves do not saturate the system amplifiers (at about 1 volt p-p). The setting for A must be a compromise between the S/N desired and the largest difference signals that are to be measured. In practice it is set so that the largest signals in the final output are nearly saturated.

It should be kept in mind that the signal-to-noise ratio which is improved in the averaging process is an effective signal-to-noise ratio. That is, the averaging process can bring out differences in intensity which would not have been visible in the original differences unless the original pictures being subtracted had a S/N of 1000:1 or better. However, the final averaged picture has a true signal-to-noise ratio of 100:1 at best. The 100:1 figure represents the inherent S/N of any picture recorded on the disc recorder. Thus, 100 distinct shades of gray is the most that could ever be read from the picture. Another way of saying this is that the difference picture has a dynamic range of 100:1. (It is possible to subtract two pictures having a much greater dynamic range than 100:1 so long as the differences between them are not to be resolved into more than 100 brightness levels.)

Dual Camera (Simultaneous) Subtraction System

In the dual camera mode the videophotometer is used to subtract two similar video images produced simultaneously by two television cameras. This mode of operation eliminates misregistration of the cancelled picture due to image motion in the interval between the times at which the two images were recorded. The advantages of the elimination of image misregistration are obvious, but they are obtained at a definite cost in system complexity and price. Accordingly, most of the operation of the system thus far has been in the single camera mode, and if the modifications to the single camera system designed to shorten the interval between the two images are successful in eliminating most of the misregistration problem, there may be little reason to use the dual camera system to obtain better image registration.

The dual camera mode retains one advantage, however, which is of extreme importance in such applications as the observation of rapid changes in weak solar magnetic fields. In the single camera mode, the two pictures which form the first subtracted pair have already been recorded on the disc recorder. Thus, the noise which must be removed in the subtraction and averaging process corresponds to a S/N ratio of about 40 db. Therefore it is necessary to average fewer pictures if the initial subtraction and ten times contrast enhancement is done directly from the live video. This means higher time resolution for a given level of field strength sensitivity since fewer frames must be averaged. Also, since the effective exposure time for a subtracted picture is shorter for an average containing fewer frames, spatial resolution should be improved. (If N frames are averaged, it takes a minimum of N/30 seconds to record them. This time interval is the time over which image motion can cause smearing in the final subtraction. The smearing is the same as it would be for a photograph taken at a shutter speed of N/30 seconds.)

The disadvantages of the dual camera mode are all of an engineering nature, and can all be easily overcome with existing technology -- at a price. First, two identical images must be presented to the faceplates of the two television cameras with no relative distortions or differences in light intensity other than those which are to be measured. Since the dual camera mode requires switching the two images from one camera to the other, a means must be found to do this with high reproducibility from cycle to cycle. Once the two images have been placed in perfect alignment on the two camera image tubes, it is still necessary to see that the two pictures are properly aligned electronically. That is, corresponding points in the two images must be scanned at the same instant by the reading beams of the two cameras. This requires precise synchronization of the sweep waveforms in the two cameras, and careful control of deflection coil and image tube geometry. Finally, the response characteristics of the two image tubes must be the same. Since the sensitivities of even good tubes vary as much as 30% over the useable area of the faceplate, careful selection is required to find two tubes which have small variations, or at least matched variations.

Fortunately, all of these problems have been solved long ago. A color television camera is essentially a three or four camera system which produces a color picture by combining red, green, and blue images made by the various cameras. Thus, color cameras face all of the problems just described. Unfortunately, the problems have been solved simply by being very careful in the construction of the camera optics and sweep coils. (The problem of matching sweep waveforms is handled simply by connecting the various sweep coils in series, thus assuring that they are driven by identical waveforms.) With modern mass production techniques, being careful means being expensive, and a cheap color camera costs about $20,000. A good one costs $100,000 or more. The system used with the videophotometer uses two synchronized black and white cameras. This provides adequate image registration for most applications over the center portion of the frame only. It would cost considerably more than the cost of the two cameras to buy a system with adequate registration to take full advantage of the image tube resolving power.

Until recently, it has seemed difficult to produce the two right and left circularly polarized monochromatic images required for videomagnetograph work using only a single narrow band filter with a narrow aperture. However, it now appears (thanks to a suggestion made by Mr. Harry Ramsey of Lockheed Solar Observatory) that not only can the two images be produced, but they can be electronically switched from one camera to another at high rates of speed, and with no positioning errors. Thus, a real test of the dual camera mode seems likely soon.

Even with the use of the latest in color television technology, it is impossible to match the images from the two cameras to one part in a thousand. Hence, it is necessary to subtract out residual differences in the same manner in which the differing response characteristics of the disc recorder heads are cancelled in the single camera system. A sample subtraction and averaging routine might go as follows:

(1) 10 (camera 1 - camera 2) is recorded on head 3

(2) switch images

(3) 10 (camera 2 - camera 1) is recorded on head 4

(4) 1/2 (head 3 + head 4) is recorded on head 1

(5) 10 (camera 1 - camera 2) is recorded on head 3

(6) switch images

(7) 10 (camera 2 - camera 1) is recorded on head 4

(8) -1/2 (head 3 + head 4) is recorded on head 2

(9) 1/2 (head 1 + head 2) is displayed as the final result

The effective signal-to-noise ratio of the resulting subtraction would be about 850:1, a substantial improvement over the single camera mode. Notice that the two cameras appear in the composite result four times, twice with a plus sign and twice with a minus sign. Thus misregistration of images and differences in camera response are subtracted out. (This assumes that switching the images from one camera to the other introduces no shift in image positioning.) Also, differences in response between head 3 and head 4 are cancelled. Since head 1 and head 2 are used only once there is no opportunity or need to cancel out their response characteristics, since the error thus introduced does not accumulate over a large number of averages. If a larger number of pictures are to be averaged, it is possible to extend the sequence in such a way as to cancel differences in response characteristics of all the heads.

The entire process, including the necessary control of peripheral equipment such as the device for switching the two images, can be controlled automatically, and averaging can be carried out to any desired level. A compromise between speed of processing and sensitivity must be struck for any given application.

System Parameters

System Transfer Noise (n_t)

The noise introduced by the disc recorder in reading two pictures simultaneously from two heads and recording the average on a third head is the system transfer noise. n_t is the most important parameter in the calculation of signal-to-noise ratio improvement through picture averaging. n_t is a function of the head used, and, in the case of the movable heads, of the track. In general, the greatest noise occurs on the inside tracks.

If a picture recorded on a video disc recorder is viewed, two components of random noise will be noticed. One component, random in space and time, is the familiar "snow" seen to some extent in any video picture. The main source of this noise is noise generated in the reading heads and the demodulators of the disc recorder. The other component, which is random in space but fixed in time, is recorded noise generated for the most part in the modulator of the disc recorder. These components were measured for picture averages from two tracks. Table 1 gives n (fixed), n (moving) and n_t for various tracks and heads. These values may vary considerably between different discs, and should be taken only as typical values.

TABLE 1

Heads	Track	n (moving)	n (fixed)	n_t
1 & 2	1	.006v	.03v	.04v
1 & 2	83	.006v	.04v	.06v
1 & 2	153	.008v	.06v	.09v
3 & 4	-	.006v	.03v	.04v

n_t is in volts peak-to-peak. (RMS ~ 1/5 P-P.) Heads 1 and 2 are both at the same track number in the above table, though they are on physically separate tracks.

Light Intensity Requirements

In use as a videomagnetograph, the subtraction system is fed by a Philips Multipurpose Camera Chain using a type XQ1023R plumbicon tube. Figure 6 gives the light intensity on the plumbicon faceplace in $\mu w/cm^2$ required for a .1% difference signal to be visible using a 256 frame composite in the single camera mode. The curve is rather conservative, and any XQ1023R should be at least this good. It should be remembered that for this level of performance the subtraction system merely requires a video signal with a S/N ratio of 100:1 or better. It can be fed with any source of video. The plumbicon cameras were chosen for reasons related to the specific application of the system as a magnetograph.

System Transfer Function

The system in its present configuration shows the final subtracted picture as a television picture displayed on a monitor. If the two scenes

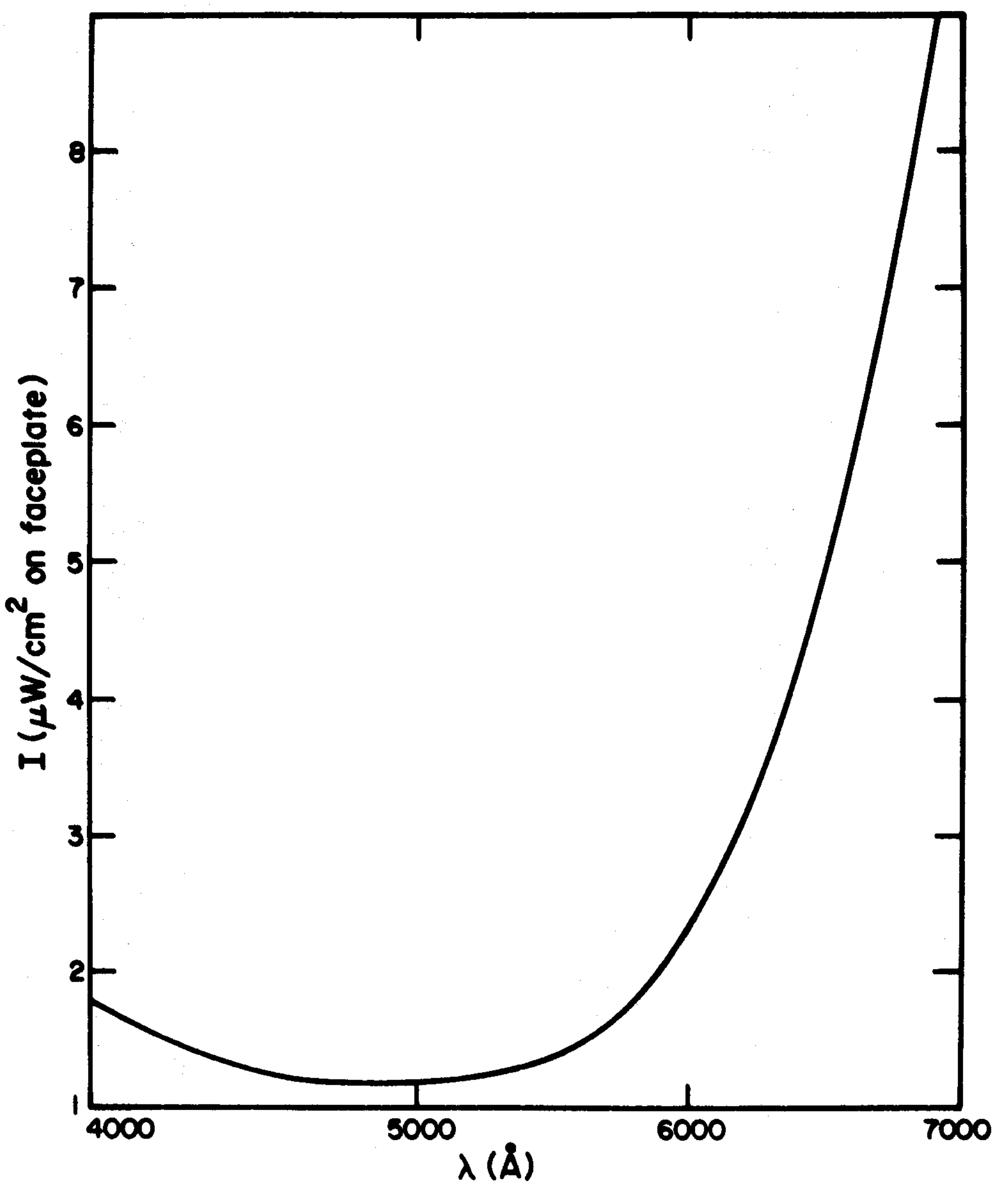


Figure 6. Light intensity on the faceplate of the plumbicon required for a 0.1% sensitivity of light intensity differences. (See text.)

being subtracted differ in intensity by ΔI_{in}, a difference signal appears on the monitor in the form of a phosphor brightness I_{out}. The system transfer function is I_{out} vs. ΔI_{in}. In general, this depends on the camera and monitor used, as well as the control settings of the entire system. If the video gain of the system is independent of the incident light level on the plumbicon faceplate (AGC circuit disabled), the curve should be linear. A representative curve is shown in Figure 7.

Critical Circuitry

Since the subtraction and averaging amplifiers are relied upon to remove any systematic noise generated elsewhere in the system, and since this must be done to at least one part in a thousand, these circuits must be carefully designed. The video disc recorder has a bandpass of 4MHz. Accordingly, accuracy in subtraction must be maintained to at least this frequency. The subtraction amplifiers, which are responsible for the initial subtraction and ten times enhancement of the two images must have a common mode rejection ratio (CMRR) of at least 1000:1 from D.C. to 5 MHz. (CMRR is the ratio of the output signal amplitude at a certain frequency when a signal is applied to only one input of the amplifier to the output signal amplitude obtained when the same signal is applied to both inputs.)

There are many operational amplifiers on the market which have a bandpass of much greater than 5 MHz and a CMRR of 100,000:1 or more. However, specifications of CMRR are usually at near D.C. frequencies, and it is difficult to find an operational amplifier which maintains an

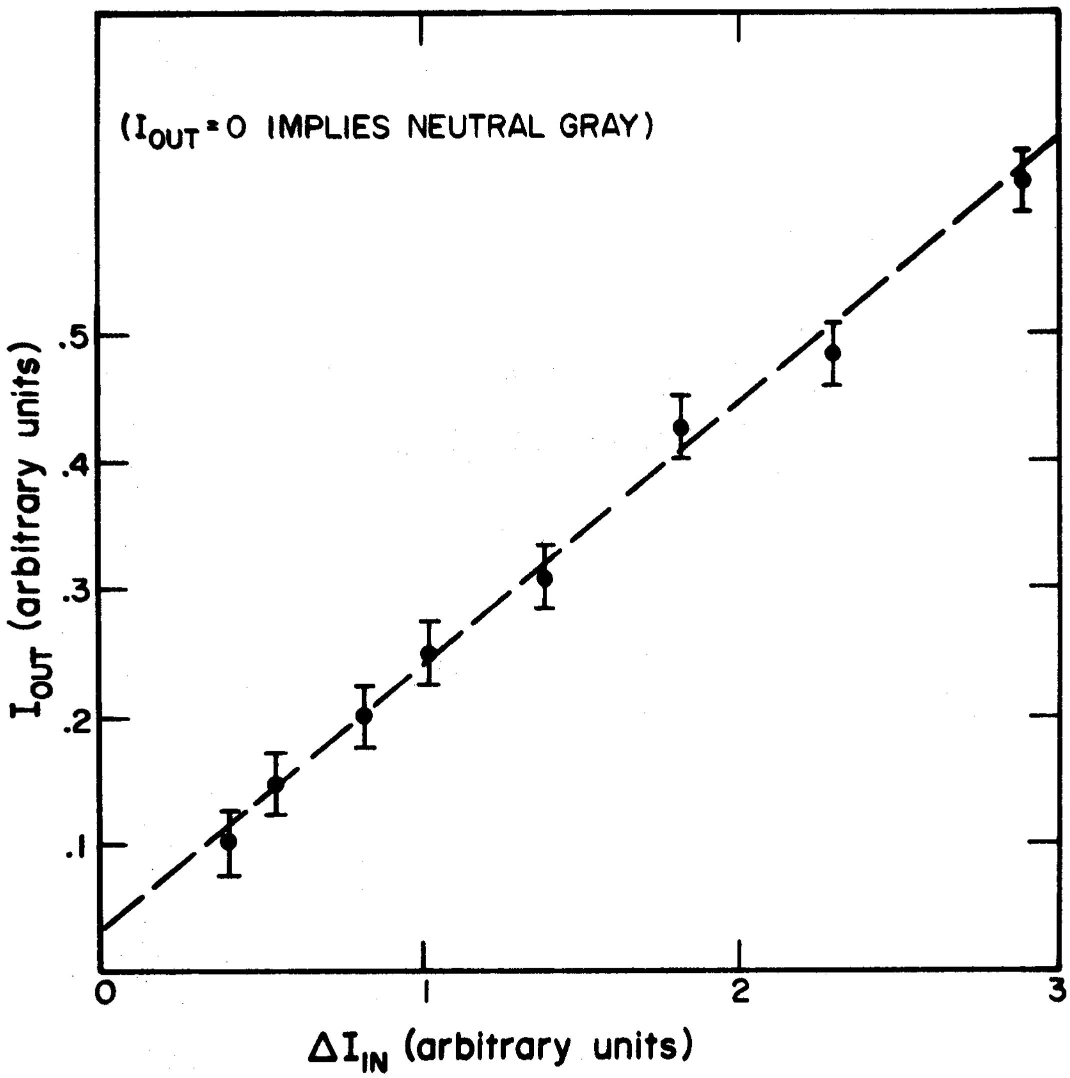


Figure 7. The system transfer function. (See text.)

acceptable CMRR at 5 MHz. CMRR drops rapidly with frequency for all operational amplifiers.

The differential amplifier used in the video photometer is a Texas Instruments SN7510L. This is a fixed gain video amplifier -- not an operational amplifier. The gain is reduced by a factor of ten by a matched pair of voltage dividers on the inputs. Although placing the dividers on the inputs of the amplifier requires careful matching of the divider resistors, both in resistance and capacitance, the full output voltage range of the amplifier is available. This would not be the case if the divider network were used on the output of the amplifier. With the addition of a small trimmer capacitor at the inputs, the SN7510L is capable of a CMRR of 3000:1 at 5 MHz.

For averaging, it is not necessary to use a fixed gain amplifier. CMRR does not affect the performance of an averaging amplifier and any operational amplifier with sufficient bandpass may be used. Accuracy of averaging is set by the input resistor network. The videophotometer uses Fairchild µA702A's for this application.

Details of the analog signal processing circuitry and construction and test techniques are given in Appendix I.

It is, of course, necessary to insure that two frames recorded on the disc at different times can be read off the disc in synchronism for purposes of averaging or subtraction. This is accomplished by running the entire system (including the sweep circuits of the television cameras) directly from timing signals recorded on two clock tracks on the disc. These clock tracks have their own read/write heads, and are monitored continuously when the system is turned on. This means that there is a direct relation between the position of the camera reading beam and the passage of a physical spot on the surface of the disc under the clock head. In effect, the recorded clock signals are used as the master oscillator for the camera sync generator. The disc itself is locked to the power line frequency. All commands to read and write pictures on the disc are given in synchronism with the disc clock tracks. This is necessary to prevent asynchronous switching transients from appearing in the final averaged picture.

There is a substantial time lag (about 1/20 of a television line) involved in reading and recording a picture on the disc. Therefore, it is impossible to average or subtract two pictures which have not been read and recorded an equal number of times. For example, a recorded picture, which has been recorded once and read once, cannot be averaged with a live picture. The recorded picture has been displaced by about 1/20 of a television line with respect to the live picture, and this displacement will appear as a registration error. Similarly a picture which has merely been recorded once direct from the live picture cannot be combined with an average of two such pictures, since the average, having been recorded twice, has been displaced by 2/20 of a television line. (The average has been recorded once when each of the two pictures composing it were recorded from the camera, and again when the two pictures were read, sent through the averaging amplifier, and re-recorded as an average.)

The time lag in the recorder must be kept in mind in designing methods of averaging large numbers of pictures. Also, special sync delay circuits must be used to prevent the final averaged picture from moving sideways off the monitor screen when a large number of pictures are averaged. This circuitry is described in some detail in Appendix I. A diagram of the time lag effect is shown in Figure 8.

The Automatic Controller

The automatic controller (Figure 9) is the unit that provides the control signals for the system. It runs on a 30 Hz clock derived from the clock track on the disc recorder, and all commands to the system are timed to occur during the vertical retrace interval between frames. In this way, any switching transients do not interfere with the video signals.

The controller itself is basically a breadboard consisting of sixteen sixteen-pin printed circuit board sockets. Each socket is supplied with a ground and a positive power supply voltage as well as a clock and a "clear" connection. (The latter is used to set initial states of any logic circuits which may be plugged into the various sockets.) The remaining 12 pins on each socket are used for interconnecting various sockets by means of patchcords. In addition to the sixteen logic card sockets the controller is supplied with twenty five output amplifiers -- each of which can supply an on/off control voltage to some piece of equipment. Finally, the controller has five input terminals so that the logical circuitry can be affected by external equipment (e.g., for time delay).

Controls provided are as follows:

(1) Two "start" buttons. Pushing a start button provides a single pulse in synchronism with the controller clock. The pulse is normally

Figure 8

Line 1 shows a live picture.
Line 2 shows the phase shift of a recorded picture due to the time lag in the disc recording circuits.
Line 3 shows a further shift resulting from reading and then re-recording the picture in line 2.

All shifts are greatly exaggerated in this drawing.

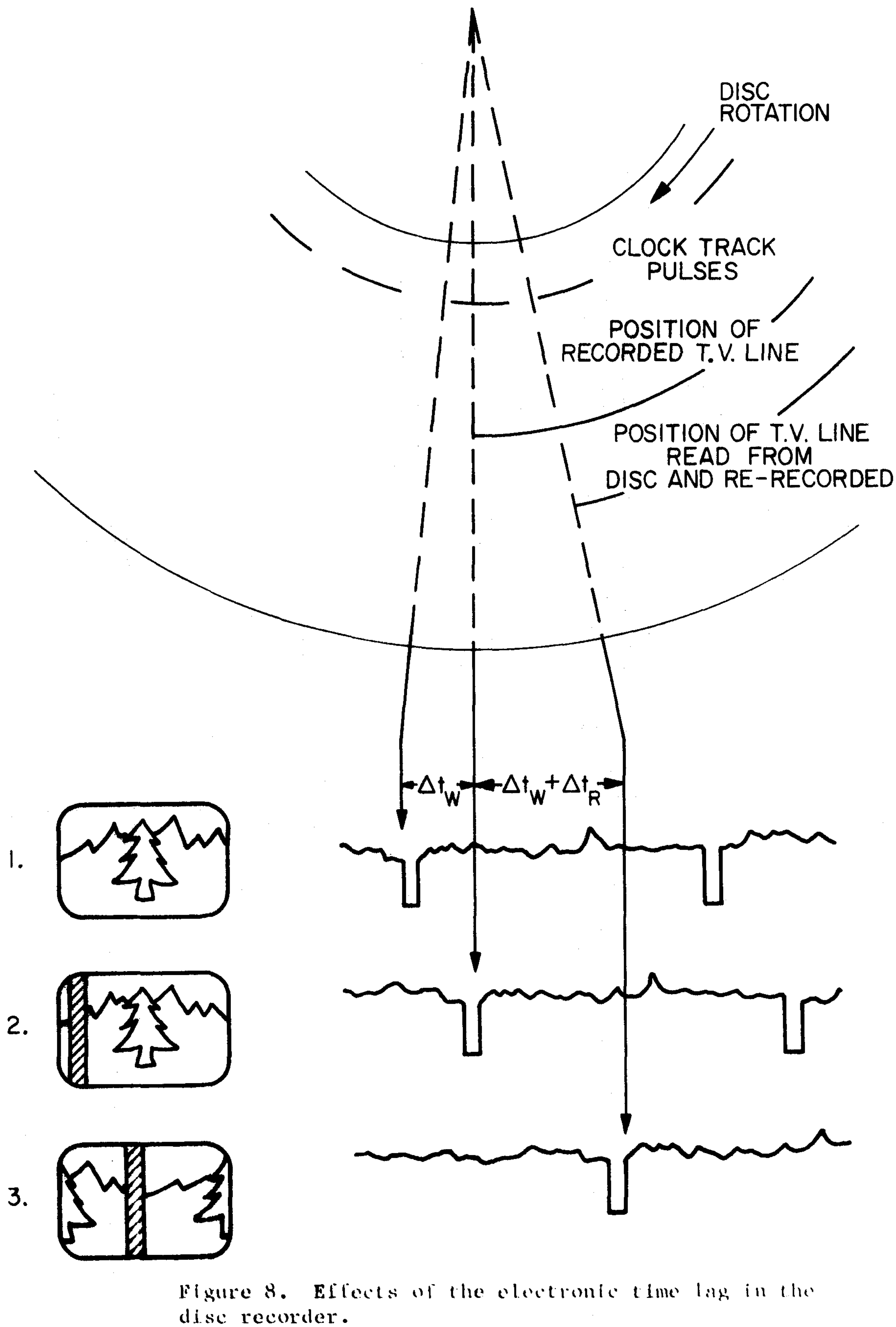


Figure 8. Effects of the electronic time lag in the disc recorder.

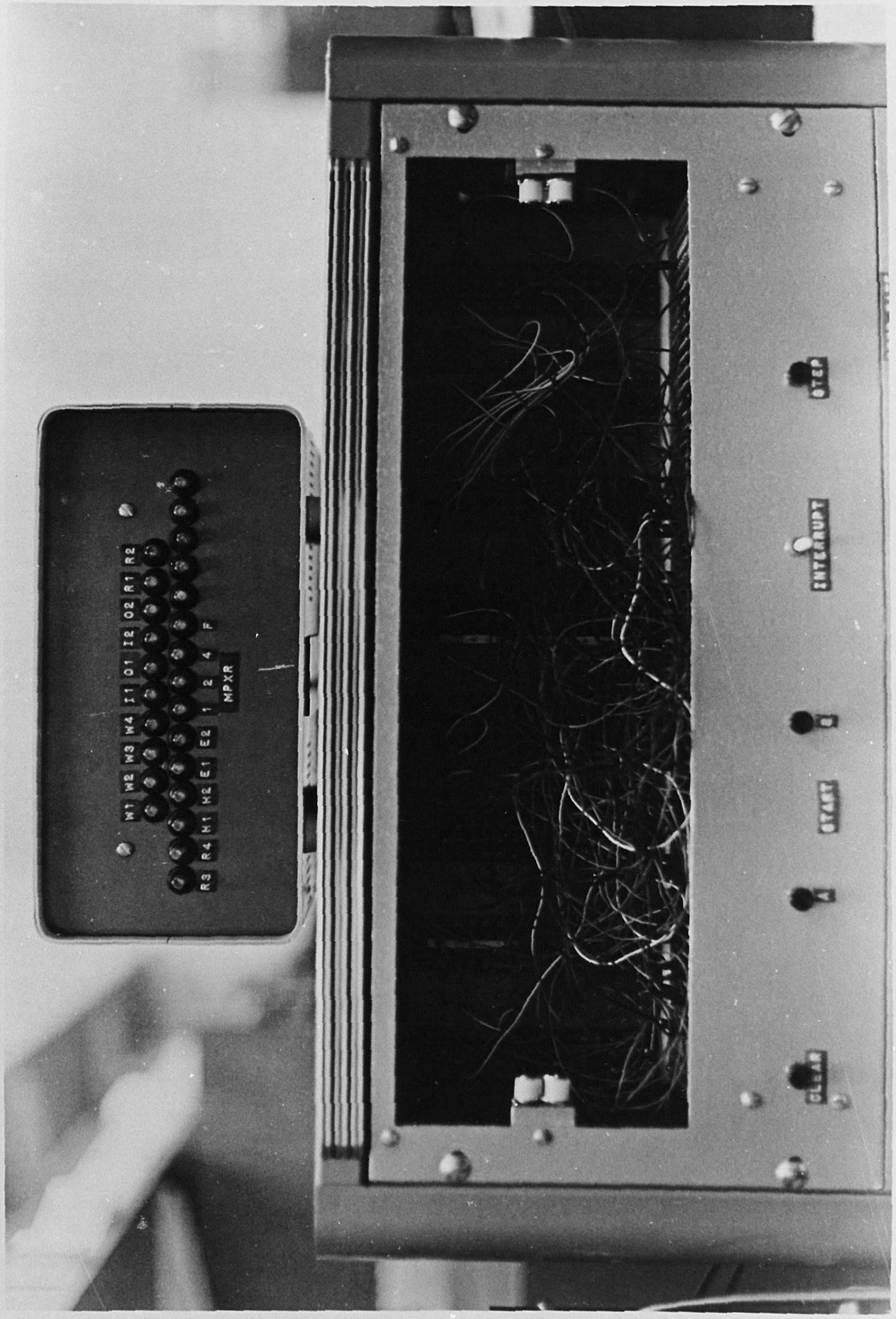


Figure 9. The automatic controller.

used to start the execution of a program or to cause the program to continue when it has paused to allow operator intervention. The two buttons are completely independent and can be used to control separate programs or as "start" and "continue" buttons on the same program.

(2) A "clear" button. When this button is pressed a high voltage appears on the "clear" terminals. This is used to initialize the memory circuits in the logic cards of a program.

(3) An interrupt switch. This blocks the clock signal. With the clock off the program stops at whatever step it was at when the switch was thrown.

(4) A "step" button. With the interrupt switch on, pushing the step button allows one clock pulse to pass. This allows the operator to single-step the program, usually for diagnostic purposes.

The controller is also provided with a set of 25 readout lights which light when a corresponding output amplifier is activated. Multiple patch-cord jacks are provided at each terminal for convenience in wiring.

The controller is very flexible since it allows the use of any sort of logic circuitry that can be fitted onto a 16 pin board. There are, however, four basic types of logic cards in current use. The use of these is discussed in detail in the section on programming the automatic controller. The controller is designed to use RTL logic, which was conveniently available when the device was designed.

The Manual Controller

The video disc recorder is designed to be controlled by TTL compatible logic circuitry. The manual controller (see Figure 10) serves as an interface to the RTL logic of the automatic controller, and also allows manual control of the disc recorder. Two three-decade "nixie tube" readouts monitor the track position of the two movable heads, both in the automatic and manual modes. Provision is made for manually reading and writing on each of the four video heads. The two movable heads can be manually stepped in and out at various speeds, or single-stepped in either direction. A "home button" is provided for each of the movable heads, which returns the head to its outermost track when pressed. Erase buttons are provided for the two movable heads. (The fixed heads do not have provision for this function. Erasure is accomplished by simply writing over the previously recorded frame.) Up to 10 seconds of live video may be recorded by making use of the "alternate" mode, which steps one movable head while writing (or reading) on another, alternating heads until all tracks are full.

The manual controller is most often used as a diagnostic tool to display the contents of the various tracks when the system is malfunctioning, or to initialize the position of the movable heads before running an automatic program.

Signal Processing

In order to place the final subtracted picture in a form suitable for display on the monitor, it is necessary to go through several signal processing steps. These are diagrammed in Figure 11. If ordinary composite

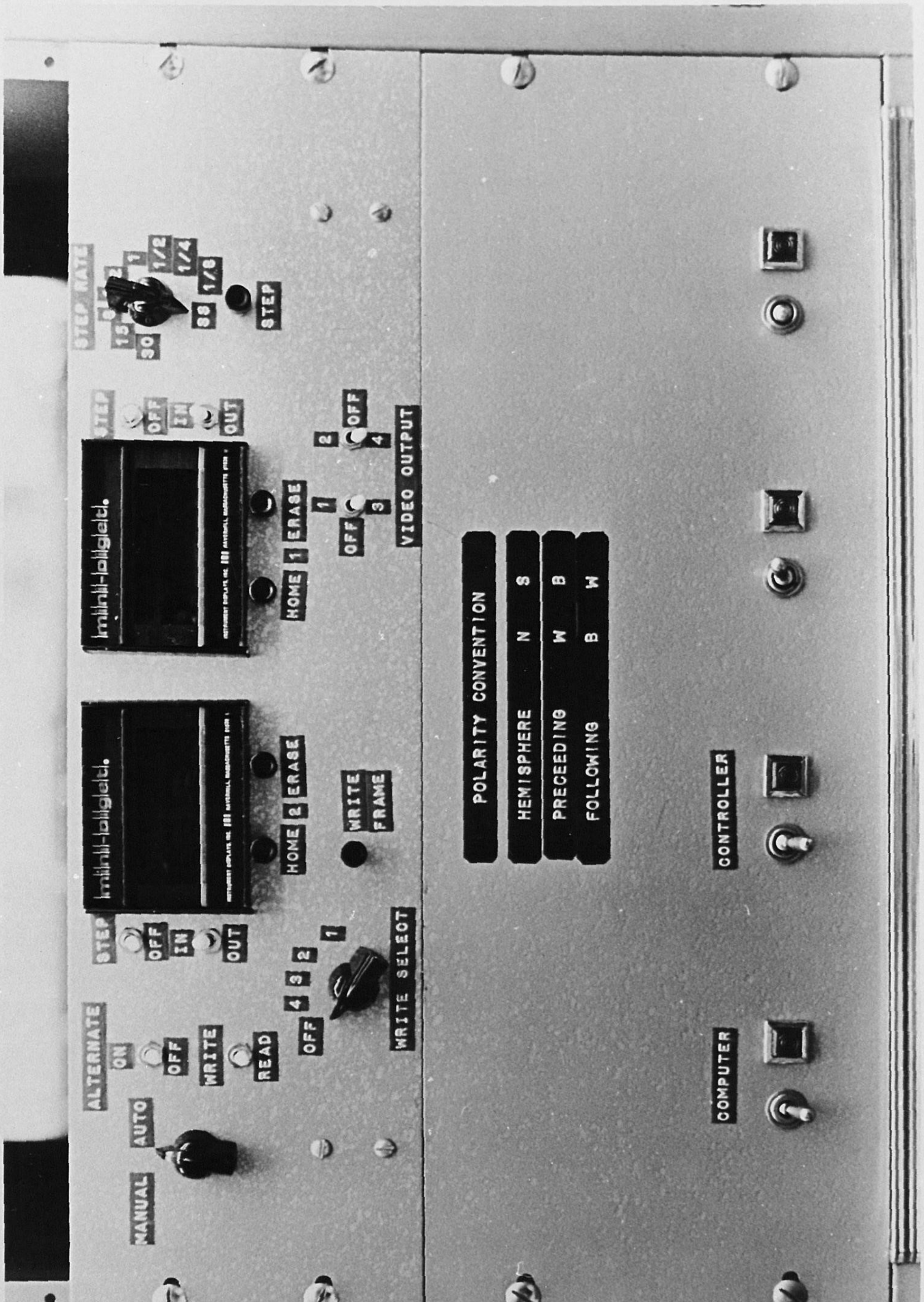


Figure 10. The manual controller.

Figure 11

1 and 2 are composite video signals to be subtracted.

1-2 shows the result of a direct subtraction. Note the high frequency spikes.

1' and 2' are non-composite video.

1'-2'. No spikes appear.

n(1'-2') shows the distortion caused by averaging many pictures.

B. The blanking waveform.

C. The compensation waveform.

D = B + C + n (1'-2'). This is the final waveform displayed by the monitor.

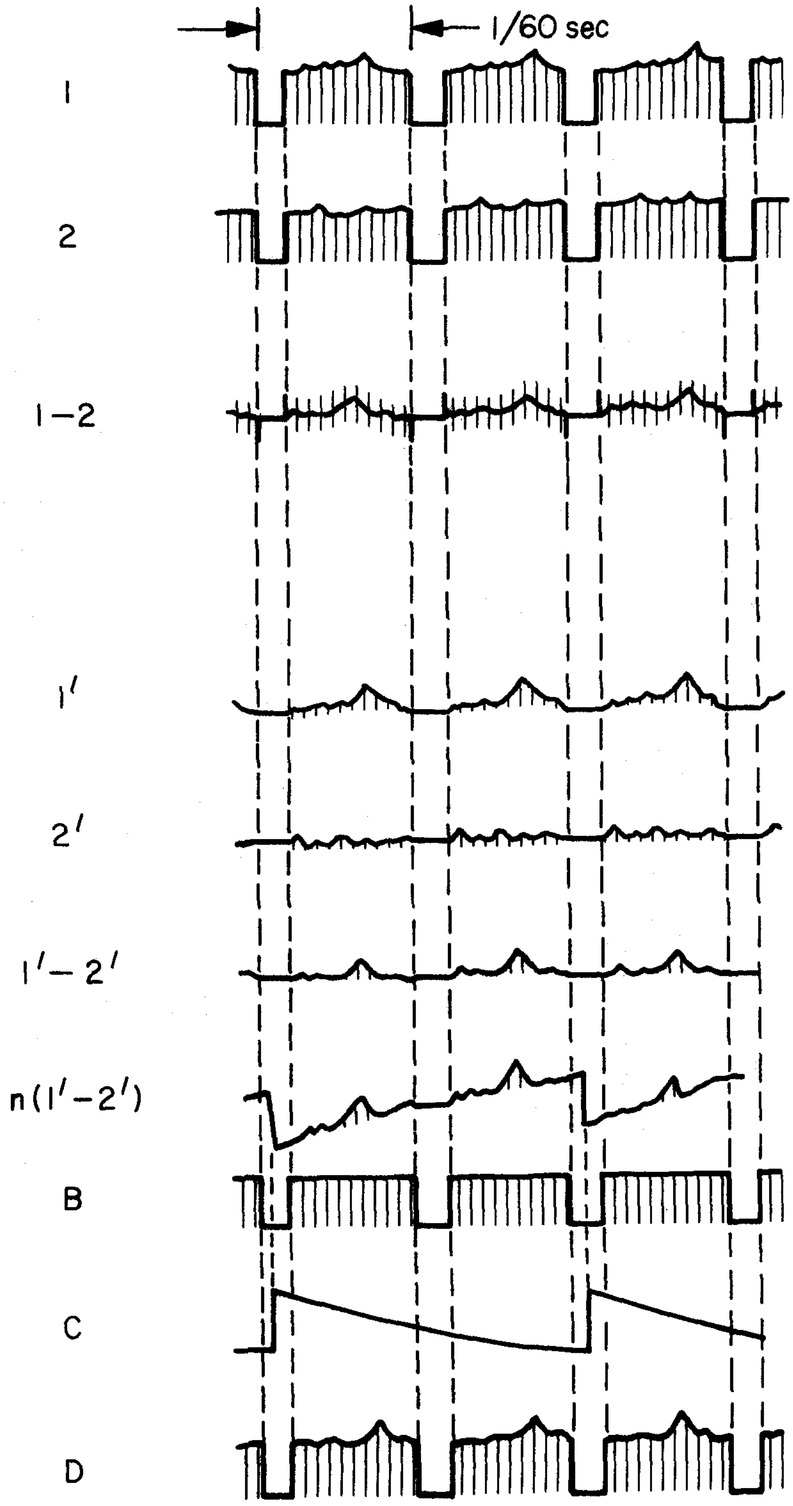


Figure 11. Signal processing.

video is used for the initial pictures to be subtracted, the subtraction will show high frequency spikes at the edges of the sync and blanking pulses as shown in the figure. (Composite video is a video signal with sync and blanking pulses added.) Since the composite video loses the sync information in the subtraction process in any event, it is best to use non-composite video from the outset in order to eliminate the spikes. The monitor is synchronized with a separate sync signal.

If a large number of subtracted pairs is averaged, a cumulative distortion appears in the waveform due to a low frequency switching transient produced by the disc recorder. The amplitude of the transient is small enough that it is not noticeable on a single recorded picture (which is probably why it has not been eliminated by the manufacturer), but the effects are increasingly noticeable on averages as the number of pictures forming the composite increases. The effect of this distortion is to produce a shading running from a dark top to a bright bottom as the picture is displayed on the monitor. The picture also seems to flicker, since the first of the two interlaced fields is darker than the second. This distortion is removed by passing the final average through a compensating circuit before feeding it to the monitor. The signal processing circuit adds a compensating waveform to the video signal which removes the distortion. This circuit also adds in a blanking waveform. The function of this is to make the retrace interval voltage levels much lower than the lowest black in the video signal. Thus the retrace lines are not visible on the final picture.

THE VIDEOPHOTOMETER AS A MAGNETOGRAPH

One of the prime purposes for which the videophotometer was constructed was for use as a magnetograph, and this is the only use to which the machine has been applied as yet, at least to any great extent. In this application, as in any other, the main problems in using the video subtraction technique involve the production of suitable video signals to be subtracted. Television cameras with suitable linearity, sensitivity, and spectral response must be found. If measurements are to be made which observe the position of features in the magnetograms either as a function of time or relative to the positions of other features, both the camera and television monitor must be highly accurate in their reproduction of image geometry. In addition, any nonlinearity must be stable, so that it can be accounted for in data reduction. The present configuration of the videomagnetograph is rather unsatisfactory in its ability to produce a geometrically accurate magnetogram, but the nonlinearities are quite stable with respect to time, and improved calibration techniques soon to be incorporated into the system should enable data reduction to be carried out with a minimum of trouble. It is also quite difficult at present to make absolute comparisons of magnetic field strength from day to day. Comparison of relative strengths of features in the same magnetogram can be made, however. Again, improved calibration methods will soon be incorporated to correct the problem.

The magnetograms discussed in this thesis were made using a 1/80 nm bandpass birefringent filter kindly loaned by Mr. Harry Ramsey of Lockheed Solar Observatory. The optical arrangement of the system is shown in

Figure 12. The specific arrangement shown is that of the solar telescope at Downs Laboratory on the Caltech campus. (Most of the data used in this thesis were taken here.) Figure 13 is a photograph of the optical system. The filter shown is not the Lockheed filter, but a new one recently placed in operation. Both filters are tuned to the FeI line at 532.4 nm.

The cameras used in the videomagnetograph are Philips "plumbicon" cameras. A photograph of one of these cameras is shown in Figure 14. The videomagnetograph operates in the single camera mode. The images are switched between right and left polarized light by mechanically rotating the quarter-wave plate shown in Figure 12. The time required to rotate the plate is about 3 seconds, which accounts for the long time interval between the recording of the two images used to produce subtracted pairs. The mechanical rotator will soon be replaced with a KDP electro-optical crystal, which will allow much faster switching and thus much reduced problems with image motion.

Details of the Optical System

The optical system of the magnetograph is designed to feed the birefringent filter with a "telecentric" beam. The prime image of the sun falls just above the field lens, where a field stop selects a rectangular field just large enough to fill the 12 by 16 mm scanning area of the plumbicon faceplate. The field stop serves to reduce scattered light and its attendant loss of contrast. The field lens images the 01 at the aperture stop. The aperture is set to allow all the light which passes through the 01 to pass, but serves to further block scattered light. The 02 lens is set its own focal length away from the aperture

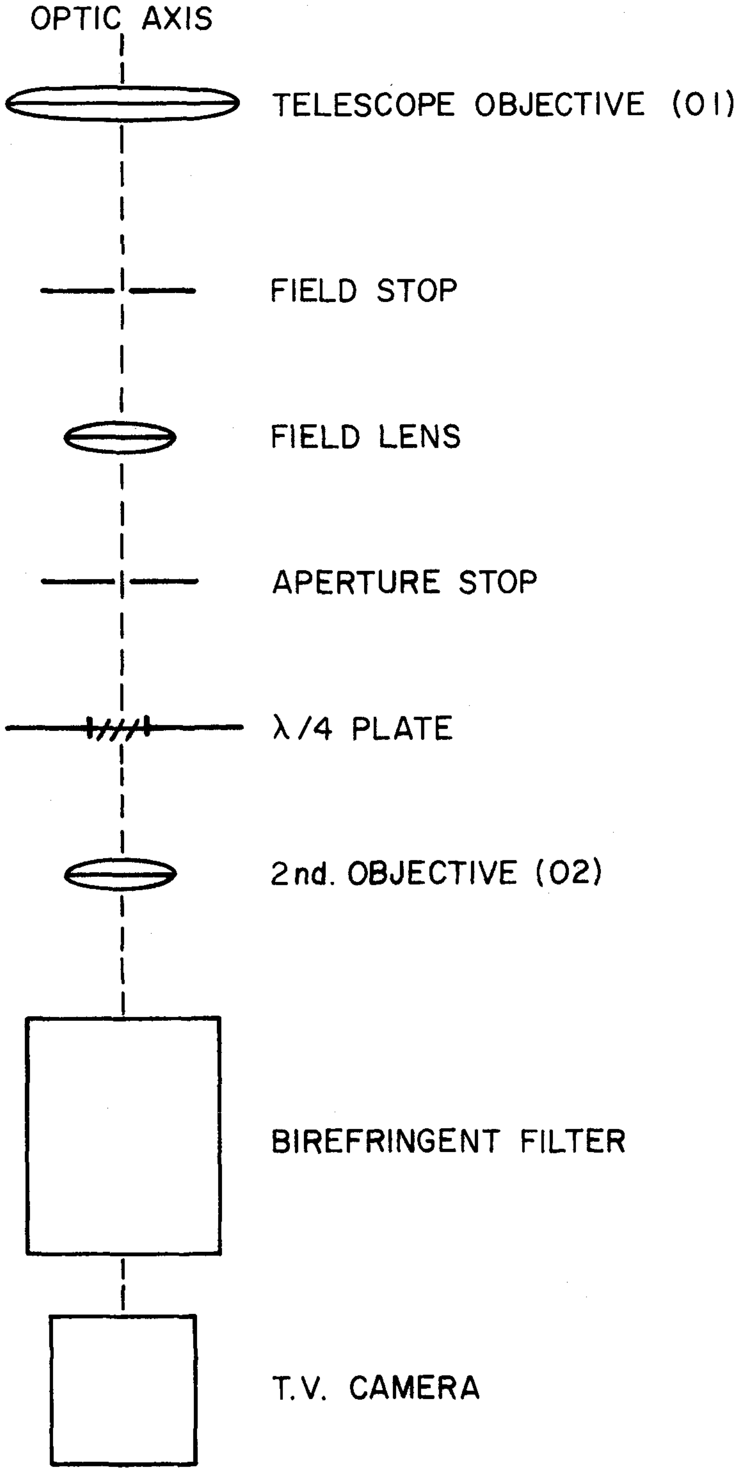


Figure 12. Optics of the magnetograph.

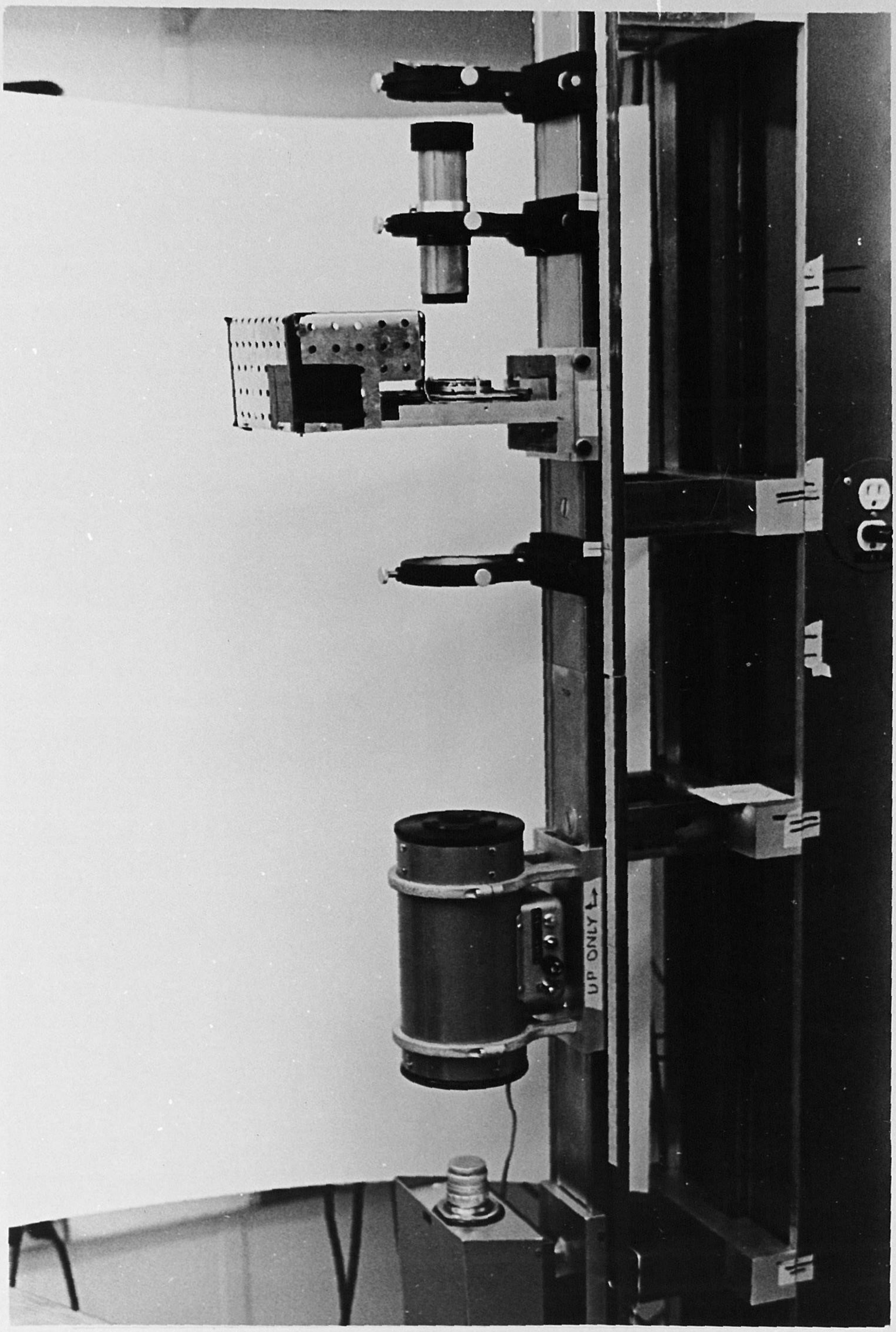


Figure 13. A photograph of the optical system.

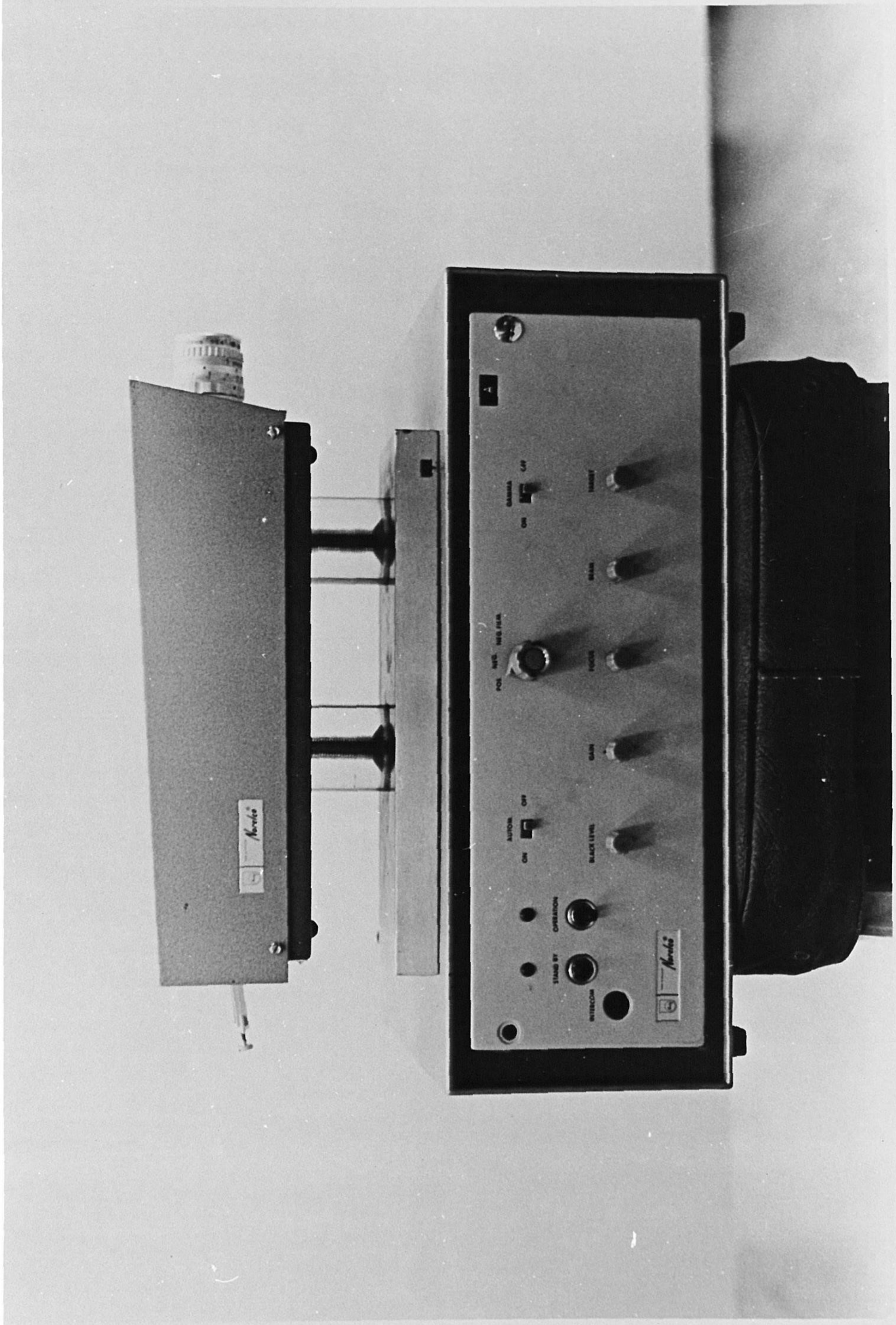


Figure 14. The Philips camera.

stop, thus re-imaging the 01 lens at infinity.

The telecentric arrangement insures that the principal rays from each point on the solar image will pass through the filter parallel to the optic axis. The bandpass characteristics of the filter are a function of the angle at which the light is passed through the filter. The use of a telecentric system insures that this angle will be the same for all points in the solar image, and thus that the instrumental parameters of the filter are the same for all points in the solar image.

Although the classical method of operation of this type of magnetograph requires the bandpass of the filter to be centered on one wing of the absorption line as described earlier, it was found that especially on smoggy Pasadena days the light levels obtained through the filter were not high enough for the best results with the television cameras in use. Mr. Ramsey therefore modified the filter so that it could be used in a way which allows the use of both wings of the line simultaneously, in order to double the light intensity which passes through the filter (Ramsey, 1971). This mode of operation is shown schematically in Figure 15.

The entrance polaroid is removed from the birefringent filter, and the 1/80 nm element placed at the front of the filter. This gives the filter a bandpass of 1/40 nm which consists of two superimposed bandpasses of 1/80 nm for the two senses of linearly polarized light. (These two senses are called "x" and "y" in the diagram) If these two bandpasses are centered as shown on the absorption line, a magnetic difference signal

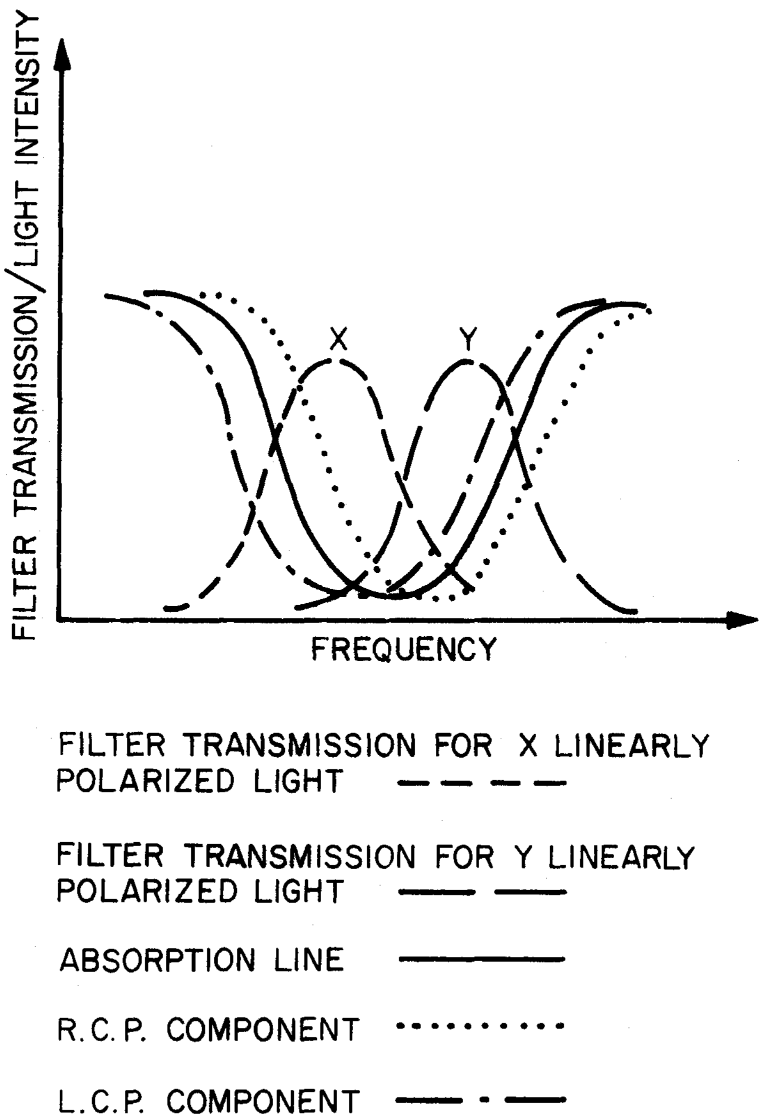


Figure 15. Two-wing subtraction using a birefringent filter.

can be produced by rotating the quarter-wave plate in the optical system. Suppose that the quarter wave plate is set so that the right circularly polarized component of the line comes out as "x" polarized light and the left component comes out as "y". Then if the Zeeman splitting is as shown, the two components will be shifted away from their respective bandpasses, and the image will appear brighter. If the quarter wave plate is now rotated by 90^{o}, then R.C.P. light becomes "y", and L.C.P. becomes "x". Therefore, for the same Zeeman splitting, the two components are now shifted toward their respective bandpasses and the image will appear darker. The net effect is that both wings of the line are used simultaneously to produce a difference signal, thus doubling the effective transmission of the filter.

Details of the Television Cameras

The cameras selected for use with the videomagnetograph are Philips type LDH 0151 plumbicon cameras. The cameras were selected for their good geometric linearity and stability, and for the wide range of controls available for matching the sweep waveforms of two cameras for the dual camera system. The cameras are equipped with independent vertical and horizontal position, size, and linearity controls. This represents the minimum in control flexibility necessary for registration of the two images in the dual camera mode. In addition, it is relatively easy to rotate the deflection coils in the camera head. This provides an adjustment of image angular position, and eliminates the necessity for providing a means of rotating the entire camera head. Sweep linearity of the cameras is accurate to about 1% over the central height circle, and the two cameras can be electronically registered to about 300 television lines over the central height circle. Image registration can be maintained to about 200 television lines over the entire viewing area.

Particularly in the single camera mode of operation, it is necessary to use an image tube with low "lag". Lag is the measure of the persistence of a television image on the faceplate of an image tube after the light source producing the image has been removed. If, for example, image A is projected on the faceplate of a tube, then replaced by image B, the image produced by the camera will contain a percentage of image A for several frames after the switch is made. In the case of the plumbicon tube, if the switch from A to B is made in the vertical retrace interval between two successive frames, a single frame is scanned, and the next frame recorded as image B, the image recorded as B should contain less than 6.5% of image A. Thus the loss in sensitivity to difference signals is negligible. In the case of an ordinary vidicon tube, as much as 30% of image A will remain, causing a correspondingly great loss in sensitivity to difference signals.

The XQ1023R plumbicon has extended red sensitivity which makes it useful at Hα and beyond. The tube can also be used to integrate at low light levels. In this mode of operation, the reading beam is turned off for several frames while the faceplate is exposed to the faint image, then the beam is turned on for a single frame and the resulting picture recorded. Maximum integration time is set by the fact that the tube is sensitive to the light from its own filament. Integration is possible for about 10 seconds before the filament illumination problem becomes critical.

The "dark current" of an image tube is the value of the output current which the tube produces in total darkness. Especially at low light levels, the dark current of an ordinary vidicon may be higher than the signal current. (The "signal current" is the part of the output current that varies with faceplate illumination and which produces the video signal.) Since the beam reading noise is proportional to the square root of the <u>total</u> output current, a high dark current means a poor signal-to-noise ratio. Also, if the dark current is an appreciable percentage of the signal current, variations in the dark current over the faceplate of the tube can cause systematic noise in the television picture. This noise appears as spots or mottling in the picture. In general, low dark current means a uniform picture, a definite advantage in the dual camera mode since it means less systematic noise to be cancelled. The dark current of the XQ1023R is about 1.6 nA as compared to 20 nA for a typical vidicon.

Other tube types which might be considered for magnetograph applications are the sec vidicon, the image orthicon, and the silicon diode array vidicon. The disadvantages of the first two are the high cost of the tubes and the associated circuitry, and a relatively poor S/N ratio. The silicon diode array combines most of the good qualities of the plumbicon with appreciably higher sensitivity (10 to 20 times). The one good quality it does not share is uniformity of field, but the newer tubes are reported to be much improved in this respect. At the wavelength of Hα the sensitivity of the silicon diode array tube is 100 to 200 times that of the plumbicon, and the sensitivity peaks at 700 to 800 nm. There is a sharp cutoff just beyond 1000 nm. For near infrared measurements in particular, the silicon diode array is the best tube to use. Unfortunately, it was not generally available when the cameras and tubes for the present system were purchased.

Other Videomagnetograph Systems Tried

Several other types of videomagnetographs were investigated before the present configuration was decided upon. These included making time exposure photographs of a television monitor on which positive and negative pictures were alternately flashed, direct subtraction of live images from two registered cameras, digital processing of video information, and slow scan video techniques.

The first of these techniques has the disadvantage that the entire dynamic range of the signal to be subtracted must be displayed in a linear fashion on the monitor. This is no great problem, and some excellent self cancellations can be made in this manner, but if the difference signal to be observed is much less than 10% of the total dynamic range of the pictures, it is almost impossible to see the differences. A monitor which can display ten well separated (to the eye) shades of gray is considered to be a good one, and since the entire dynamic range of the picture must be spread over the ten shades, a 10% difference corresponds to a single shade of gray. A 1% difference is totally invisible, to say nothing of a 0.1% difference. Since there is no means of electronically enhancing the difference signal, the system is entirely useless as a solar magnetograph. It might be useful as a motion detector in a high contrast scene, however.

Direct subtraction from two live images has already been discussed indirectly. The major problem is that two cameras cannot be matched to a part in a thousand, and since something like a video disc recorder is needed to subtract out the differences in the cameras, it is just as well to take advantage of the disc recorder to build a system like the present one.

Digital processing of video information at standard commercial frame rates poses problems in high speed digitization of the video signal, and the rapid storage of the video information. Work along these lines at the Aerospace Corporation (Janssens and Baker, 1971) has resulted in considerable success in producing a digital videomagnetograph which stores the digital difference information on a high speed digital disc recorder. The advantages of the digital approach are primarily those of increased ease in computer processing of results. The analog approach was chosen in order to take advantage of the greater simplicity of analog signal processing. Now that some experience in operating the analog system has been gained, it seems that it may be possible to build analog systems for more limited applications than the present version at a 50% reduction in price. (It is also, of course, possible to build even more flexible systems for even more money.)

The slow scan approach offers the possibility of much better S/N ratios through the use of a reduced video bandwidth. Digitization is also much easier at slow scan rates. The main reason that slow scan was decided against was that since slow scan television does not have the advantage of the large commercial television market, equipment seems to be more expensive. It was decided to stay with the cheaper and more varied standard television format for the first attempt at a videomagnetograph. Nevertheless, a digital slow-scan system offers considerable promise, and should be further investigated. Slow scan analog techniques also offer the promise of high sensitivity with relatively simple circuitry.

Calibration of the Videomagnetograph

There are three major aspects to be considered in calibrating a videomagnetograph. What is ultimately wanted, of course, is a precise measurement of magnetic field strength and polarity as a function of position on the solar disc. From an instrumental point of view this means that it must be possible to determine precisely what effect a given difference in light intensity in the two images to be subtracted will have on the final difference picture as displayed on the monitor, and ultimately as photographed for final storage. In order to translate this light intensity difference into a magnetic field strength, both the instrumental parameters of the filter and the physics of the absorption line used must be known. Finally, any distortions in image geometry introduced by the system must be precisely known, in order to allow for them in measuring the positions of features observed.

In its present state, the videomagnetograph is useful primarily as a tool for measuring polarity, lifetimes, and morphology of solar magnetic features. There is no easy way of measuring field strengths except relative to other features in the same magnetogram. The instrumental parameters of the Lockheed filter are not well known, and no means has yet been provided to ensure that control settings of the system are set in the same way at all times. In fact, as a rule, the controls are often adjusted to better display a particular feature under particular conditions. To solve the problem of varying control settings a step wedge has been ordered which will provide a standard difference signal to be recorded on every frame, or at least every time the control settings are changed. This must be a step wedge with transmissions varying from about 95% to 99% in 0.5% steps.

A cross-hatched reticle will soon be installed in front of the plumbicon faceplate. This will provide a positive measure of geometric distortions. Distortions at present measure about 2-5% of the picture height, and in many cases they can be estimated by comparing the relative positions of solar features when the same features appear in different regions of the television screen on two magnetograms taken close together in time but with the telescope centered on different points on the solar disc. If relative motions of magnetic features are large compared to the distortions estimated in this way, such motions can be measured with some confidence.

The threshold level of the videomagnetograph is relatively independent of control settings, and lifetime measurements can be made with confidence. Since distortion is negligible over small areas of the screen, morphology of small scale features is reliable. The system's main strength is, at present, the ability to watch small scale motions of solar magnetic fields through high resolution magnetic movies.

Details of experiments measuring the calibration parameters of the system as it presently stands, along with the results of those experiments, are given in Appendix II.

Practical Operating Considerations

Under normal clear sky conditions, even in Pasadena, there is plenty of light for magnetograph operation. Magnetograms have even been made through moderately heavy clouds. The television cameras are normally operated in the AGC (automatic gain control) mode. In this state the cameras automatically adjust their gain to compensate for varying light intensities. Under these operating conditions the output of the system is approximately proportional to $\Delta I/I$, rather than to ΔI as in the fixed gain mode.

Most of the magnetograms made so far have been averages of 128 subtracted pairs, or 256 recorded pictures in all. Due to the three second time required to rotate the quarter-wave plate, there is little reason to attempt to record the two polarities as sequential pairs of single pictures. Time is saved by recording 128 pictures of one polarity, rotating the plate, and recording 128 pictures of the opposite polarity. Thus only two rotations of the quarter-wave plate are needed per cycle. (The plate must be rotated back to its original position to start the next cycle.) Three seconds has been found to be ample time for the guider errors and seeing to do their worst, and so nothing is lost by taking the data in two large blocks. It takes about 10 seconds to record the initial pictures, and about 45 seconds to subtract and average them. Thus, about 1 magnetogram per minute can be made.

A magnetogram made with this level of averaging will generally show anything that will appear in a K line photograph as significantly brighter than the quiet sun network. Comparisons with Mt. Wilson magnetograms show the threshold level to be about 10 gauss as indicated on the Mt. Wilson magnetograms. (See Figure 16.) Bright plage and sunspot fields tend to saturate when the gain on the averaging amplifier is set to best display the weaker fields. (See the section on the single camera operating mode for a discussion of the gain settings.) In general, it is not possible to

Figure 16

A Mount Wilson magnetogram with contours of ±10, ±20, ±40, & ±80 gauss is shown in the upper picture.

A mosaic of videomagnetograms from the same date is shown in the bottom picture. The magnetograms were taken at Downs Laboratory at the California Institute of Technology.

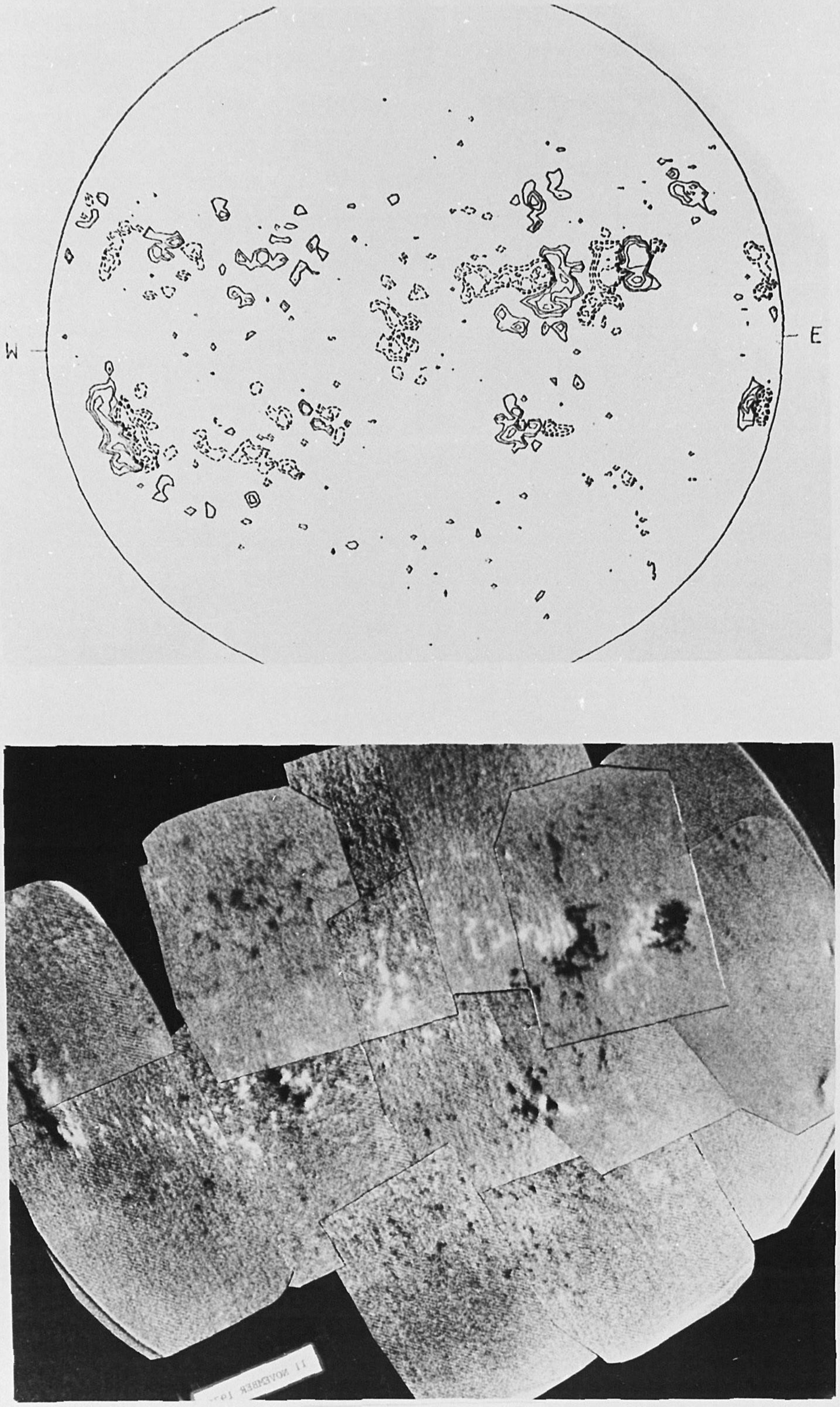


Figure 16.

set the system for optimum observation of all field strengths at once.

If only the stronger fields in and near sunspots are of interest, it is possible to average fewer pictures -- 32 or 64 perhaps. Photographic averages of ten or twenty 256-picture magnetograms show the quiet sun network surprisingly well, and this indicates that averaging 2000 or so pictures might be fruitful in studies of weak fields. This has not been done at the telescope at Downs Laboratory since rotation of the solar image from the siderostat would cause misregistration over so long a time span. The technique will be used at the Big Bear Observatory during the summer of 1971, however.

An observing technique which has proven extremely fruitful is the production of selected frame time-lapse movies. Guider errors produce enough misregistered frames that the bad frames can be quite distracting if every frame is included in a time-lapse movie. In the selected frame mode, the automatic controller pauses after every magnetogram, and the operator presses one button if it is to be included in the movie; another button if it is not. If the frame is to be included, the monitor screen is automatically photographed, and the next magnetogram is started. If the frame is rejected, the controller simply starts the next magnetogram. In spite of the fact that the time intervals between frames taken in this manner have a certain random component, movement of magnetic flux can be much more easily followed without the distraction of fluctuating misregistration patterns. No accuracy in data analysis is lost, since the time of each frame is clearly indicated on a clock mounted on the monitor and photographed with each frame.

A somewhat subtle misregistration effect should be mentioned at this point. If the misregistration is relatively small, there may be no obvious misregistration pattern visible, yet the relative positions of black and white features will appear to shift with respect to each other. This effect is illustrated in Figure 17. The shift of the relative positions of black and white areas is nearly always present in magnetograms made with the manually rotated quarter-wave plate, and should always be assumed to be there. If no overall misregistration pattern is observed, the effect is no larger than about 5 seconds of arc on a 2" image, but it should be kept in mind if relative positions of dark and light features are to be measured. This problem should also go away when the KDP plate is installed.

In order to realize the full potential of the videomagnetograph, it is necessary to have guiding accurate to perhaps one second of arc. This is as much because most of the interesting magnetic phenomena on the sun require high resolution to see as it is because the magnetograph has any intrinsic requirement for high accuracy guiding. It is absolutely necessary, however, to have guiding of sufficient accuracy so that the image does not move more than the resolution of the picture during the time interval between the recording of the two polarities to be subtracted. This time interval is 1/15 of a second for the KDP plate, and about 7 seconds for the mechanically rotated quarter-wave plate. Misregistration will be a problem precisely to the extent that this requirement is not met.

Under conditions of poor seeing, noncoherent misregistration may occur. Our experience has been that this is a minor problem even with the mechanical quarter-wave plate if the seeing is good enough so that anything of

Figure 17

1 shows a section of a videon line.
2 shows another signal, properly registered, to be subtracted from 1.
1 - 2 shows the difference signal. Δx is the true distance between the two features.
2' shows the same signal as 2, but now misregistered.
1 - 2' shows the difference between 1 and 2' $\Delta x'$ is the new apparent separation between the two features. The slight misregistration signal on the right would not be noticeable on the monitor screen.

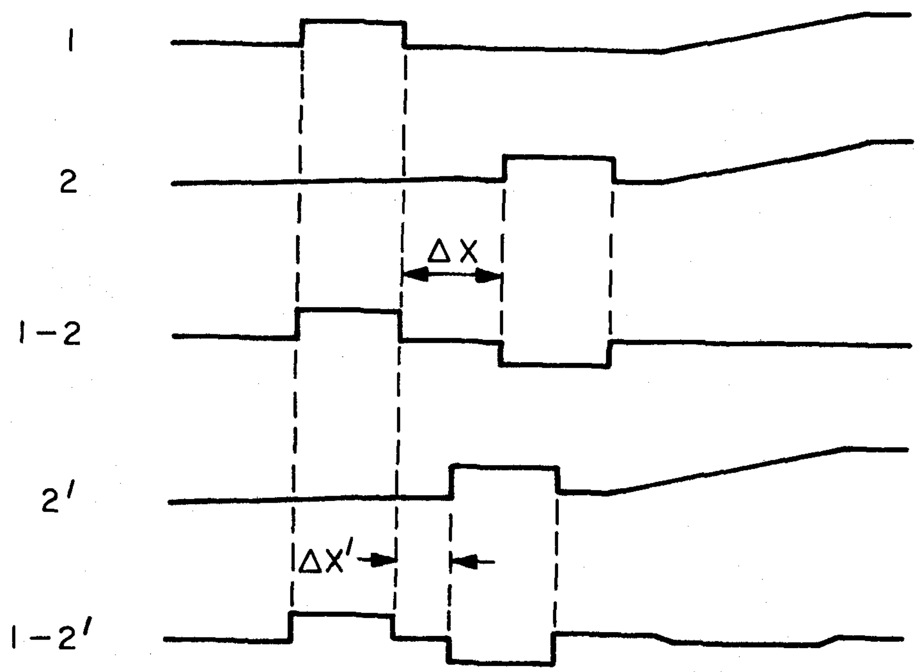


Figure 17. The effect of misregistration on the relative positions of black and white features.

interest can be resolved by any means. The KDP plate will mean that only seeing fluctuations with periods shorter than 1/15 of a second will affect the system. Tests using self cancellations indicate that, at least at Downs Laboratory, this sort of seeing has a negligible effect. (See Appendix II.)

The best resolution obtained on the sun at Downs Laboratory is about 5 seconds of arc. The limit of resolution in this case seems to be the telescope optics. The limit of resolution so far as the videophotometer is concerned can be taken at about 350 lines per 12 mm of image dimension on the faceplate of the image tube (or about 30 lines per mm). The best resolution on the sun thus far obtained is about 3 seconds of arc at Big Bear. It is necessary to reach this level of resolution to see much in the way of fast changing magnetic phenomena.

Although the automatic controller is quite flexible, at least an hour or two is generally required to make any major change in a program, and this characteristic should be kept in mind when planning experiments. The automatic controller is somewhat sensitive to power line transients and usually requires resetting every ten or twenty minutes. Therefore it cannot be left running unattended for long periods of time. Problems likely to be encountered in the use of the automatic controller are discussed in detail in Appendix III.

Of all the various units in the system, the one that consistently gives the most trouble is the disc recorder. It has its own peculiar set of mechanical and electrical idiosyncrasies with which it behooves one to become intimately familiar. Appendix V is addressed primarily to those who may be involved with the use of the particular machine which was used in the original magnetograph. Every machine has its own set of peculiarities.

Peripheral Equipment

The major items of concern here are the quarter-wave plate rotator and the 16 mm monitor camera. These are described in Appendix I in terms specific to the present system. The main thing to remember in designing such equipment is that the controller is sensitive to transients, and accordingly, relays, motors, etc., must be carefully shielded. Due to the finite scan time of the television monitor, photographs must either be taken with a camera whose shutter is synchronized with the video frame rate or with a shutter speed long compared to 1/30th of a second. Otherwise uneven pictures will result. The present system uses the latter approach. One-half second works well.

The System as a Portable Magnetograph

The videomagnetograph was designed as a portable system, and it can be considered as one in the sense that it can fit into one station wagon and can be set up at an observing site in a few hours. The observing site in question, however, must be air conditioned, or at least cool. The disc recorder will not operate properly at temperatures much above 75^{o}F. The disc recorder is also sensitive to dust, and should be used only in a reasonably clean atmosphere. No clean room techniques are necessary, but smoking should not be permitted in the vicinity of the disc, and it should not be operated under excessively dusty conditions.

If the disc recorder is carefully protected from jars, it is possible to transport the unit with the disc in place. However, for long or rough trips it is best to remove the disc and carry it separately in its special box. The floating table should also be locked down as described in the disc manual. The above procedures must always be followed when the disc is shipped by commercial carrier.

The birefringent filter is very fragile, and should be carried by hand. The other units of the magnetograph require only ordinary care in handling. After a long trip, circuit cards or components may be found to be loose, especially in the automatic controller. Care should be taken that exposed pins on cables are not bent.

Plans are under way to change the mounting configuration of the magnetograph to make it more easily portable. The major change will be to remount the various electronic components so that the plugging and unplugging of cables is minimized, and so that the system disassembles into a few units of reasonable size. The videomagnetograph is sufficiently bulky, however, that it seems unlikely that it can be made into a true field instrument.

A special right-angle optical mount has been made so that the videomagnetograph can be used with any telescope that can project an image vertically down onto a flat surface (see Figure 18). If such an image is not available, special mounting arrangements will have to be made for the telescope to which it is to be attached. It should be remembered that room is required to mount the camera head, filter, and quarter wave plate, as well as optics necessary to provide a telecentric beam for the system.

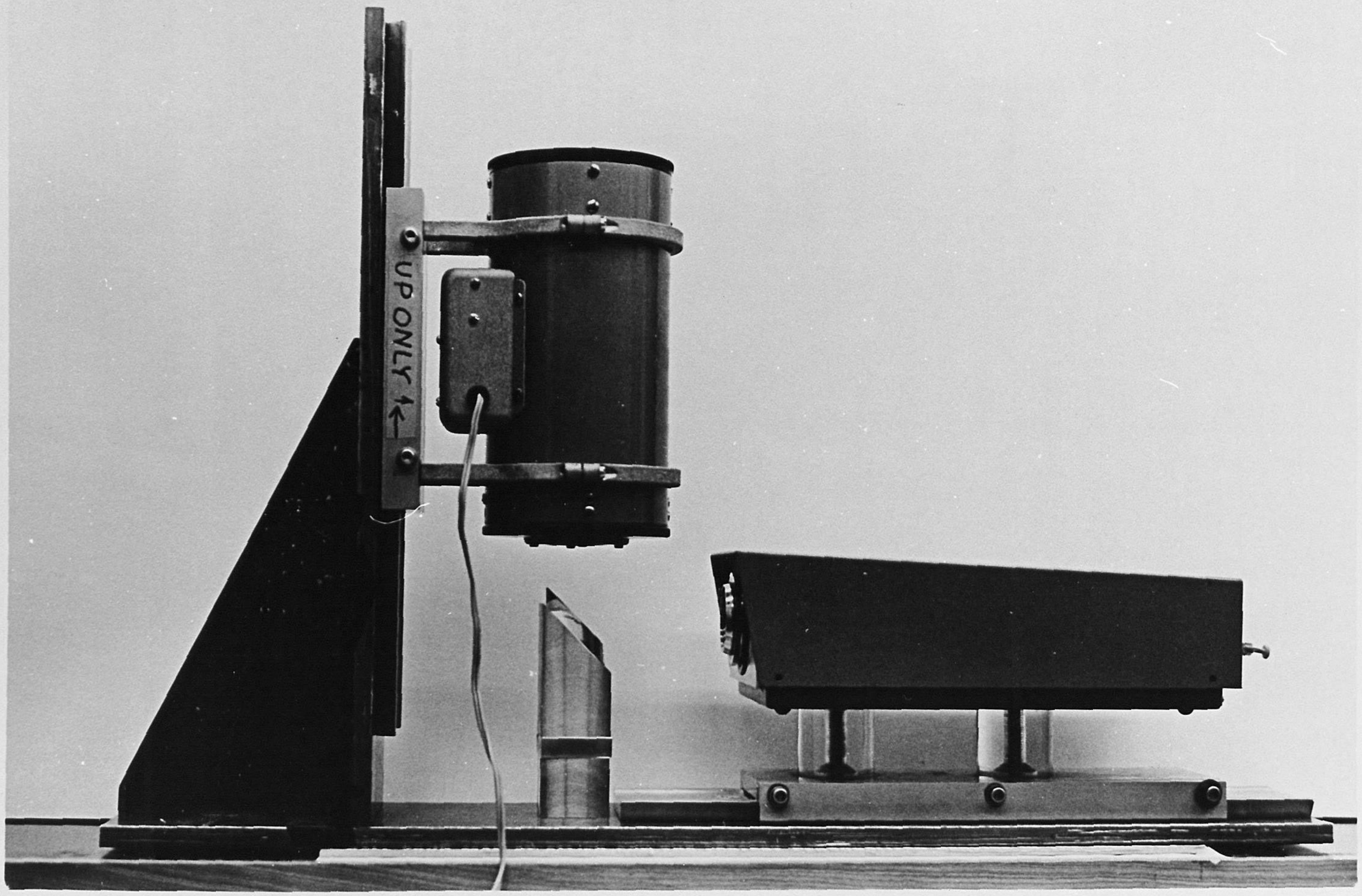


Figure 18. The right angle optics mount, shown with the birefringent filter and television camera in place.

Telecentricity is not an absolute requirement, however, and the filter will work reasonably well with a simple converging beam and an aperture stop to prevent light from being scattered from the inside walls of the filter. The filter system should not be used for solar work with a beam hotter than f/16. This degree of convergence, even in a telecentric system, degrades the filter performance enough that it should probably be considered a limit even for non-solar work where heat is not a problem.

Comparison With Non-Video Techniques of Making Magnetograms

The major advantages of the present system lie in the immediate availability of results combined with a reasonably high spatial resolution and field sensitivity. If the highest possible spatial resolution and freedom from geometric distortion is desired, then film should probably be used, if the loss in sensitivity can be tolerated, and if a large number of pictures are not to be processed. The videomagnetograph is unsurpassed for ease of making time-lapse movies.

If the highest possible field sensitivity is required, then if low time resolution and low spatial resolution can be tolerated, photomultiplier techniques should be used. There is increasing hope, however, that video sensitivity will soon reach that of photomultipliers.

Again, it should be stressed that the strong point of the present system lies in the production of large numbers of medium-high resolution magnetograms for the study of the motions of magnetic structures.

A powerful research tool can be made of analysis techniques using a combination of videomagnetograms and K-line spectroheliograms. The magnetograms can be used to determine field polarities, and the spectroheliograms to determine field geometry. Aside from the intrinsic interest in comparing magnetograms with K-line and Hα structures, such a technique makes it possible to deal quite easily with the geometric distortions in the magnetograph if good K-line pictures are available. The incorporation of calibration procedures into the magnetograph should soon make this procedure unnecessary.

It is worth mentioning another technique which has been found to be quite valuable, this being the subtraction of difference pictures made photographically using the magnetograph. The necessity of making unity gamma positives is eliminated, and the pictures can be registered by hand. Only a single subtraction is required. Dr. S. Schoolman has worked out an excellent program for the automatic controller that serves this function. Producing a subtracted pair in this way takes only a minute or two. It may be worthwhile to produce simplified versions of the system for this purpose alone.

FUTURE DEVELOPMENTS AND APPLICATIONS

Video technology is still growing at an extremely rapid rate. Some of the newer developments that bear on differential video photometry, such as the silicon diode array tube, have already been discussed. The purpose of this section is to point out some of the directions in which further attempts should be made to turn the new technology to the use of solar instrumentation.

Video disc recorders have been substantially improved in the past few years, and further improvements in signal-to-noise ratios, bandwidth, and reliability can be expected. Subtraction accurate to 0.1% will almost certainly be possible in the near future, without the need to average large numbers of pictures. In fact, it may be possible now by using several video heads in parallel as one head. Improvements in low noise current amplifiers have recently made it likely that cameras with 60 db signal-to-noise levels will also be available. Thus, a system similar to the present one will probably be capable of performance at least an order of magnitude better than that of the present system, at least in terms of sensitivity. Systematic errors will still have to be subtracted out, however, and this means that a drastic drop in the price of such a system is not likely. A disc recorder or similar device will still be required as a high speed, high capacity memory to store the video information for subtraction, at least if commercial television rates are used.

As mentioned before, one area where research should probably be done is in slow scan television systems. These have a much higher intrinsic signal-to-noise ratio due to their reduced bandwidth, and the lower rate at which information is accumulated makes digital handling of the video much easier.

One of the most exciting developments in electro-optical devices in recent years is the linear silicon diode array. This is an array of silicon diode light sensors individually wired so that they can be read out one by one. These arrays can be purchased with up to 128 diodes on .0025" centers. One manufacturer says that he can make an array 3" long with individually wired diodes on .0025" centers. So far he has only made an array 64 diodes long, but he's willing to try. Whether or not he can do it now, the capability will soon be there. The importance of these developments is that they make the construction of multichannel magnetographs extremely simple. A 128 diode array is being marketed by Fairchild Camera and Instrument Corporation which has a built-in logic circuit designed to allow the individual interrogation of each diode. Two of these could be placed over the exit slit of a spectroheliograph equipped with a beamsplitter. The outputs could be fed to two twelve bit analog-to-digital converters, and the diode array swept once, say, every .01 seconds. The digitized outputs could then be immediately subtracted from each other, and simultaneously combined with a difference correction signal stored in 4048 bits of random access memory contained in two integrated circuits (available from Texas Instruments, Inc.). This correction signal would have been recorded just before with the quarter-wave plate set for no difference between the light fed to the two arrays. The digital difference signal could be recorded for computer analysis, or converted to analog and used to drive an array of light emitting diodes. The array of light emitting diodes would move along with the spectroheliograph. A photographic plate held stationary above the array would produce an immediate difference picture complete with all the electronic enhancement needed.

Sensitivities to magnetic fields should be on the same order as those of photomultiplier systems. The whole thing would cost at most about $1000 to $2000. It would be so compact it could be battery powered and carried around in a lunch pail -- or perhaps more importantly, launched into orbit.

The future applications of differential video photometry are almost limitless. As better low light television cameras are developed, the use of the system can be extended to differential colorimetry and polarimetry of faint light sources, such as planets and nebulae. High resolution doppler studies might be made to reveal fine structures in the velocity fields of nebulae. Such studies could be made in a fraction of the time required for photomultiplier aperture scanning, and would permit the comparison of large numbers of objects, or the monitoring of many objects from night to night. Time lapse movies could be made where they might be expected to show something - perhaps in planetary work.

Applications exist outside of astronomy in any field where it might be interesting to make measurements of differential colorimetry or polarimetry over the entire surface of a differentiated specimen. Geologists might have use for the speed of analysis offered by the technique. Chemists might find it of use in monitoring the progress of rapid but subtle color changes. The diode arrays, of course, offer promise in the design of rapid-scanning spectrometers, a point that anyone who might be interested in the spectroscopy of rapidly changing systems should keep in mind.

In a more applied vein, small changes in crop colors could possibly provide early warning of disease. The video technique could be used either to cancel photographs, or to cancel pictures stored on magnetic tape to detect changes on the order of a part in a thousand. The same technique could be of use to oceanographers, for the study of color changes in ocean currents. Differential infrared measurements could pinpoint developing hot spots in dormant volcanos. All of these applications make use of the videophotometer's ability to rapidly and conveniently process large and highly differentiated fields of view.

It would be possible to go on for another page or two listing various other possible applications, but the above suggestions should serve to indicate the range of utility of this instrument and related ones. The differential video photometer should prove to be a highly valuable instrument with many uses.

PART II - A STUDY OF MAGNETIC FIELD DIFFUSION IN WEAK PLAGE REGIONS

INTRODUCTION

Before discussing the detailed analysis of the data, a brief qualitative description of the appearance of the videomagnetograms is in order. There are two basic types of magnetic observations which have been made: the daily magnetic surveys and the time-lapse movies. The movies which have been made up to this time have covered time periods of up to about 6 hours with about 1 minute between frames. One particularly good movie was taken at Big Bear Solar Observatory, and some of the data for this thesis were taken from it.

In watching a time lapse movie with a resolution of 5 arc seconds or so, one is struck primarily by the fact that nothing much seems to be happening. The first impression that one gets in watching a movie taken over a time span of several hours is that nothing at all occurs. This is not the case, as we will see later, but it is true that there are few obvious large scale motions of the magnetic features.

The daily surveys bear this impression out to a large degree. There is a high degree of correlation between even the detailed magnetic features as seen on two successive days. There are some notable exceptions to this, however. Often a bright point of magnetic flux which was visible on the previous day will be seen to have disappeared overnight. Other bright points will have appeared where none were visible before. Also, the relative positions of bright points identifiable from the previous day will have shifted slightly, but definitely.

Misregistration makes observations of the motion of magnetic fields very difficult near sunspots, where the large light intensity variations produce large signals with only a little misregistration. Therefore, this thesis will only be concerned with observations some distance from sunspots, in the weak plages of old active regions. The remarks just made concerning the appearance of the magnetograms apply to the weak plages, as well as to the bright plages near sunspots, but not so near as to be affected by the sunspot misregistration errors.

Considerable progress has been made toward the understanding of the solar cycle by Leighton (1964, 1969), who has created a model of the solar cycle which proposes, among other things, that once magnetic flux has erupted from the solar surface in the form of a new active region, it disperses solely under the influence of the solar differential rotation and a random walk, the latter being brought about by the supergranulation convection cells. The success of the model in explaining many of the observed features of the solar cycle can be taken as an excellent argument for its validity. Nevertheless, there has been little work done on the observation of the detailed motion of the magnetic flux in old active regions. Several interesting questions might be asked. For example, what is the detailed nature of the diffusion process responsible for the dissolution of active regions? Is this diffusion process always the same throughout the life of the region, or does it undergo qualitative changes as the region grows older and more diffuse? We know on the one hand that magnetic fields strong enough to produce sunspots profoundly influence the velocity fields in the regions they occupy. On the other hand, the very weak fields presumably responsible for the quiet-sun calcium network seem to be pushed around more or less at will by the solar convection currents. It would be interesting to investigate the motion of fields of intermediate strength, say a few hundred gauss.

The random walk used in Leighton's model need be a valid approximation only for transport of flux over distances comparable to a solar radius and for times comparable to a solar cycle for the model to work. In this thesis, I am interested in observing the diffusion of magnetic flux over distances of a few thousand kilometers, and times of a few hours or days.

Given Leighton's model of the solar cycle and the qualitative observations given above, there are several obvious things to measure. First, it is desirable to pick an old region in which no new flux appears during the observational period. Thus the dissolution of the region can be observed without complications. In the weak plage regions where this study was carried out, bright points were observed with lifetimes which seemed to be long compared to the generally accepted lifetimes for the supergranulation convection cells. The lifetime of these points of strong magnetic field was measured. This lifetime is of interest, since if it is indeed significantly longer than the lifetime of the supergranulation, the fields in weak plages cannot be assumed to be simply pushed around by the convection cells.

It was found that many bright points could be identified for several days, and that the relative positions of the various points in a pattern of magnetic field changed from day to day. This motion was analyzed to see if it indeed had the character of a random walk (after the removal of the differential rotation by means of a computer program), and if so, if it could be responsible for all or most of the transport of magnetic flux in the region. Since it was found that this motion of bright magnetic points was not sufficient to account for the rate of flux dispersal required by Leighton's model of the solar cycle (Leighton, 1969), and by earlier measurements (Babcock, 1963; Leighton, 1964), another type of flux dispersal was looked for. The clue to the second type of flux dispersal was in the observation that bright points would suddenly appear and disappear on the daily surveys. This matter is discussed further in a later section of this thesis.

LONG LIVED MAGNETIC STRUCTURES IN PLAGE AREAS

One of the more striking phenomena seen in videomagnetograms is a relatively long lifetime for the magnetic features associated with weak plages. The persistence of the large scale geometry of these features has been noted in K-line spectroheliograms (Howard, 1967), but in the K line the detailed structure of the brightness patterns seems to change completely from day to day. In the videomagnetograms a high degree of correlation exists even in the details of the features over a twenty-four hour period, and a lifetime of about 3-4 days would seem to be typical of the bright "vertex points" of the supergranulation. Since these vertices remain visible for a relatively long period of time, it is possible to observe the motion of the points from day to day, using the daily videomagnetograph surveys which were carried out during the fall of 1970 and the spring of 1971 at Downs Laboratory.

The surveys consisted of a mosaic of magnetograms covering the entire active zone of the sun, taken daily whenever conditions permitted. The chief advantage of the videomagnetograph for such a survey is the ease with which a large area of the sun can be covered with relatively high (about 5 arc seconds) spatial resolution. This application of the videomagnetograph is not one that uses the instrument to the best advantage, since it does not allow the exploitation of the ability to make time-lapse movies. Nevertheless, the availability of large numbers of high resolution surveys makes statistical analysis of magnetic features much simpler than it has been heretofore.

One particular sequence of surveys, running daily from January 4, 1971 through January 9, 1971, was chosen for particular study. The choice was based on the 6 day length of the sequence, which was one of the longest continuous sequences of good daily surveys available, and on the availability of suitable features for study close to the center of the solar disc.

One particular magnetic region was singled out for intensive study. This was a region of weak plages, far from any active regions with visible spots. The region remained close to the center of the solar disc throughout the 6 day period, and thus correction of projection errors was not so critical in the evaluation of the data as it would have been if a region nearer the limb had been studied.

The region studied was in the northern hemisphere and was of leading polarity. This is the leading portion of McMath region 11108. The region is quite old, being primarily composed of elements of regions first appearing 3 and 5 rotations earlier (SGD 319, 1971). The region is shown as it appeared on January 4, 1971 in Figure 19. Figure 20 shows the same region in the K line. (The K line picture is from the Mt. Wilson survey.) Figure 21 shows the region as mapped by the Mt. Wilson magnetograph. This magnetograph is a special plot showing only fields stronger than 10 gauss. (Courtesy of Dr. Robert Howard of the Hale Observatories.)

Lifetime Analysis of the Magnetic Features

In order to measure the lifetimes of the magnetic features, it was necessary to devise a method of identifying the same feature after an elapsed time of 24 hours. This was particularly difficult, since the more interesting features were the bright "vertex points" of the enhanced

Figure 19. Magnetogram of the leading portion of McMath 11108. North is up and east is to the right.

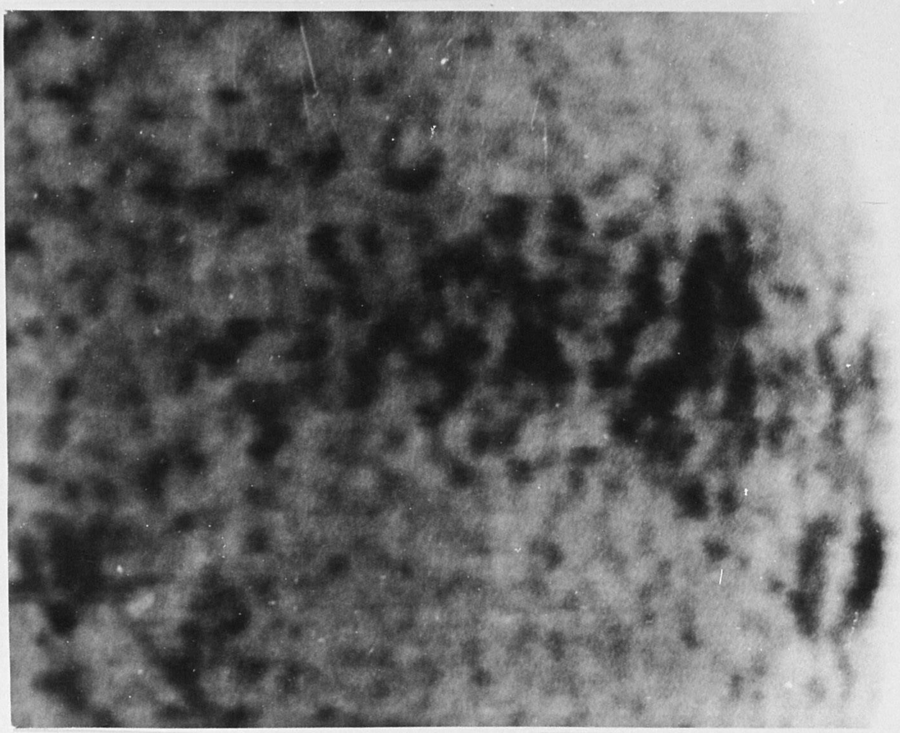
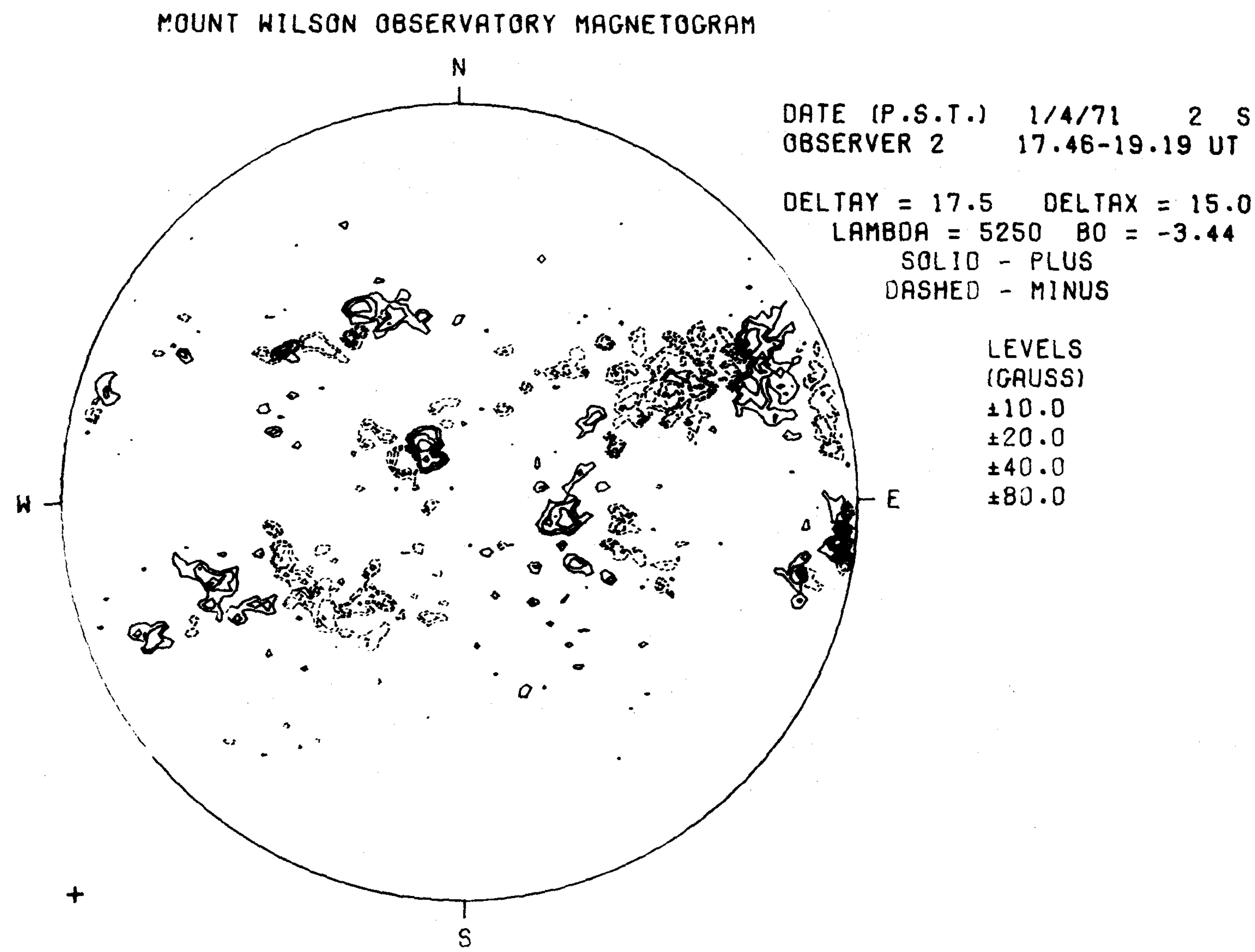


Figure 20. Mt. Wilson K line survey showing McMath 11108. The portion covered by Figure 19 is near the center of the picture.


MOUNT WILSON OBSERVATORY MAGNETOGRAM
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SOLID - PLUS
DASHED - MINUS
LEVELS
(GAUSS)
±10.0
±20.0
±40.0
±80.0

Figure 21

magnetic network in the weak plages. It was hoped that the true lifetime of the individual points could be measured, rather than the lifetime of the overall pattern formed by these points. In particular, it was not possible to use cross-correlation techniques over large areas of the magnetograms, since it was considered probable that a particular point could move relative to other points while still retaining its identify. Such motion would cause the correlation index to drop artificially fast with respect to time, and would result in a lifetime measurement which was too low.

A computer program was devised to translate points observed on one day into their predicted positions on the next day. The program took into account all projection factors, and differential rotation according to the formula given by Allen for "floculli" (Allen, 1963). The formula used was:

$$\text{Angular velocity} = 13^{\circ}.49 - 2^{\circ}.7 \sin^2\phi \text{ degrees per day}$$

where ϕ is the solar latitude.

It was not always possible to identify "vertex points" in the sense that such points are located at the vertices of a pattern of well defined cells. As seen both in the K line and in the magnetograms, cells in the magnetic network are often incomplete, with several walls and vertex points missing. Accordingly, it was decided to measure the lifetime of the bright points considered as local maxima in the magnetic field and only secondarily as vertex points in a cell pattern.

Thirty prominent points were located on the magnetogram for January 6, 1971 which corresponded to definite local maxima in the magnetic field. These 30 points were then followed from day to day until they disappeared, or until no more magnetograms were available. The available magnetograms allowed the points to be followed backward in time for 2 days, and forward for 3 days.

The number of the original 30 points identified on January 6 still visible on successive dates before and after the 6th is plotted in the histogram in Figure 22a. The full width at half maximum of this curve is about 4 days, which can be taken as a measure of the lifetime of these features. The generally accepted lifetime for the supergranulation cells is about 20 hours (Simon and Leighton, 1964). The lifetime of the bright points is significantly longer.

Figure 22b shows a lifetime histogram including all identifiable points (a total of 42) on January 6. This histogram gives a lifetime of about 3 days. Thus, inclusion of the weaker points seems to decrease the measured lifetime. Weak points apparently do not live as long as strong ones.

The points used in this study were obtained by placing a sheet of clear acetate over the magnetograms for January 6, and marking the center of each bright vertex point on the acetate. Not all of the points visible on the magnetogram for January 6 were used in the study, since part of the area covered in this magnetogram was not visible in all of the magnetograms for the other days in the sequence. The thirty points so marked were then assigned coordinates with respect to a Cartesian coordinate system with the origin at the sun's center and with the y axis running along the polar axis of the sun.

The position and orientation of the magnetograms with respect to this coordinate system was determined with the help of the daily K line survey of the sun made at Mt. Wilson. Since there is virtually a

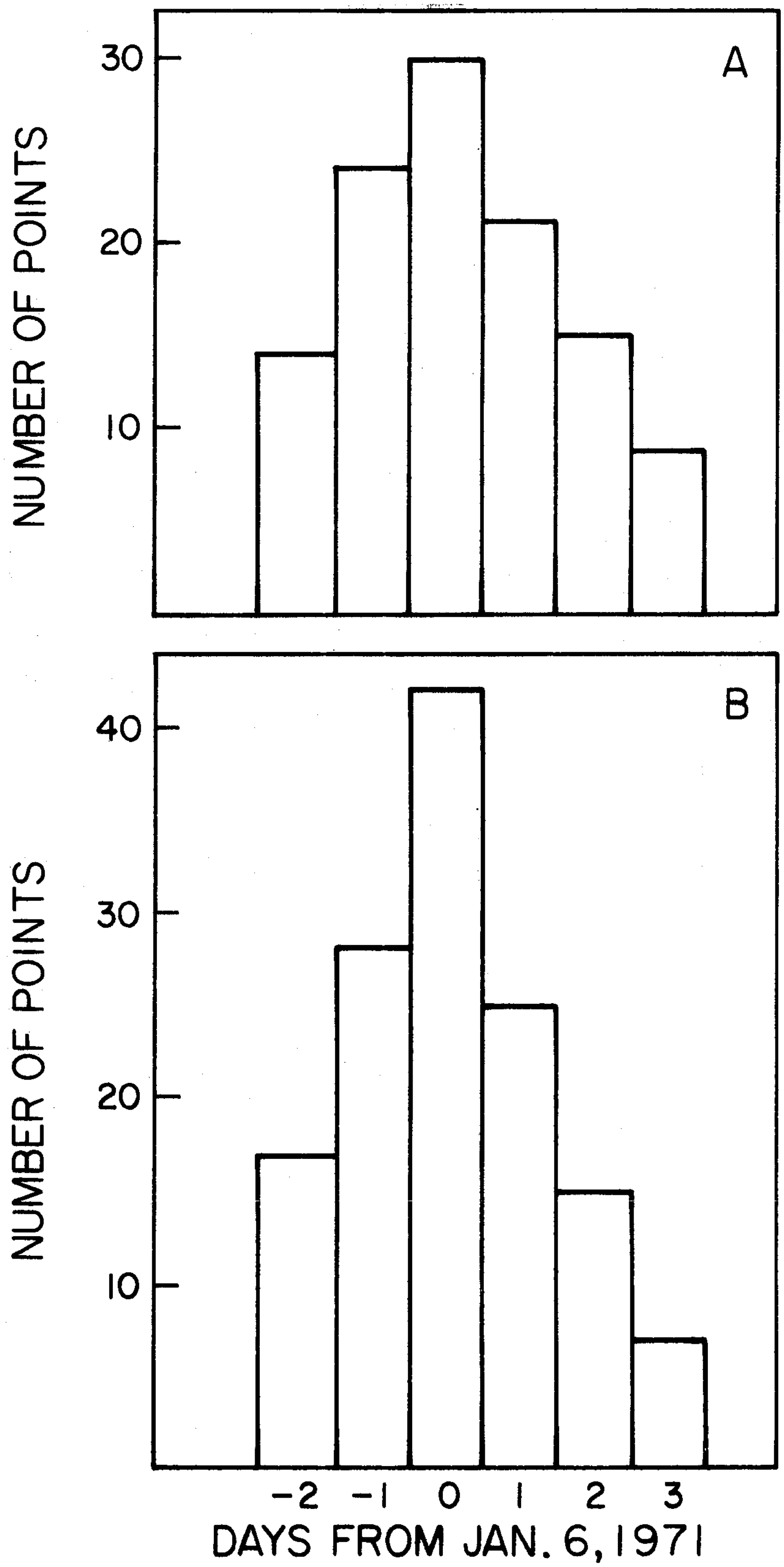


Figure 22. Lifetime of bright points. Figure 22a shows the lifetime histogram of 30 prominent points. Figure 22b includes all identifiable points (42 total).

one-to-one correspondence (with some exceptions which will be discussed in detail later) between the magnetic field features seen in the magnetograms and the bright network seen in the K line, it was possible to project slides prepared from the Mt. Wilson surveys on a piece of cardboard in such a way that the scale of the projected image was the same as the scale of the magnetograms, and then to position the magnetograms on the solar image by superimposing the K line and magnetic features. The magnetograms used in the study were 4" x 5" transparencies prepared from 35 mm photographs of the video monitor. Once a magnetogram had been registered with the K line image, the position of the corners of the transparency were marked on the cardboard. The position of the poles and limb of the sun was also marked. (The poles of the sun are marked on the Mt. Wilson surveys.) After the position of the magnetogram for the first date was thus located on the solar disc, the Mt. Wilson survey for the next date was projected on the cardboard, the poles and limb aligned with the positions marked for the previous date, and the position of the next magnetogram marked (see Figure 23). The y axis of the coordinate system was then drawn in along the polar axis of the sun as shown on the Mt. Wilson plates, and the entire coordinate system then constructed.

The coordinate axes and the magnetogram positions constructed in the manner described above were transferred to a piece of graph paper. The graph paper served as the coordinate grid in terms of which the positions of the individual magnetic points were determined. The corners of the magnetogram for a particular date were marked on the same piece of acetate that was used to mark the positions of the magnetic points. These corner marks were then placed in register

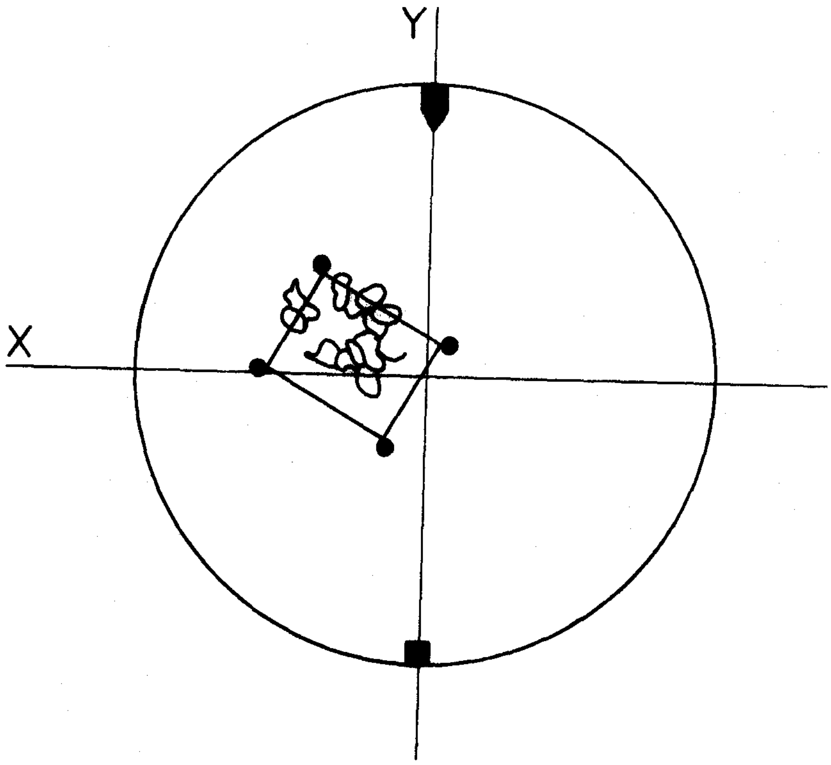


Figure 23. The position of a magnetogram on the solar disc is determined by superimposing the magnetogram on a full-disc K-line picture of the sun taken the same day, and marking the position of the magnetogram corners.

with the positions shown on the graph paper for that magnetogram, and the coordinates of the magnetic points were read off the graph paper grid.

There are a number of possible sources of error in such a method of coordinate determination. The most important of these is the rather poor quality of the Mt. Wilson surveys. The tracking was not of the highest quality when the pictures were made on the Mt. Wilson spectroheliograph, and as a result most of the images are somewhat egg shaped. This means that the assigned coordinates cannot be taken too literally as an exact determination of the position of the magnetic points on the solar disc. In fact, the position predicted by the computer program for a pattern of magnetic points based on the coordinates assigned on the previous day and on the expected solar rotation in 24 hours often disagreed by as much as 30,000 kilometers. Also, the Mt. Wilson surveys were not taken at exactly the same time as the magnetograms, and in view of the poor quality of the surveys, no attempt was made to correct for this factor. For these reasons, the coordinates assigned to the magnetic points should be viewed as adequate only for the purpose of removing projection effects from the data, and, to some extent, for removing effects of differential rotation. These coordinates are not sufficiently good to make absolute predictions of the positions of the points from day to day. A difference in position of 30,000 km is, of course, quite large compared to the resolution of the system, but a displacement of this amount will cause only a slight error in projection correction factors. (The worst case error in the projected size of the magnetogram is about 5000 km over the <u>entire</u> region of interest.)

In order to measure the lifetime of the magnetic points, the positions of all identifiable magnetic points were marked on sheets of acetate for the dates of January 5 and January 7. The resulting patterns of points were compared with patterns obtained from the extrapolation of the thirty points plotted for January 6 backward and forward in time, respectively. If a point shown on the pattern for January 6 (as projected to January 7) was also found on January 7, it was considered to still be in existence. Those points still in existence were then projected forward to January 8, and so on until the histogram was completed. The points in existence on each date were all marked before the projections had been made, and without reference to the magnetograms for any other date. This was done in order to provide a reasonably objective criterion for the disappearance of the magnetic points. They were considered to have disappeared if they were not noticed in an attempt to mark all such points without reference to any other magnetogram than the one being marked. (It was usually possible to convince one's self that there was still a trace of magnetic field at the site of a point that had "disappeared", once the projected location was known, but such a criterion of the point's existence would be much more subject to psychological factors than the criterion actually used.)

Since the projected locations of the points were not absolutely accurate, it was necessary to register the pattern of points projected for a given day with the pattern of points actually observed. This was done by hand for the purpose of determining the lifetime of the points. After the two patterns were registered, the two sets of points were compared. Since there was a small component of "random walk" motion visible in a 24 hour period (the various points making up the pattern had moved slightly with respect to the other points in the pattern), the points in the two patterns almost never fell exactly on top of each other. It was therefore necessary to establish some criterion for deciding whether a point in the pattern had simply moved, or whether it had disappeared and a new point had appeared nearby. The criterion used was that if the two points were closer together than a distance equal to about one half the average separation between neighboring points in the pattern it was considered to be the same point. (Actually the distance used was the diameter of a hole in a draftsman's template that happened to be about the right size. The size of the hole is shown in Figure 24.) In practice, this criterion was used only a few times. Either the points in the two patterns lay very close together, or they were widely separated. Figure 24 shows the superposition of the projected pattern from January 7 and the pattern of points observed on January 8. The persistence of the points is more dramatic when the pattern of points projected from the 7th is superimposed directly on the magnetogram from the 8th. This is shown in Figure 26.

Due to the component of random motion visible in the point pattern from day to day, it was difficult to identify points unambiguously if they were projected through time for more than 24 hours. Accordingly, once a point was identified as being the same as one which had been projected from the previous day's pattern, it was then projected forward to the next day from its observed position. Thus there was never more than a single day's random motion to worry about in identifying points. This day-to-day projection was, of course, used in moving both forward and backward in time from January 6.

Since the identification of the bright magnetic points might be considered a highly subjective process, an attempt was made to measure

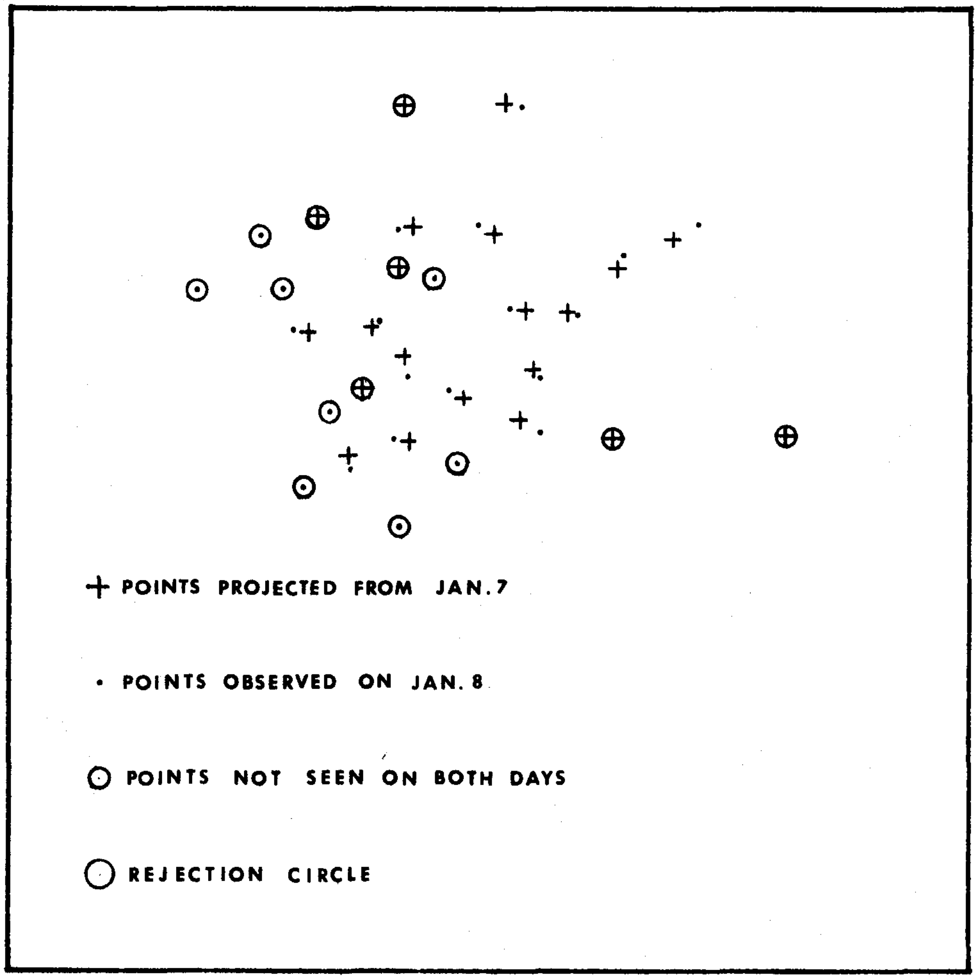


Figure 24. A plot of points observed on January 8 and points projected from January 7.

the degree of subjectivity involved. This was done by requesting two different inexperienced observers to locate the bright points in the magnetogram for January 6, and comparing their results with a plot made by an experienced observer. The two inexperienced observers were given the following set of instructions:

"We are looking for the center of 'vertex points', which are localized bright spots in magnetic field patterns. These bright spots may either be isolated or arranged in a pattern of cells with dimmer 'cell walls' connecting the brighter 'vertex points'. A vertex point is distinguished by the following criteria:

1. It is a local maximum of the magnetic field.
2. It is sufficiently brighter than the background grey level so that it can be definitely recognized.
3. Vertex points must be brighter than the large-scale mottling of the grey background (caused by misregistration)."

Using these instructions, the two inexperienced observers marked an average of 66% of all points in common with the experienced observer. In general, the experienced observer tended to be more confident about marking weak points near the background level, and the inexperienced observers tended to mark more local maxima in the areas of high magnetic field, where differentiating adjacent points was difficult.

Since the experienced observer did all the other data reduction in this study, and since two other observers agreed with his point identification an average of 66% of the time, the lifetimes measured by this method might be taken to be repeatable to within about 35%. (The two observers agreed with the experienced observer 66.6% of the time and 64.6% of the time, individually. 78% of all points identified were identified by at least two observers.)

Apart from possible human error, it seems likely that the lifetimes might be slightly low due to projection effects which would weaken the line-of-sight magnetic field strength as the region moved toward the limb. The number of points remaining, of the original 30 picked on January 6, had dropped to 15 or less within two days of that date moving both forward and backward in time. At no time during this interval was the region of interest more than 41^{o} from the solar center. Thus, projection factors on the order of 1.4 would be observed in the magnetograms for the 4th and 8th.

Figures 25, 26 and 27 show the magnetograms studied from the 4th through the 8th of January. Each magnetogram has the points projected from the previous (or succeeding) day superimposed. Only the points surviving from the original 30 points of January 6 are shown on each day.

Motion Analysis of the Bright Magnetic Points

Since the bright vertex points observed in the magnetograms are sufficiently long-lived that they can easily be followed for a period of 24 hours, and since they exhibit a certain component of random motion with respect to the other points comprising the magnetic region, it is of some interest to attempt to make some quantitative measurements of the character of this random motion. For one thing, if the random motion is large enough, it could be a significant contributor to the diffusion of magnetic flux in weak plage regions. If the component is not large, then some other mechanism of flux diffusion should be sought.

A computer program was written, which, given the observed coordinates of a set of field points on two successive days, projects the points observed on one day to their predicted positions on the second

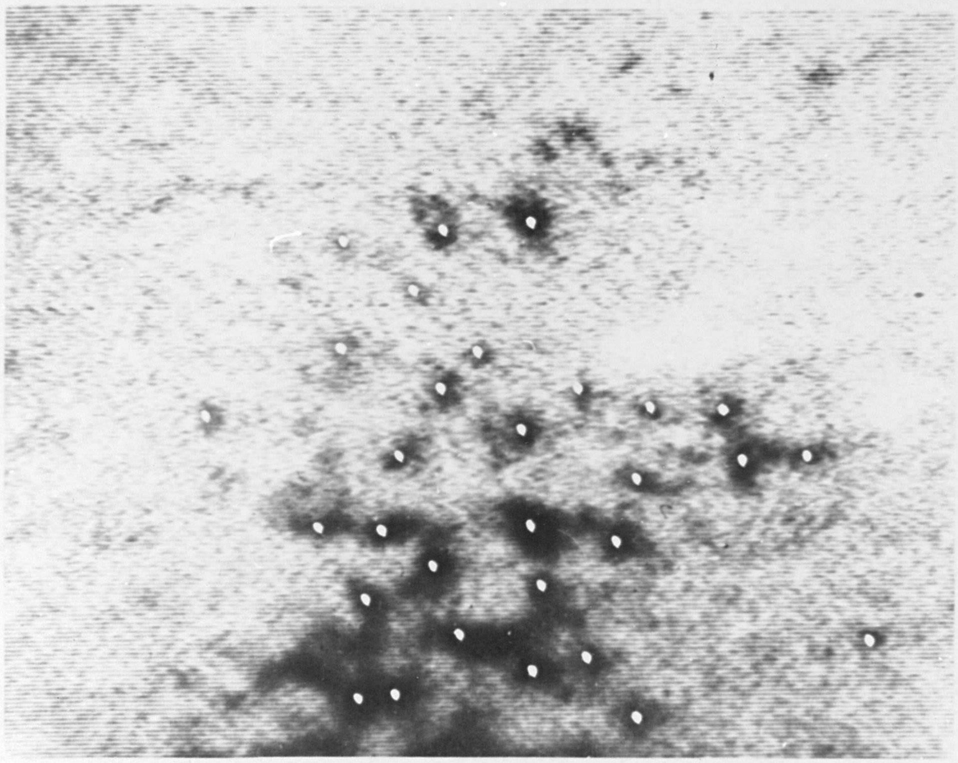


Figure 25. The magnetogram for January 6, 1971, with the original 30 points marked.

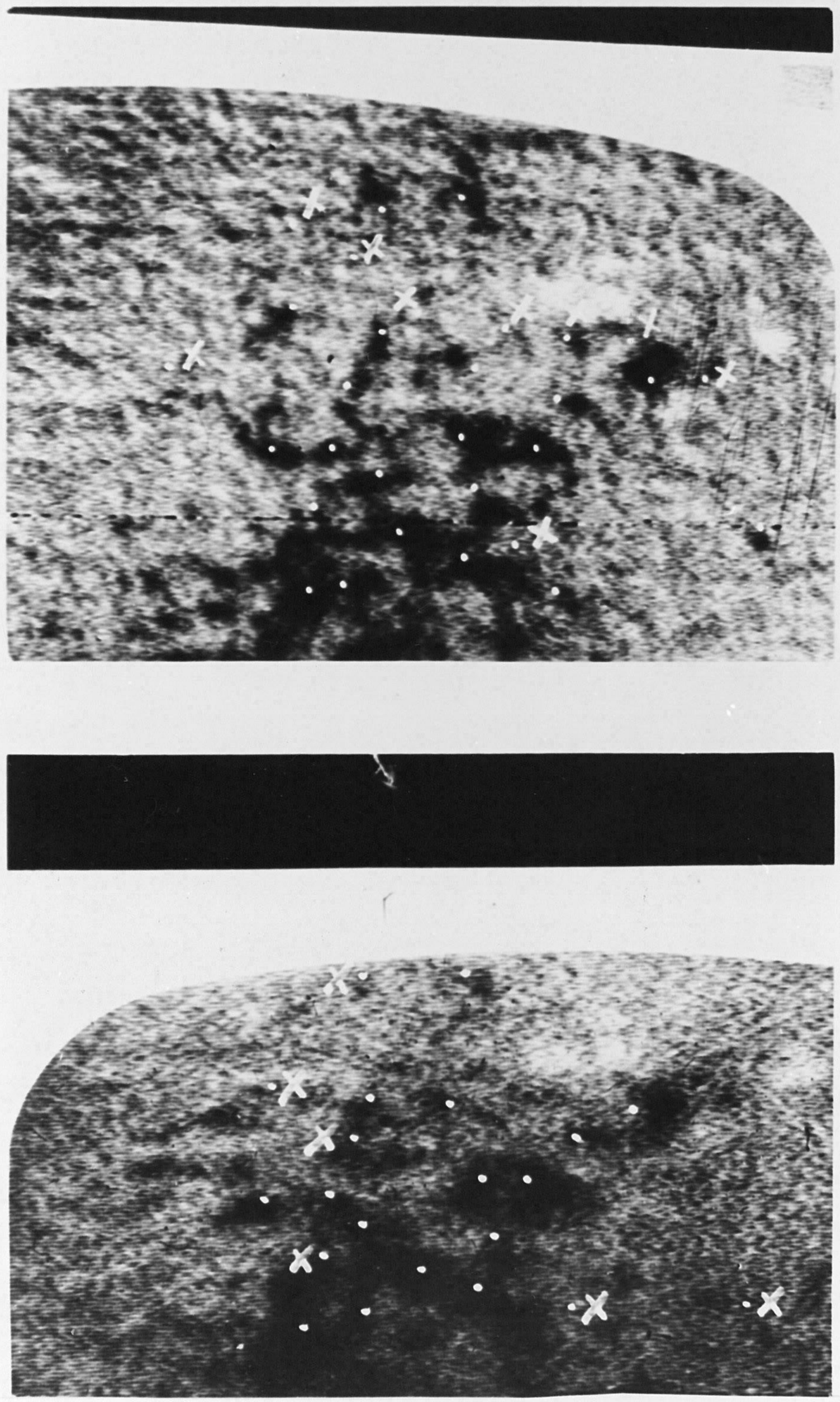


Figure 26. Magnetograms for January 7 and January 8. Projected positions of points observed on the previous day are marked with dots. Dots with an x nearby mark projected positions of points which have disappeared.

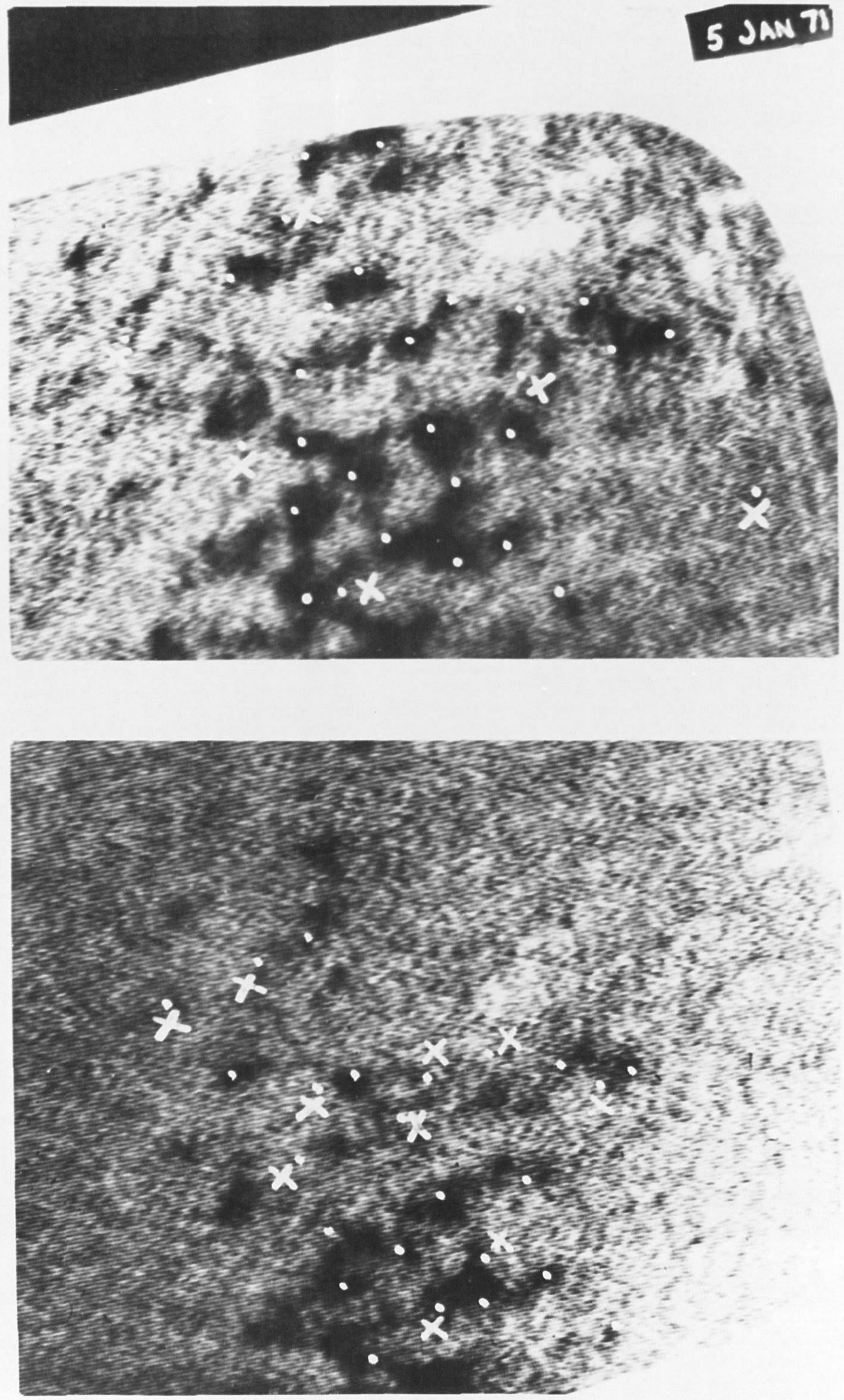


Figure 27. Magnetograms for January 4 and January 5. The dots mark the expected positions of points projected backward in time.

day, registers the two patterns of points so that there is no net displacement in x, y, or θ for the points in the two patterns, and then calculates the remaining displacement from its original position for each point in the pattern. The computer takes into account all projection factors including the P and B angles for the sun. The differential rotation is also included according to the formula given earlier in the discussion of lifetimes of the magnetic features.

In addition to printing out the x and y displacements of each point in the pattern, the program prints out the R.M.S. displacement for all points in the pattern together with the error in this displacement computed from the scatter observed in the displacements of the individual points.

It was assumed for the purpose of the data analysis that the motion of the points was essentially a random walk process. This means that the square of the displacement of the points should increase linearly with time. If we let D_i be the observed displacement of the i'th point, then the average displacement squared per unit time is given by:

$$D^2 = \frac{T}{t}\left[\frac{1}{N}\sum_{i=1}^{N} D_i^{\,2}\right]$$

where N is the total number of points in the pattern, t is the time over which the displacement was observed, and T is the unit time interval. The error of this displacement squared is given by:

$$\sigma_2 \qquad \sqrt{\frac{\sum_{i=1}^{N}\left(D^2-\frac{T}{t}D_i^{\,2}\right)^2}{N(N-1)}}$$

where σ_2 is the standard deviation for the mean value D^2. The R.M.S. displacement observed for the points is given by:

$$D = \sqrt{D^2}$$

and the standard deviation σ_m measured for d is given by:

$$\sigma_m = \sigma_2 / \frac{d(D^2)}{dD} = \sigma_2 / 2D \quad .$$

Now if the process responsible for the movement of the magnetic field points truly has the nature of a random walk of many steps over the observation period of about 24 hours, then the x and y components of the displacement of the magnetic points will have a Gaussian distribution. If this is assumed to be the case, then the observations made can be considered to be a sampling of N displacements out of an infinite population having a Gaussian distribution, and the standard deviation of D can be calculated. It is given by:

$$\sigma_c = D / \sqrt{4N}$$

The above formulas are discussed in Appendix VI.

It is of considerable interest to compare the values of σ_m and σ_c. If they are significantly different, they indicate that the process responsible for the motion of the field points is not a pure random walk, at least not on the time scale of 24 hours. If the two values coverge after a longer period of time, then some information may be gained as to the lifetime of whatever factors are causing the motion of the field points.

In order to estimate the effect of seeing, television non-linearities, and plotting errors on the measured value of the R.M.S. displacement of the points, several null tests were run. The first null test was done by locating the positions of 10 points on the magnetogram for January 5, then locating them again without reference to the first plot. The R.M.S. displacement between two sets of points was 1246 ± 218 km. This displacement was calculated by use of the same pattern registration routine as was used for the reduction of all data, except that the program which calculates the projected position of the points after a change in time was not used since both sets of points came from the same magnetogram.

It is interesting to notice that if the locating errors are roughly Gaussian in their distribution, the predicted scatter for a displacement of 1246 km is about $\pm$ 197 km.

A second null test was run to include the effects of seeing and non-linearities in the television picture. This test was done by comparing patterns of ten points in each of three different magnetograms made of the same region at about the same time. These magnetograms were also made on the 5th of January, and they include the magnetogram used for most of the measurements (lifetime, R.M.S. displacement, etc.) on that day. This magnetogram will be referred to in the discussion of the null tests as magnetogram number 1. Magnetogram number 2 was separated in time from magnetogram number 1 by 22 minutes, and showed the same region in a different part of the television screen. Magnetogram number 3 was separated in time from magnetogram number 1 by 2 minutes, and showed the same region in a different part of the screen from either of the other two pictures. If distortions in the television image were causing the shape of the pattern of points to vary depending on where it was on the television screen, the effect should show up in this null test. Also, since the patterns of points were taken from different magnetograms, the effects of seeing should be present. The R.M.S. displacement measured in this null test was 2234 $\pm$219 km. for magnetogram 1 versus magnetogram 2, and 2660 $\pm$ 343 km. for magnetogram 1 versus magnetogram 3. The value derived from the composite of the two figures is 2456 ± 216 km. This latter figure represents a 20 point composite. It should be noted that if the errors contributing to this measured R.M.S. displacement had a Gaussian distribution, then the expected scatter corresponding to a displacement of 2456 km. would be 274 km. The somewhat lower measured scatter is possibly due to nonlinearities in the television picture, which would introduce a non-random component into the apparent displacements of the points.

The value 2456 ± 256 km. is used later in reducing the data taken in measuring the R.M.S. displacement of the magnetic points from day to day.

At this point it might be wise to digress slightly to point out that the computer registration routine removes any net displacements in x, y, and θ that exist between the two patterns being registered. It might therefore be asked how any non-random component can still exist in the observed R.M.S. displacement of the points. This can happen if distortions in the television system cause a change in the scale of the image when the image is moved from one part of the television screen to another (by re-aiming the telescope, for example). These scale changes can be along any axis. Figure 28 shows a hypothetical 4 point pattern. Figure 28A shows the pattern as seen near the top of the screen. Figure 28B shows the pattern as seen near the bottom. This particular television system is assumed to be suffering from an extreme case of non-linearity in the vertical direction. The picture is "squashed" at the bottom and "stretched" at the top. Figure 28C shows the two patterns as they would be registered by the computer program. Notice that there is no net displacement in the vertical direction. There is, however, an R.M.S. displacement of D,

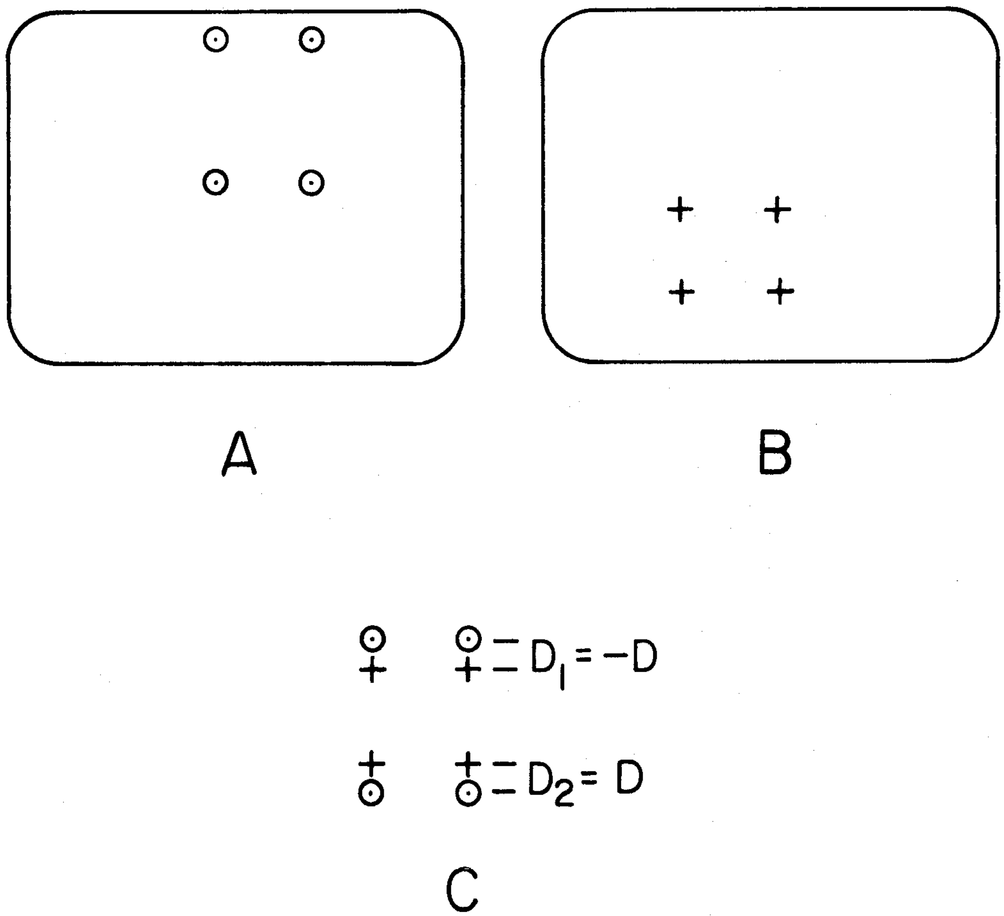


Figure 28. Displacements caused by television non-linearities. (see text)

and no scatter. This is admittedly a worst possible case, but it should serve to illustrate the effect.

It should be pointed out that such an effect might also be caused by a real scale change of the pattern on the sun. Such a change might be caused by a coherent expansion of the magnetic region, for example. No real solar effects would be expected in a time span of a few minutes, however, and it is reasonably certain that the non-random component observed in the null test is due to non-linearities in the television system, and can serve as a measure of them.

Tt was mentioned that no means were available to check the consistency of the system linearity from day to day. It can only be hoped that the observers who took the surveys did not touch the size or linearity controls on the television system. They were instructed not to do so. It is fortunate that the main significance of these R.M.S. displacement measurements is that the random motions of the magnetic points are insufficient to account for the rate of flux diffusion measured by observation of the rate of expansion of the boundaries of magnetic regions. Any errors which are not properly known would only serve to make the R.M.S. displacement larger. The magnetograph measurements can at least put an upper limit on this parameter, and that limit is low enough to be significant. Also, the magnetograph measurements were independently checked by a similar analysis of K line spectroheliograms.

The R.M.S. displacement of 21 points compared in magnetograms taken on the 6th and 7th of January was 7296 $\pm$ 522 km. These were the same points identified as still existing on the 7th out of 30 points identified on the 6th in the section on lifetimes of the magnetic points.

The positions of the points were marked before the identification was made, so there is little chance of the point pattern being more similar than it should be because of unconscious adjustment of the positions of the points in the two fields to match each other. When corrected for the additional displacement due to seeing, plotting errors, and television non-linearities, the value becomes 6870 $\pm$ 560 km. (This is corrected to an exact 24 hour interval.) The scatter expected for a Gaussian distribution of displacements is 750 km. Thus the observed scatter of 560 km is somewhat lower than the expected value for a true, many-step random walk process.

As a second test, the R.M.S. displacement of 16 points visible from the 5th through the 7th of January was measured over a period of about 48 hours. The result obtained was 9118 $\pm$ 816 km. (Corrected to a 48 hour perid.) The scatter expected from a pure random walk is 1140 km. Thus, there still exists some deviation between the measured and predicted error in the displacement.

Since the statistics become rather poor in this one region, no attempt was made to trace the R.M.S. displacement of the points for periods longer than 48 hours. More studies over longer periods should be done in the future.

The ratio of the R.M.S. displacements obtained for the two time periods is 1.34. This indicates a movement which is approximately proportional to the square root of the elapsed time, as expected for a random walk process.

A composite of 24 hour displacements measured for 106 points over the entire 6 day period gives a result of 7983 $\pm$ 331 km. Corrected for observational errors, this becomes 7596 ± 357 km. Expected scatter for a many-step random walk is about 390 km.

A statistical test was made to see if there was any significant deviation from the scatter expected for a random walk. There was none. (See Appendix VI.)

A scatter plot has been made for the 106 points analyzed for motion. It is shown in Figure 29. This scatter plot is not corrected for plotting and observational errors, since these are only known on a statistical basis, not for individual points. It is possible to perform a statistical test on the scatter plot to determine if there are too few points near the center of the scatter plot for a true random walk. This test was performed because several observers seemed to feel that there should be more. If a circle with a radius of just under 3000 km is drawn around the center of the scatter plot, it will be found to contain 7 points. The probability of finding 7 or fewer points in a circle of this radius, if the points were drawn at random from the random walk distribution best fitting the observed points, is .024. Therefore, the effect is undoubtedly significant. It is, however, probably not real. The most probable explanation is distortion in the television system. It is significant that the same effect does not appear in the study made of bright points in the K line.

A total of 53 points were classified as either "weak to medium" or "bright". The 26 points classified "weak to medium" had an R.M.S. displacement of 8301 ± 799 km, and the 27 points classified "bright" had an R.M.S. displacement of 8715 ± 854 km. (These values are uncorrected for plotting errors and distortion, and are not corrected to an exact 24 hour time period. The error quoted is an estimate based on the

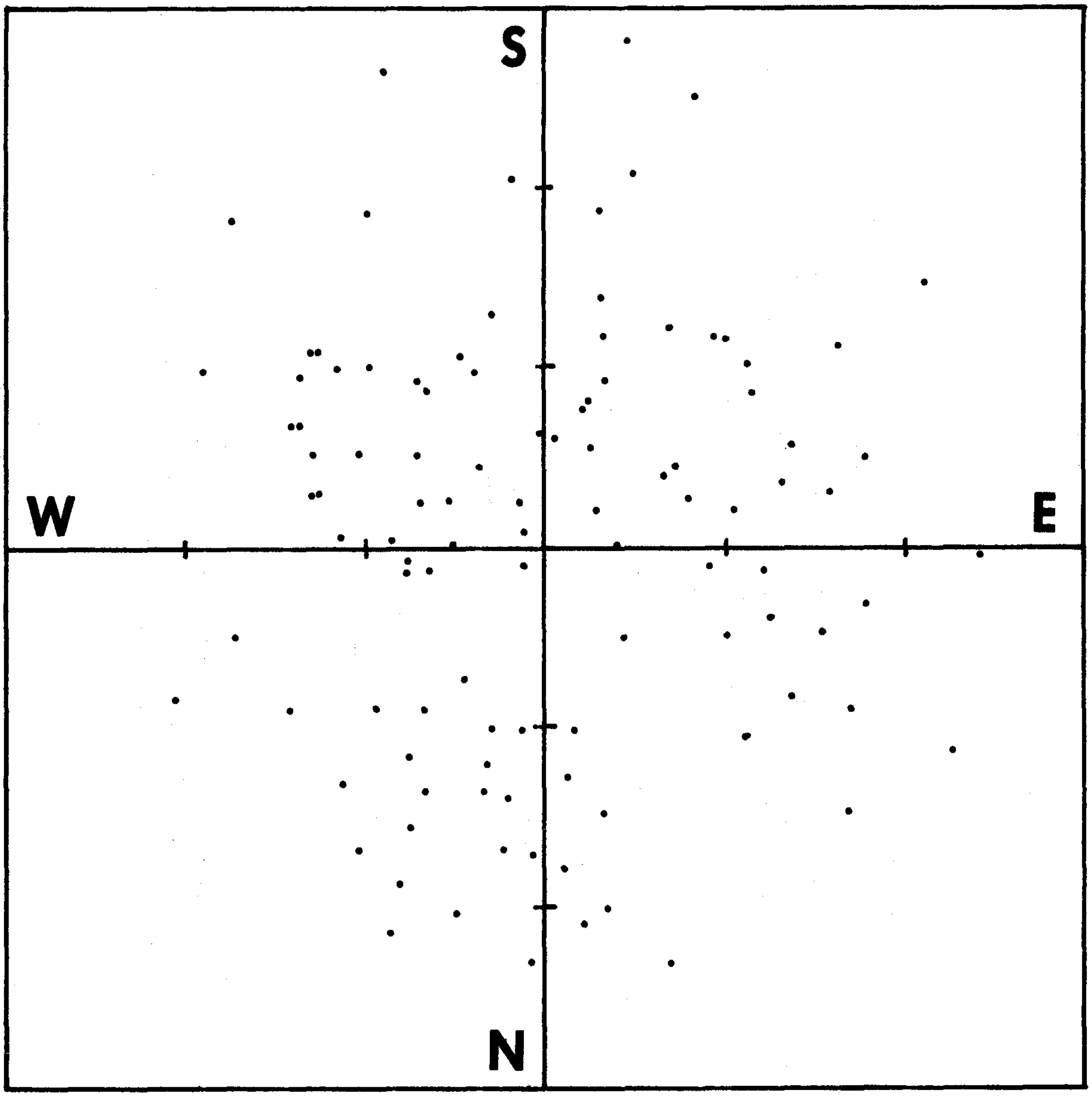


Figure 29. A scatter plot showing the motion of 106 magnetic points in 24 hours. Axes are marked at 5 km intervals.

expected error for a random walk. Only the relative magnitude of the two values is of any significance.) The conclusion to be drawn here is that there is no significant difference in the observed amount of R.M.S. motion as a function of the relative strength of the points as seen in the videomagnetograms.

Finally, a test was made to determine if there was any correlation between the direction in which a point moved in one period of 24 hours and the direction in which it moved in the next 24 hours. A correlation coefficient was calculated for a total of 63 points which could be followed for at least two periods of 24 hours. The coefficient measures the correlation between the direction of motion observed in the two intervals. The data used were uncorrected for plotting and instrumental errors, since these were not known for individual points. The correlation coefficient was .016. There is no statistically significant (at the 90% level) correlation observed in the direction of motion from one day to the next.

A Summary of Results Pertaining to the Magnetic Fields

The major results thus far obtained which can be considered reasonably independent of unknown distortions in the video system are:

1. The bright "vertex points" have a lifetime which is long compared with the lifetime of the supergranulation cells as measured by correlation techniques. The lifetime of the vertex points is about 4 days.

2. The vertex points undergo an R.M.S. displacement of about 7600 km over 24 hours. Although video distortions may account for some of the measured displacement, they have hopefully been removed in the above figure.

3. Regardless of any distortions, 9000 km can be considered a safe upper limit for the R.M.S. displacement of the features studied.

4. There is no conclusive evidence that the motion of the points is anything but a random walk. The small number of points showing small displacements is probably instrumental.

Several things should be kept in mind in interpreting these results. The points studied are all from a single region of leading polarity. The computer program which analyzed the data removed any net displacement of the group as a whole. Thus, the above conclusions do not rule out a systematic displacement of the entire region. All displacements were measured relative to the average position of the points being analyzed. Finally, the region studied was an old one. The characteristics quoted above may not be typical of all regions, especially of newly developing ones.

In an attempt to obtain further confirmation of the magnetograph data in those cases where instrumental distortions may have affected the conclusions, several K line spectroheliograms from Mt. Wilson have been studied in order to check conclusions 2 and 3. These measurements are discussed in the next section of this thesis.

MOTIONS OF BRIGHT POINTS IN THE CALCIUM NETWORK

A series of full disk K_3 spectroheliograms taken at Mt.Wilson in September of 1961 was studied in order to provide confirmation of the magnetograph data regarding the motion of the magnetic field points. The K line pictures offered several advantages in the study of the motion of solar structures. The pictures were full disc, which allowed the precise determination of the location of bright points with respect to the solar limb. The automatic guider was used in the production of the spectroheliograms, and thus the egg shaped images that are characteristic of the Mt. Wilson daily surveys did not occur. Finally, considerably less distortion was present in these pictures than in the magnetograms, since there was, of course, no electronic imaging involved in their production. The expected result was that the R.M.S. displacement measured for bright spots in the K line pictures would be smaller than that obtained from the magnetograms, since fewer distortions would be found to be present. The K line measurements would also serve as a check on the observation that the scatter observed in the magnetic displacement measurements was too small for a many-step random walk.

There were two main difficulties involved in making the K line measurements. The first was that the solar poles were not marked on the K line pictures. The poles were located to within about 2^o by observing the apparent motion of sunspots across the disc of the sun from day to day. The edges of the plates taken on successive days were aligned, and the solar discs for the various days were superimposed. The apparent positions of several prominent sunspots were then marked for each day, and the path of motion plotted. The sun's polar axis was assumed to bisect the sun and to be perpendicular to the paths traced out by the spots. The variation in the paths traced out by the various spots used was about 2^o, or, rather, this was the variation in the orientation of the polar axis with respect to the edge of the plates as determined from the paths of the various spots.

The second difficulty encountered in the analysis of the K line plates was the problem of identifying the same features on subsequent days. The number of features seen in the K line is much greater than that seen in the magnetograms, and therefore the unique identification of a feature on one day with a feature on another is difficult, and somewhat arbitrary. The weaker features in the K line tend to change considerably from day to day, and this throws a confusing factor into the identification of the longer lived features. Indeed, the chief advantage of the magnetograph in allowing the observation of the long-lived features is probably that of providing a sensitivity threshold which removes the distraction of the weaker fields.

Figures 30 and 31 show K-line pictures for the 8th and 9th of September, 1961. These were the pictures from which the data were taken for the measurements described below. These spectroheliograms were taken by George W. Simon and Robert B. Leighton at the Mt. Wilson 60 foot tower.

The K line data were analyzed in the same way as described in the section on the motion analysis of the magnetic points. The analysis was done by a different person than the one who analyzed the magnetic points. The points analyzed were again identified as local maxima in the brightness pattern, with the additional criterion that the points measured should be "significantly brighter" than the general level of the quiet sun network. This study is considerably more subjective than the corresponding work done with the magnetograms, since in the case of the magnetic study all points visible above the background were studied. In the case of the K line, it must be decided if each particular feature should or should not be included in the study.

Another difference between the K line and magnetogram studies is that while the magnetogram study was made of points in a single region, the K line study covered a large area of the sun containing several

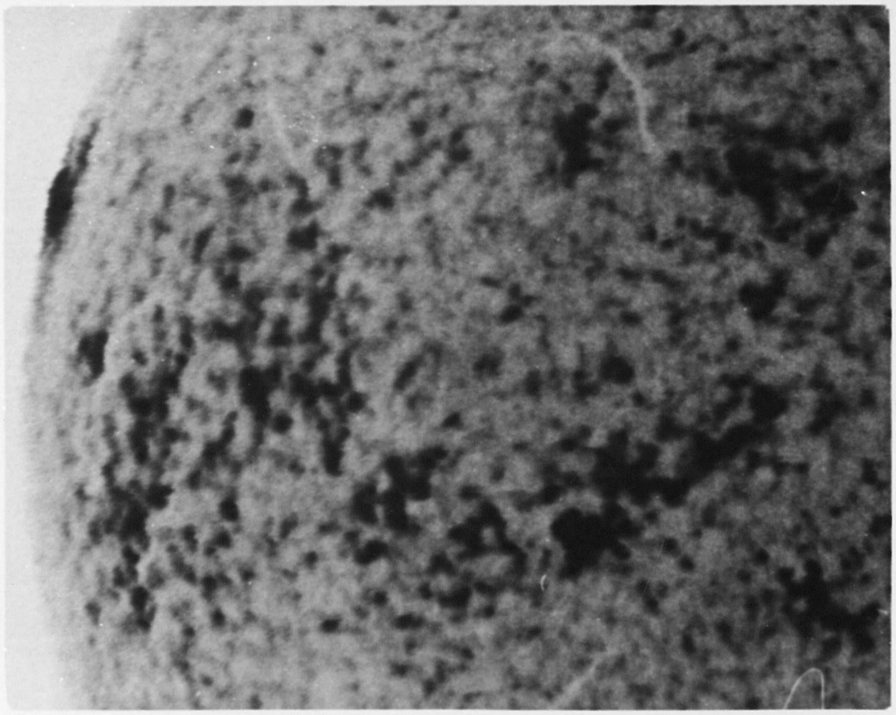


Figure 30. A K_3 picture for September 8, 1961.

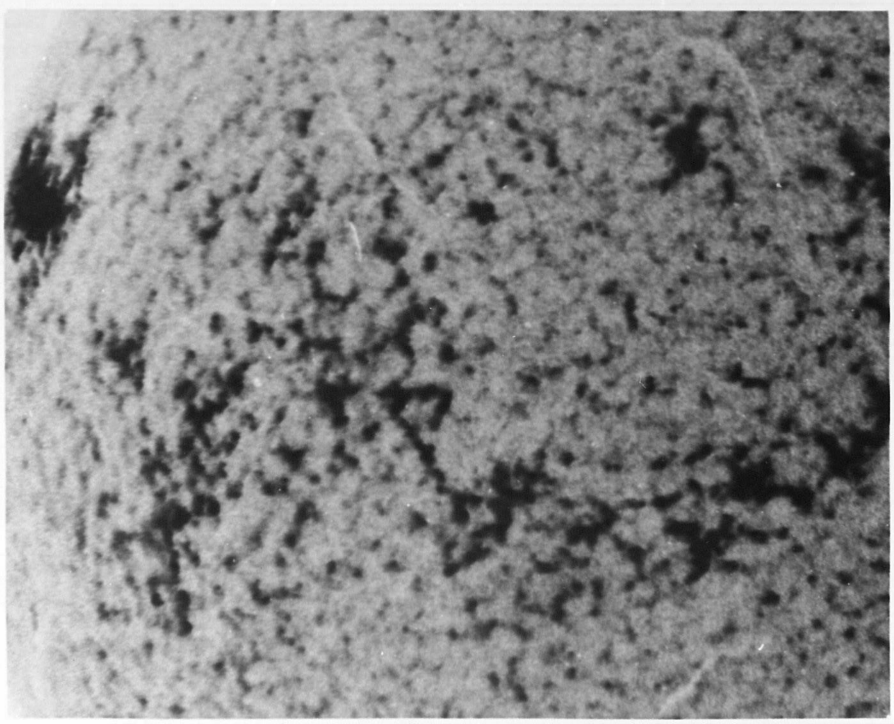


Figure 31. A K_3 picture for September 9, 1961.

different regions in various stages of development. Thus the two studies are not directly comparable, at least where any systematic effects which may be due to factors present within a specific group are concerned. On the other hand, if the two studies give about the same value for the R.M.S. displacement of the points studied, there is a clear indication that something real is being measured. Figure 32 shows a scatter plot for the motion of 132 points between September 8 and September 9, 1961. The R.M.S. motion measured is 9052 ± 378 km in 24 hours. Corrected for plotting errors, this becomes 8560 ± 422 km.

An analysis of the scatter plot for the K line shows that there is no lack of points near zero displacement compared to the number expected for a random walk. This result argues against the interpretation of the magnetic scatter plot as the result of a solar process which tends to prevent points from returning to their original positions. At least there seems to be no tendency for this to be occurring simultaneously in all of the various regions comprising the K-line pictures. Thus, the effect could not be due to a general tendency for all regions to undergo coherent expansion in time, although it could be due to such a coherent expansion in McMath 11108.

FINAL CONCLUSIONS FROM THE MAGNETIC AND K LINE DATA

The conclusions which can be reached as a result of the statistical study of the lifetime and motion of the bright "vertex points" are:

1. The lifetime of the points is 3-4 days.
2. The points which retain their identity for at least 24 hours undergo a random walk with a R.M.S. displacement of less than 9000 km in 24 hours.

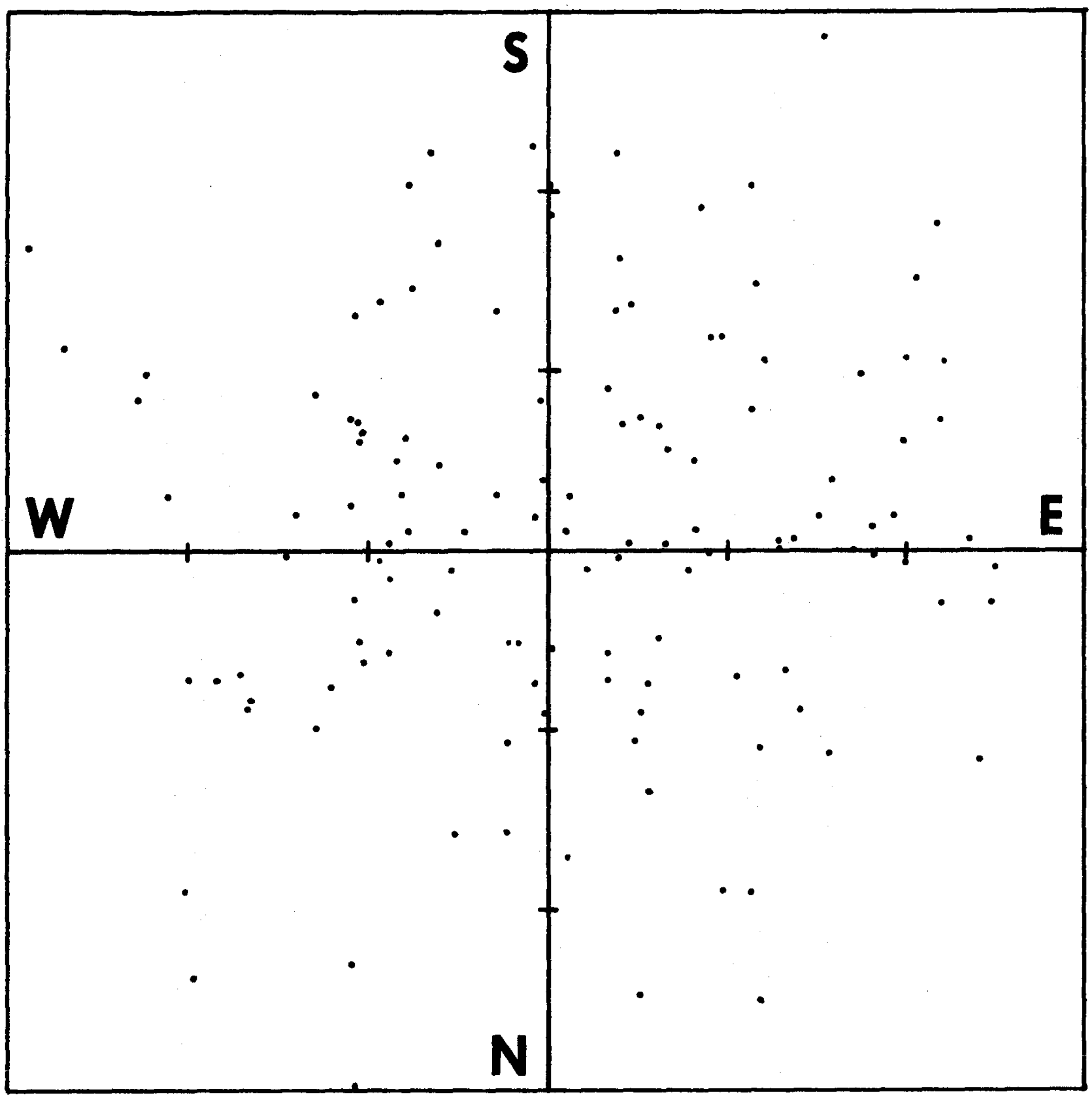


Figure 32. A scatter plot showing the motion of 132 K line points in 24 hours. Axes are marked at 5 km intervals.

3. Relative to the average location of all points in a certain region of interest, there is no definite indication of any systematic motion other than that due to the general expansion of a group of points characteristic of a random walk process. It should be kept in mind that differential rotation has been removed in this study.

It is possible to determine several things from these conclusions. The first is that displacement of the magnetic points (considered as entities which neither lose nor gain magnetic flux during their lifetime) is capable of causing the diffusion of magnetic flux through the motion of the points as units. The value of displacement measured (less than 9000 km per day) corresponds to a diffusion coefficient of less than 3000 km^2/sec. (This coefficient represents the rate of growth of the area of a magnetic region expanding only through the mechanism of the random diffusion of the points as discrete entities.) This dispersal rate is about 1/3 the rate previously observed for the expansion of magnetic regions. Measurements made by Babcock (1963) and Sheely (Leighton, 1964) indicate a dispersal rate of about 10,000 km^2/sec. Thus, we have a strong indication of the existence of some other diffusion mechanism.

The second conclusion which can be reached is that the close approximation of the scatter plots to those expected for a random walk indicates that the step time for the random walk process is short compared to 24 hours. Thus, the supergranulation convection currents are probably not directly responsible for the observed motion of the points, although fluctuations in the strength of the convection cell velocities on a time scale short compared to the lifetime of the cell itself may contribute to the displacement of the magnetic points. It seems possible that the granulation may be responsible for this motion. Again it should be stressed that this statement only applies to those points with lifetimes of at least 24 hours, since these were the only points for which displacements were measured.

Finally, we may conclude that a class of magnetic "vertex points" exists which has a lifetime long compared to the lifetime of the supergranulation cells. This means that these points are important considerations in the mechanism of flux transport in regions such as McMath 11108. The field cannot simply be assumed to be pushed around freely by the convection cells of the supergranulation network.

A SECOND KIND OF FLUX DIFFUSION IN THE ENHANCED MAGNETIC NETWORK

In addition to the quantitative measurements of the lifetime and motion of the magnetic points, there are two other qualitative observations which seemed to have a definite bearing on possible mechanisms of flux transport. First, when bright magnetic points appeared or disappeared, they seemed to do so simply by appearing or disappearing in place, rather than moving to a considerably different position. It might be argued that large motions might occur "overnight", but one thing which was definitely established by the time-lapse magnetic movies which were made using the videomagnetograph was that large-scale motions of magnetic structures over a period of several hours were quite rare.

The second important observation was that points usually appeared or disappeared "all at once", rather than by a gradual change in intensity over several days. This is a statement which can only be made relative to an impression of the average intensity of the points in the region of interest, since the overall signal strength was not well controlled from day to day. Nevertheless, the effect seems to be real.

The motion and lifetime analysis of the magnetic points suggests that a rough model can be constructed of the weak plage network in which the network is considered to be a checkerboard with long-lived and motionless (except for the random walk discussed in earlier sections). points of enhanced flux at the corners of some of the squares. Every so often one of the points disappears, or appears where no point had been seen before. It might be reasonable to look for a mechanism in which flux is passed from corner to corner in a relatively short (compared to 24 hours) period of time. Thus, a point could appear at a new location by the mechanism of the quick transport of flux from a neighboring point, or from several neighboring points where the field was too weak to be noticeable. The appearance of flux in place would not be interpreted as the appearance of new flux, but rather as the concentration of flux at that location by a process that was too quick to have much chance of being observed in a study with 24 hour time resolution. The disappearance of flux from a particular location would be explained in an analogous fashion.

With this rough model in mind, the daily surveys were re-examined to see if any evidence could be found for the existence of such a phenomenon. Almost immediately, the pictures shown in Figure 33 were found. Figure 33B shows a region of the sun with two magnetic points

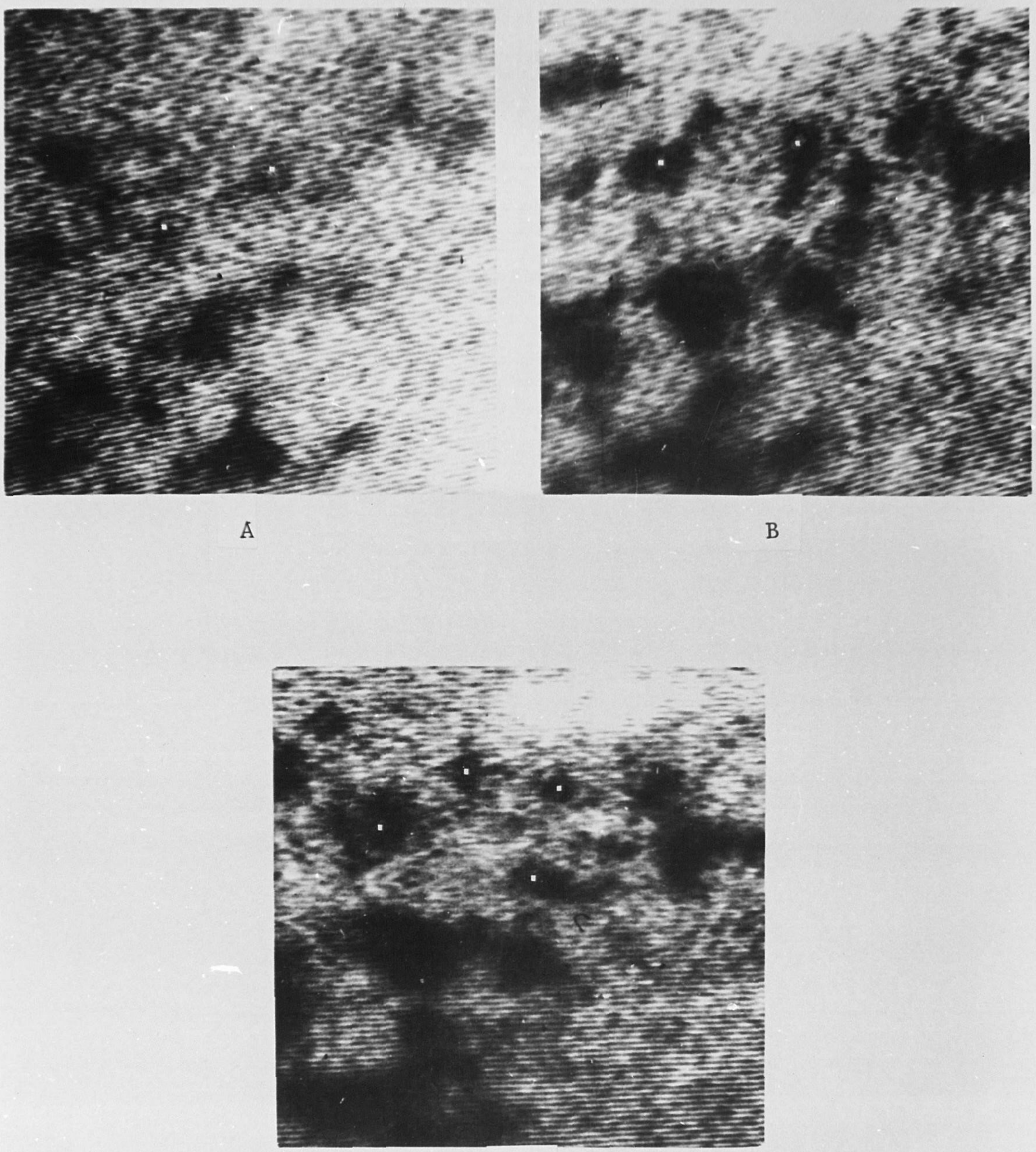


Figure 33. A: original points. B: points with flux tongues. C: double points.

with a tongue of flux extending out from them. Figure 33A shows the same region on the previous day, and Figure 33C on the following day. Apparently, the two points have shot out a tongue of flux, and were caught by the magnetogram in Figure 33B as they did so. After the tongue had extended out from the points, the original points became much dimmer, and in one case, a new flux point appeared where none had been before, but at the location to which the tongue of flux had extended the day before. In the other case, a point of flux already in existence at the end of the flux tongue grew considerably brighter.

Several time-lapse videomagnetogram movies made by Dr. S. Schoolman at Big Bear Observatory were examined for more examples of these "squirting vertices", and more examples were found. One particularly nice example is shown in Figure 34. Unfortunately the videomagnetograph has not yet been operated for a long enough period of time to have accumulated very many good movies. More movies should become available during the summer of 1971, and hopefully some statistical analysis of this phenomenon will be possible. Until such an analysis is made, it is impossible to say just how important the phenomenon is as a means of flux transport, but it seems possible that this phenomenon may be responsible for much of the flux transport that occurs in enhanced network regions of the sun.

One speculation as to the mechanism behind the phenomenon of the "squirting vertices" is that the long-lived vertex points "channel" the supergranulation cells so that they appear always in the same places, centered in the squares of the "checker-board". These cells do, however, appear and disappear with a characteristic lifetime of about

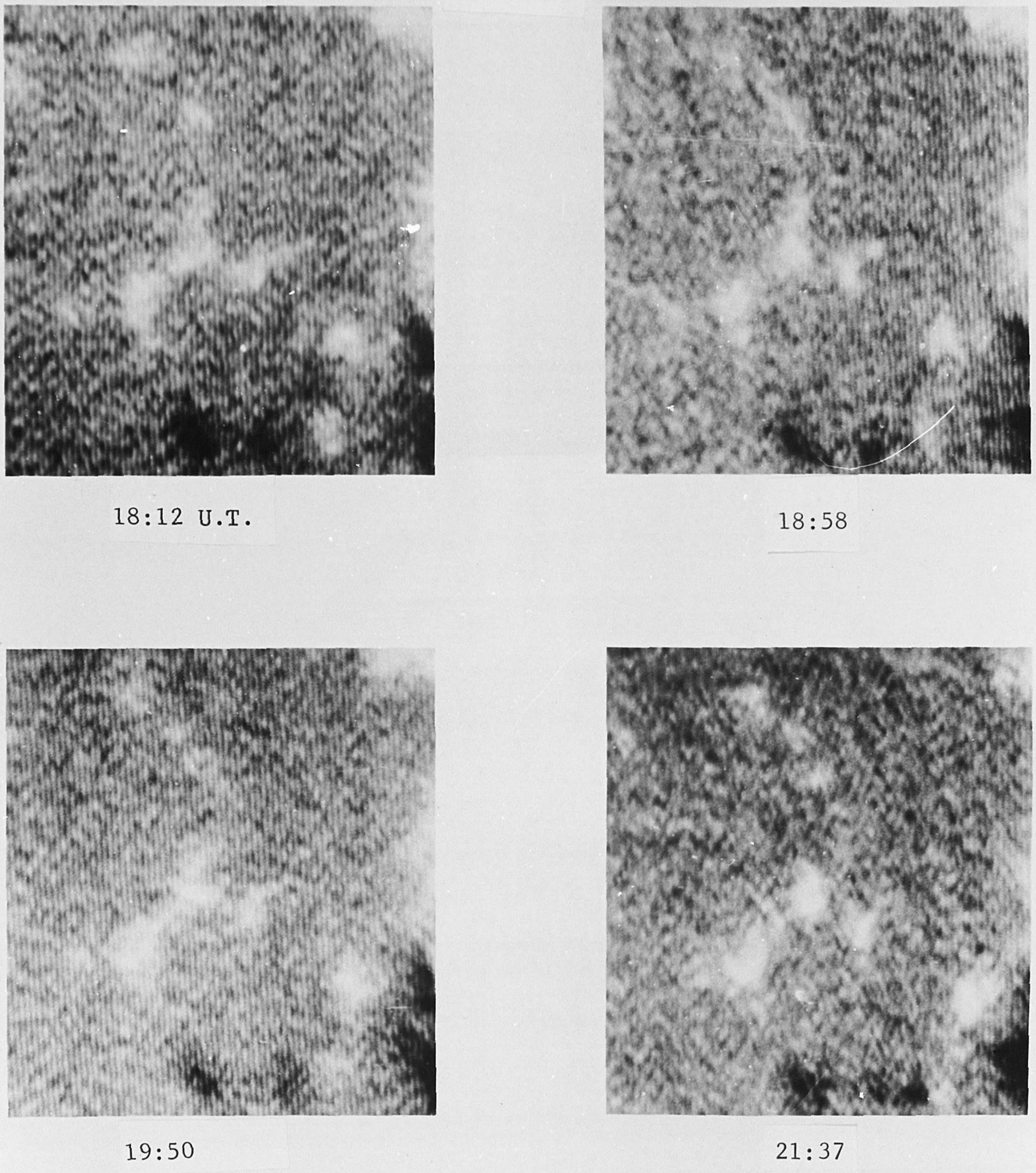


Figure 34. The point at the top center extends a tongue of flux and forms another point just above it. The process takes less than 2 hrs. The point at the left moves to the right and is absorbed into the large, bright spot to its right. The process takes about 3-1/2 hrs.

20 hours. Occasionally, the convection currents in two adjacent squares of the "checkerboard" will die out together, making the points at their common corners unstable, and causing any field concentrated there to squirt out to a new location. Figure 35 shows the proposed mechanism diagrammatically. It should be emphasized that considerably more work must be done, particularly in the area of comparing high resolution time-lapse magnetic movies with simultaneous doppler movies, before this mechanism can be considered to be much more than speculation. The "squirting vertices" do occur, but since so little is known about them at this time, any mechanism purporting to explain them, including the present one, is primarily useful as a guide to future experiments.

It seems likely that the "squirting vertices" may not always occur in so explicit a form. For example, one of the two events shown in Figure 34 involves the rapid motion of an entire weak vertex, rather than an extension of an elongated tongue of flux from the original vertex. Other forms of flux motion less easily categorized can be seen in the movies. The more complete understanding of the precise forms flux transport can take will have to await more and better time-lapse movies.

In the few cases which have been studied, the flux tongues seem to move with a velocity of about 1 or 2 km per second. The studies of this motion are not as yet sufficient to say more than this.

To summarize, the magnetic field in weak plages can be considered as a network of relatively stationary points of flux, with lifetimes of 3-4 days. These points move as units in a random walk which has a characteristic step time which is short compared to 24 hours. This

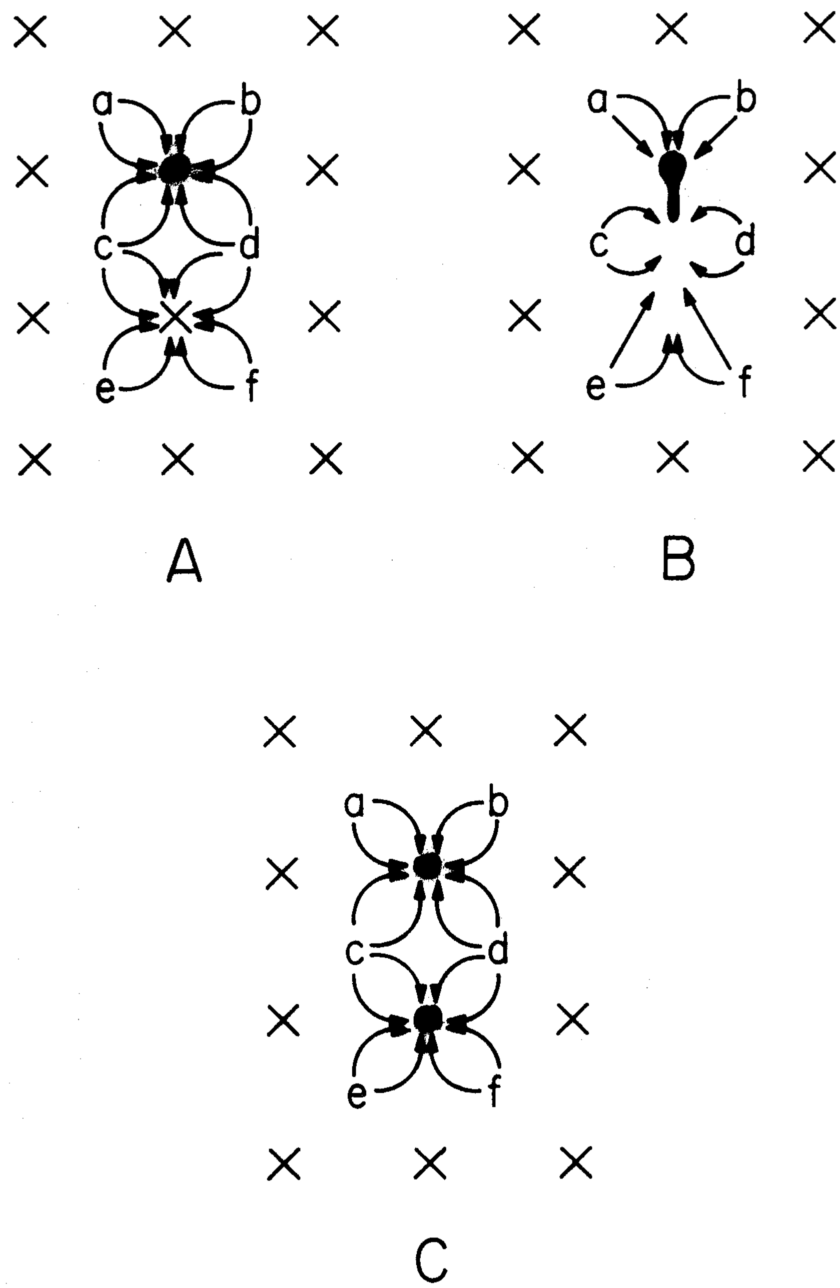


Figure 35. In (A), magnetic flux is trapped at the vertex of a,b,c, and d. In (B), c and d have weakened, allowing flux to flow toward e and f. In (C), a vertex point is established at a new location, as c and d become stronger again.

random walk is not, however, the major form of flux diffusion. Probably, most of the diffusion takes place in the form of sudden squirts of flux from one point to another. The magnetic field does not usually diffuse by slow "oozing" from one point to another, but rather by discrete jumps which transport flux over distances of the order of 10,000 to 20,000 km in times of one or two hours.

FUTURE STUDIES

Plans are currently being made to make simultaneous time-lapse magnetic and K-line movies in a program using both the Big Bear solar spar and the Mt. Wilson 60 foot tower. It is hoped that the combination of the two techniques of observation will give considerable information regarding the detailed structure of the solar magnetic field. The K-line movies will give some indication of the total magnetic field strength, and the magnetograms of the radial component. Together, they will enable information to be obtained concerning the vector field. Also, the K-line pictures will be less susceptible to geometric distortion, and it is hoped that point positions can be followed in an absolute sense, rather than relative to the geometric mean position of the magnetic region.

Most of the improvements in calibration techniques mentioned in this thesis will have been incorporated into the videomagnetograph, and this should enable direct measurement of the relative, if not the absolute, strengths of the magnetic fields on a day-to-day basis.

In addition to running daily K line/magnetograph comparisons, it is also planned to make simultaneous doppler and magnetic measurements.

These should be particularly interesting, since they will allow the comparison of the motions of magnetic flux and the local velocity field. These measurements should provide considerable insight into the mechanisms behind flux diffusion on the sun.

The Doppler measurements may be made alternately with the magnetic pictures by taking advantage of the KDP plate as a half-wave plate to switch the filter from one side of the line to the other. If this scheme does not prove practical, the Doppler movies will be made at Mt. Wilson, using the camera developed by Alan Title (1966), and the cancellation machine developed by Phillip Roberts (1970).

This program should be continued for at least the next year or two, and should provide a considerable amount of information regarding the magnetic field of the sun. The measurements will, of course, not be confined to the study of fields in weak plage regions. The video-magnetograph is particularly useful in the study of rapidly changing fields, such as may be associated with solar flares. The program will cover a wide range of magnetic events, and will be aimed at the discovery of new phenomena as well as the study of known ones.

Continuing observations of this type should be made over an entire solar cycle, or several cycles. It is quite possible that the detailed processes which are thus observed will change only in quantity, and not in quality as the solar cycle progresses, but any changes which do occur could be of significance as a direct indication of which properties of the solar field are most affected by the solar cycle, and this in turn may permit a better understanding of the solar cycle itself.

APPENDIX I - CIRCUIT OPERATION

Automatic Controller

Figure A1 shows a block diagram of the automatic controller. (See also Figure 9.) The main feature of the controller is two panels containing a number of pin jacks. These jacks are interconnected with patchcords to form a program. The larger of the two panels is the "logic panel", where most of the wiring necessary to form the logic of a program is done. The smaller panel is the "I/O panel", which contains terminals for connecting the logic circuitry to the output amplifiers for the purpose of driving external equipment. The I/O panel also contains terminals allowing signals to be fed into the logic circuitry from external equipment, as well as a set of terminals for buffer amplifiers used in programming, and terminals allowing start pulses to be fed to the logic circuitry. (See Appendix III for a detailed discussion of the uses of these terminals.) The circuit cards containing the logical elements necessary for a particular program are plugged into the back of the logic panel into a set of sixteen 16-pin Vector sockets.

Input and output to external circuitry runs from the I/O panel to a set of screw terminals on the rear panel. Inputs from external equipment are not buffered. Twenty five indicator lights are provided, one for each output amplifier. They are mounted in a separate box and are connected to the controller through a cable which plugs into a socket on the back panel.

The 60 Hz clock, which synchronizes the automatic controller with the disc, is brought in through a BNC connector on the back of the chassis.

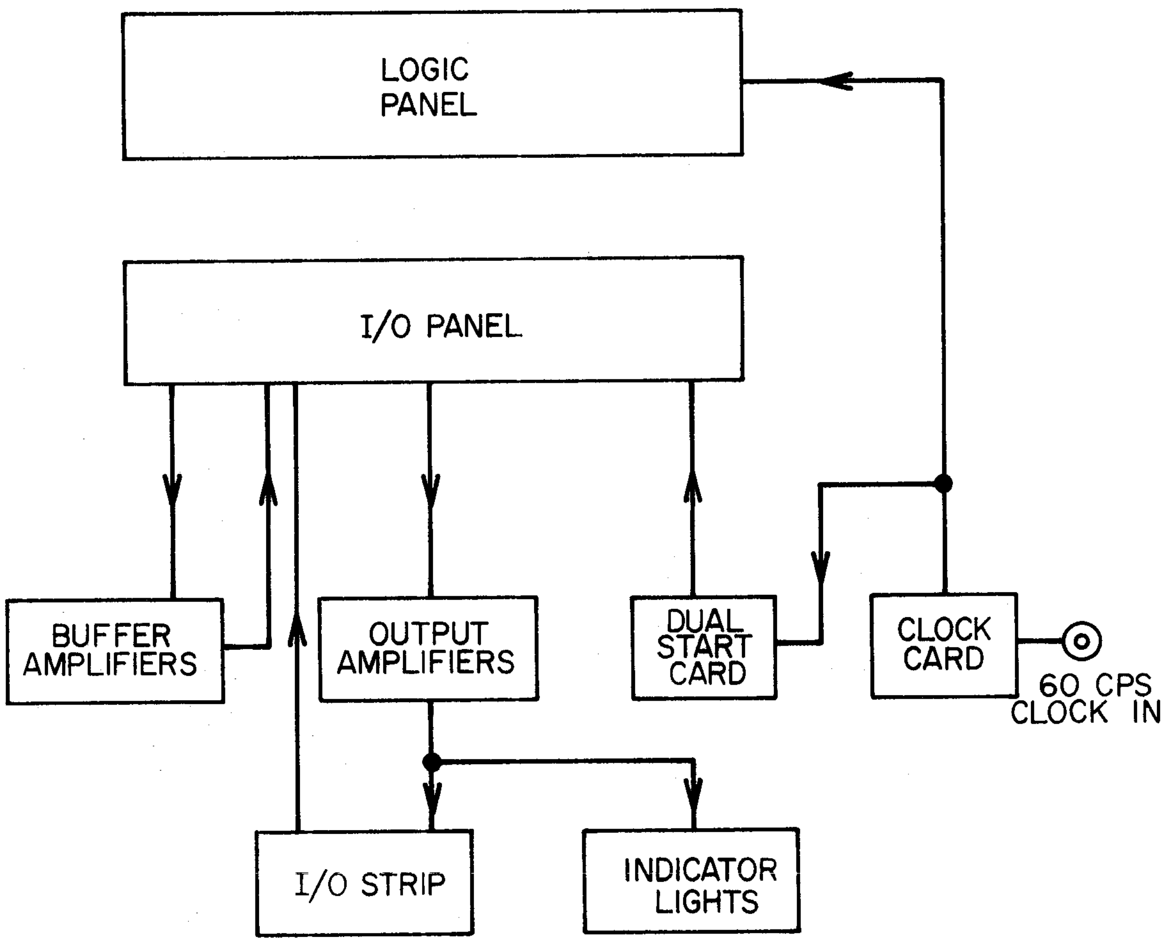


Figure A1. A block diagram of the automatic controller.

Near the BNC connector is a switch which permits the clock signal to be either a standard 0 to +4 volt TTL logic signal, or a 0 to -4 volt television vertical drive signal. The system normally uses a TTL level 60 Hz clock signal produced by the sync interface. A second switch on the back of the chassis allows the selection of either 75 ohm termination or high input impedance if the clock is derived from a television vertical drive signal. The 60 Hz clock is fed to a "clock card", the output of which is connected to a dual "start card" used for generating "start" pulses in synchronism with the clock (see Appendix III). The clock card produces a 30 Hz clock from the system 60 Hz clock. The 30 Hz clock is necessary in order to operate the disc recorder in synchronism with the video frame rate, which is 30 Hz, or half the vertical drive frequency. The clock card also provides the logic necessary to allow the clock to be interrupted and single-stepped, while making sure that the 30 Hz clock does not lose its original phase relationship with the disc. The 30 Hz clock is fed to the logic cards, and accordingly all switching is accomplished at a rate of 30 Hz.

Detailed schematics for all of the circuitry are available in a separate videomagnetograph manual, and will not be repeated here. They should be referred to in case any trouble shooting is required.

Wiring on the Main Chasis

The logic panel is divided into 16 columns of pin jacks, each column consisting of 14 rows of 4 jacks. The four jacks in each row are completely equivalent (they are wired together). The four jacks are merely for convenience in providing multiple tie points for patchcord wiring.

Each column corresponds to a sixteen pin logic card socket mounted on the back of the logic panel. Only 14 of the 16 pins on the socket are wired to the front panel, the other two pins being the power supply and ground connections.

The fourth row of socket pins from the top has the 30 Hz clock permanently wired to it. The clock is available at any of these pins in any column for use in programming. The third row of pins from the top is connected to the clear line through a diode. Pushing the "clear" button places a high voltage (+3.6 v.) on the clear pins of each column. This voltage is used to initialize the state of the logic circuits on all the cards in the program at once. The diodes permit resetting an individual card under program control without affecting other cards in the program.

The output amplifiers consist of two low power inverters in series, to provide a lower load for the logic circuits, followed by a high power driver amplifier to operate external circuits. The driver amplifiers are mounted in sockets to allow easy replacement. The input of each output amplifier is connected to a block of 10 pin jacks on the I/O panel. The 10 jacks are wired together and are completely equivalent. The multiple jacks are only for convenience in wiring. There are 25 blocks of jacks corresponding to the 25 outputs on the rear panel. The output of each driver amplifier is connected to a single screw terminal on the rear panel, where external equipment may be connected. Output voltages are RTL compatible (0 to 1 vdc.).

Each output amplifier is also connected to a multi-pin socket on the rear panel, which is in turn connected through a 25 twisted pair cable to a separate chassis which contains an indicator light for each amplifier. A light is on when the output of the amplifier to which it is connected is high. It is necessary to use twisted leads in the cable to avoid cross-talk between the outputs. The indicator lights are driven by simple one-transister amplifiers. The lights are powered by a simple unfiltered 12 vdc power supply contained on the indicator chassis.

The I/O panel also contains eight double rows of 4 jacks each, located just behind the output blocks. Each row of four jacks is wired together. These are inputs and outputs to buffer amplifiers. Each buffer amplifier has the capability of driving 80 low power logic gates. The row of jacks nearest the front of the controller is the output, and the row nearest the logic panel is the input. As before, the multiple jacks are for convenience in wiring only. These buffer amplifiers are further described in Appendix III.

There are five input jacks on the far right of the I/O panel. Each of these is wired directly to a screw terminal on the rear panel.

On the left of the I/O panel there are two jacks from which single pulses in sync with the 30 Hz clock may be obtained for the purpose of starting a program sequence. A single pulse is generated here by pushing either the "start A" or the "start B" button on the front panel. There is one jack for each button. The operation of these controls is governed by the clock card and the start card. Two other controls which are involved with this circuitry are the "interrupt switch" and the "single step button".

The 60 Hz clock is fed through a voltage adjusting network which serves to interface either TTL logic or video vertical drive with the RTL logic of the controller. The output from this network is then fed to a simple J-K flip-flop which performs a division by two to produce a 30 Hz square wave. The square wave is fed to a one-shot which produces a string of clock pulses about half as long as the television vertical retrace interval. Since the logic cards make transitions on the falling edge of the clock pulses, this insures that any switching transients will occur in the middle of the vertical retrace interval, and thus will not appear on recorded pictures.

Throwing the interrupt switch causes an inhibiting voltage to appear on the "clock one-shot", unless the one-shot output is high. This manner of gating the clock insures that the divider flip-flop does not lose its phase relation with the 60 Hz clock, and also means that if the interrupt switch is thrown while a clock pulse is being generated, the pulse is allowed to complete normally, rather than being cut off instantly. This means that the falling edge of the pulse occurs after the proper timing interval.

The output of the clock one-shot is fed to the logic cards through a high power buffer amplifier. A second J-K flip-flop is slaved to the divider flip-flop in such a way that it can only flip from a low to a high output state in phase with the divider flip-flop. Its J-K inputs are controlled by a set-reset flip-flop which is set by pushing the single-step button. Pushing the button causes the J-K flip-flop to make a single low-high transition on the next rising edge of the divider output. The flip-flop remains high until the button is released, then, on the next rising edge of the divider output, drops low and remains there until the button is pressed again. The output of the flip-flop is fed to a one-shot, the output of which is run through an OR gate with the regular clock to the clock output buffer. Thus, single clock pulses can be generated when the clock is in the interrupted state.

The 30 Hz clock is fed to a pair of J-K flip-flops with their J-K input levels controlled by the "start" buttons. The outputs of the flip-flops go through one-shots to the start jacks on the I/O panel. When a start button is pressed, the next falling edge of the 30 Hz clock triggers a flip-flop output change from low to high, which in turn generates a pulse from the one-shot with the pulse rising edge virtually simultaneous with the falling edge of the 30 Hz clock. Since a start pulse to a logic card activates the first output on the rising edge of the pulse, this configuration allows proper timing of start pulses, so that they coincide with logic card transitions (which occur on the falling edge of the 30 Hz clock). This matter is discussed in more detail in the sections on the logic cards.

The Logic Cards

The Sequence Card

A sequence card is basically a 9 bit shift register with appropriate control gating. A high voltage level on the reset input sets all the outputs of the shift register flip-flops to zero. An incoming "start" pulse is sent directly to a one-shot, the output of which is a pulse short compared to the clock period. The one-shot pulse simultaneously sets the set-reset flip-flop which is the first in the shift register chain, and sends a reset pulse to the set-reset flip-flop which controls the clock gate. This action turns on the first output of the sequence card, and allows subsequent clock pulses to reach the triggers of the shift register. At the next clock pulse, the second output of the shift register goes high, simultaneously turning off the first output by resetting the set-reset flip-flop which controls the first output. Subsequent clock pulses cause the high level to propagate down the shift register in the usual manner. Since each J-K flip-flop merely copies the value on the flip-flop preceding it, the high level will disappear on the next clock pulse after it reaches the ninth output. No further high levels will appear in the shift register unless another is placed on the first flip-flop by another start pulse. It is not necessary to make any provision for turning off the clock gate to prevent other high levels from appearing.

The main operating characteristic to remember about the sequence card is that the first output goes high immediately on receiving a high level on the start input. Thus, if the first output is to control anything that is to be synchronous with the clock falling edge, the source of the start level must be separately synchronized. This synchronization is automatic if the source of the start pulse is a sequence card. The synchronization is also provided for the start buttons. However, the asynchronous nature of the start input must be remembered when starting a card with pulses from external equipment.

The clock gate can be turned off by setting the set-reset flip-flop controlling it. This is set by placing a high level on the input of a "pause" one-shot. When this is done the clock gate blocks the clock pulses until a pulse is received at the reset input. The reset pulse can come either from the start input, where it merely insures that the gate is open, or from the continue input. The pause inputs are normally fed from one of the sequence card's own outputs by means of a patchcord between jacks located on the card itself. There is one jack for each output and three for each pause input.

If the pause inputs are not actuated, the sequence card merely turns on its outputs one after another in sequence as the high level propagates down the shift register. If an output is wired to a pause terminal, however, the clock is blocked when that output is reached, and the shift register remains in that state ("pauses") until the clock is unblocked. Since a one-shot must be triggered by a low-high transition, a single one-shot wired to two adjacent outputs would not cause a pause at the second, since it would see only a continuous high level. Therefore two pause one-shots are provided. If two or more outputs in sequence are to be paused they must be wired alternately to the two one-shots. The pause one-shots are timed to produce a slightly longer pulse than the start one-shot. This allows pausing at the first output. The start one-shot and the pause one-shot are actuated virtually together in this condition, and the longer pause pulse insures that the set input on the clock gate will still be on when the reset input goes low. Thus the clock is blocked and the card is placed in a paused condition.

A one-shot is provided on the card with its input wired to a pin jack on the card itself, and its output wired to the "end" terminal on the p.c. board. This can be used to provide a control pulse at any point in a sequence by wiring one or more of the outputs to the one-shot. (Adjacent outputs cannot be wired to the end one-shot for the same reason that they cannot be wired to a single pause one-shot.) The "end" output provides a pulse rather than a level output, should that be useful in driving external equipment.

<u>The Loop Card</u>

A loop card is basically an eight bit binary counter with appropriate control logic and a means to detect any desired total on the counter.

A reset pulse sent to a loop card turns off the "actuate" output gate and inhibits the count input one-shot. An input to the "start" one-shot resets the counter to zero, removes the inhibit from the count input, opens the actuate gate, and sends out an actuate level, the rising edge of which is in coincidence with the rising edge of the start input. Like the sequence card start, the loop card start is asynchronous.

After the loop card has been started, an input to the count one-shot causes a set-reset flip-flop to be set to a high level. This causes the actuate output (which in the meantime has remained high) to drop to zero. The next clock pulse causes the set-reset flip-flop to reset to a zero output. Since the output of the flip-flop is connected to the counter string, the counter string advances one count on the falling edge thus generated. At the same time, the actuate rises to high level, thus triggering a start pulse in the card under control. The count one-shot produces a longer pulse than the clock one-shot, so that if the count input comes simultaneously with a clock falling edge (as is always the case if the count input comes from a sequence card) the count pulse will override the pulse from the clock one-shot. The clock is fed to the clock one-shot through an inverter so that the one-shot triggers on the falling edge of the clock pulses.

The number of cycles the controlled section of the program is to repeat (minus one) is set by placing jumper wires across appropriate pairs of jacks located on the card. When the number set (in binary) on the card is reached, the output of the sense gates goes from low to high. This happens on the next clock pulse, at the same time that the actuate output goes high. Thus the controlled circuit receives one more actuate pulse. When the output of the sense gates goes high, the counter string is inhibited from responding to further count pulses, the actuate output is temporarily locked high, and the inhibit is removed from the end one-shot. When the final count pulse is received from the card under control, the pulse from the count one-shot is fed immediately to the end one-shot, which is no longer inhibited. An end pulse is thus produced simultaneously with the final count pulse. The end pulse is fed to the front panel through the end terminal, and also resets the loop card.

The Multi-length Pause Card

This card contains an eight bit binary up counter and eight exclusive OR gates. The OR gates each have one input connected to one of the counter outputs, and the other input connected to a terminal on the front panel. When the binary number reached by the counter matches the number wired to the terminals on the front panel, the output of the two sense gates wired to the OR gates goes from low to high. The counter trigger is connected to the clock. When an input is applied to the reset input, or when the sense output goes high, a set-reset flip-flop is set to a high level. The output from the set-reset flip-flop resets the counter string and inhibits it from responding to the clock pulses. The low-high transition in the flip-flop output actuates the output one-shot. When a low-high transition occurs on one of the two inputs, the set-reset flip-flop is reset and the counter begins to count on the next clock pulse. (The two inputs must be actuated alternately if they are actuated from two sequential outputs. Otherwise no low-high transition will appear.) When the number patched in from the outside is reached by the counter, the flip-flop is set and a pulse appears on the two outputs. Two outputs are brought out to the front panel, purely for convenience in wiring. The function of the multi-length pause card is to put out a pulse a fixed number of clock pulses after it is actuated. If a sequence card is to be paused for N steps, the number N-1 must be patched into the multi-length pause card. This is because a sequence card continues on the next clock pulse after a continue pulse is received.

The Variable Address Card

This card has one input and eight outputs. The outputs are gated by a BCD-to-DEC decoder according to a binary code patched in from the front panel. When the binary code for a particular output is patched into the card, whatever goes into the input comes out the output selected, and only that output. The card can be thought of as a programmable single pole, eight throw switch.

The Patchcords

Each patchcord has a diode wired in it to allow several logic outputs to drive a single input. This provides a "wired OR" logical function.

The Manual Controller

The block diagram in Figure A2 shows the manual controller. The primary function of the manual controller is to provide control signals in the proper form to match the control logic built into the disc recorder. Therefore the design of the manual controller is largely dictated by the particular disc unit it is to operate, in this case the Data Disc 1800 R.P.M. video disc file.

The system 60 Hz clock is fed to the manual controller from the sync interface. The system clock drives the "clock and manual write circuit". In this circuit the 60 Hz clock is divided by two by a flip-flop. The 30 Hz square wave from the flip-flop is fed to a one-shot with a pulse length of about 500 microseconds, which produces a train of 30 Hz clock pulses with their falling edges well inside the vertical retrace interval. The 60 Hz clock is also passed through two isolation inverters after which it is available for use by other circuits in the manual controller. The 30 Hz clock is also available to other circuitry.

The 30 Hz clock drives a second J-K flip-flop. The J and K inputs of this flip-flop are controlled by a set-reset flip-flop. The set-reset is set by pushing the "write" button on the front panel of the manual controller. The write button is wired in a "perfect switch" configuration. The output of the perfect switch is connected to a one-shot, and the one-shot pulse (much shorter than the clock period) sets the flip-flop. Thus, after the write button is pushed, it must be released and pushed again to have any further effect on the set-reset.

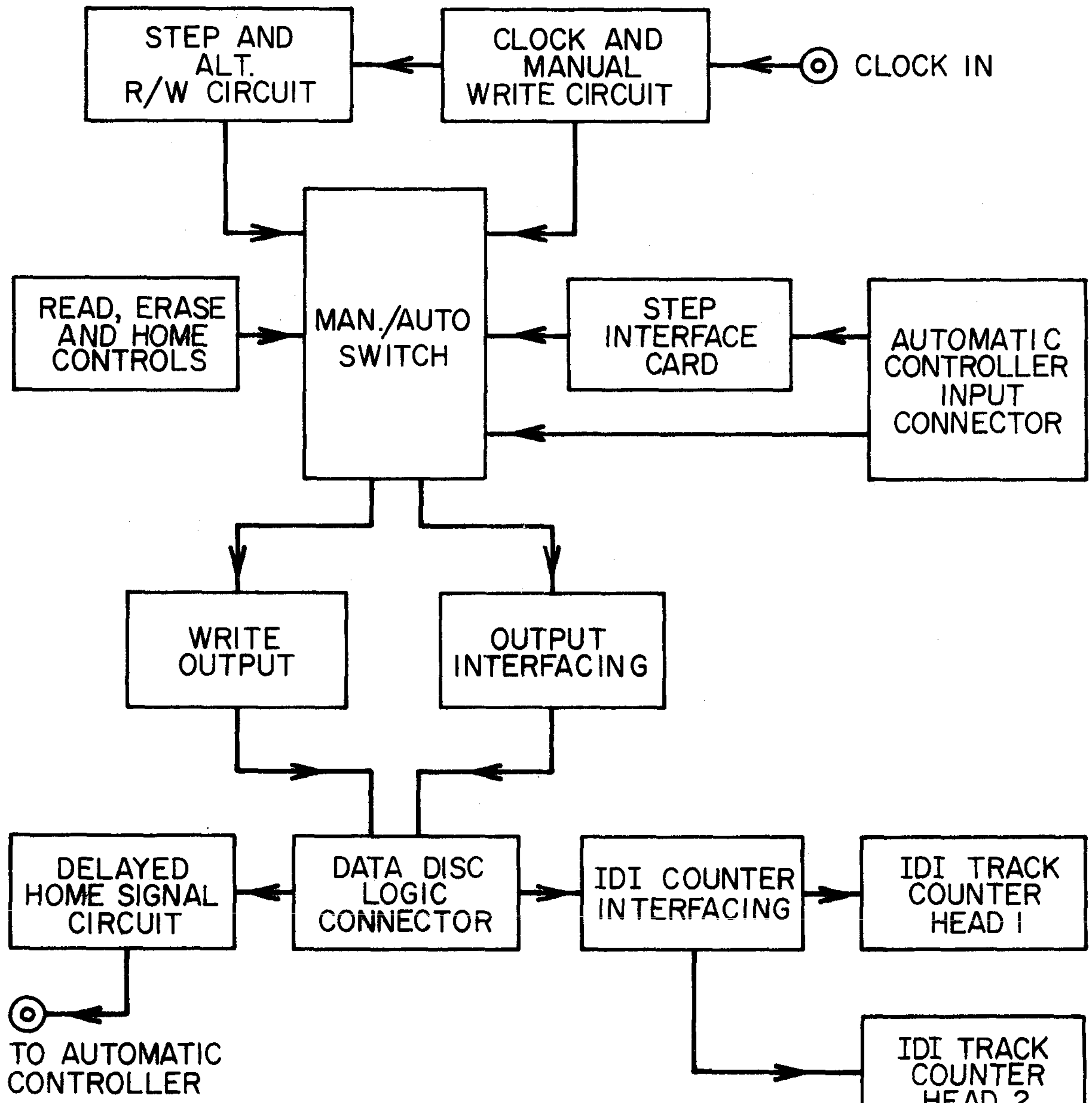


Figure A2. A block diagram of the manual controller.

When the set-reset has been set, the J input on the J-K flip-flop is set high, and the Q output is triggered high on the next clock pulse. The $\bar{Q}$ output simultaneously drops low, and since the $\bar{Q}$ is connected to the reset input on the set-reset flip-flop controlling the J input, the J input drops low. The next clock pulse triggers Q low, and subsequent clock pulses have no further effect unless the set-reset is set again by pushing the write button.

The Q output is thus high only between the next two clock pulses immediately following the time the write button is pressed. The Q output is fed through a diode to the "write select" switch, which allows it to be sent to the write command input on the data disc for any one of the four video heads. The write select switch also has an "off" position.

The "read, erase, and home circuit" is the simplest part of the manual controller. The disc control logic merely requires a high (+5 vdc.) level on the appropriate command line to perform each of these functions. The two "video output" switches on the front panel merely switch the power supply to whichever command line is selected. There are two command lines for each demod in the disc recorder, and each switch controls one demod, allowing it to read from either of two video heads.

The "erase" buttons (one for each movable head) also just connect the 5 volt power supply to the appropriate command line. They should not be held down too long, since the erase coils on the video heads will burn out after several seconds of continuous erasure.

The "home" buttons, one for each movable head, place a high level on the appropriate command line when pressed. To avoid transients on the command line, which seems to be sensitive to them, the home buttons are wired with set-reset flip-flops in a perfect switch configuration.

The "step and alternate read/write circuit" is primarily a nine stage divider chain. The divider chain is driven by the 60 Hz clock. The clock drives a J-K flip-flop, which is gated by the "step" button. The step button is wired in a perfect switch configuration. The output of the first J-K flip-flop in the divider string drives a 500 microsecond one-shot, which in turn drives the other flip-flops in the string. The one-shot insures that the timing of the step commands will occur in the middle of the vertical retrace interval. The Q and $\overline{Q}$ outputs of any flip-flop in the divider string may be selected by the "step rate" switch. This allows a step rate of anywhere from 30 to 1/8 steps per second to be selected. The Q and $\overline{Q}$ signals are fed to the "step 1" and "step 2" switches, respectively. These switches serve to pass the step signals to one or both of the two movable heads. The square wave step signals from the step switches are connected to two one-shots which produce the required 1 microsecond pulses for the disc recorder command lines. The one-shots are inhibited when the step button is not pressed. The one-shot controlling movable head 1 is driven by the Q signal, and the one-shot controlling head 2 is driven by $\overline{Q}$. This means that the two heads are stepped alternately. The only exception to this is at the 30 step per second rate. The step signal is taken from the 500 microsecond one-shot in this case, and the two heads step virtually together.

The two 1-microsecond one-shots are connected to the disc command lines through switches which select the proper command line for stepping the respective heads in or out.

One of the positions of the step rate switch selects the single step mode. The signal selected in this case comes from a J-K flip-flop which has its J-K inputs controlled by the perfect switch of the step button. It provides a single transition on the next clock pulse after the step button is pressed. If the step switches are set so as to allow signals to pass to both heads, the two heads will step simultaneously, since both heads are driven from the Q output of the flip-flop.

The square wave output from the divider string is fed to two set-reset flip-flops which are connected to the Q and $\overline{Q}$ output line beyond the step switches. One of these flip-flops is set by Q, and reset by $\overline{Q}$. The other flip-flop is connected in the opposite manner. The outputs of the flip-flops are fed through an "alternate function enable" switch (DPST) and then to a DPDT switch which selects either the read or the write command lines for the movable heads. The set-reset flip-flops are phased with the step output one shots so that when the alternate function enable switch is closed and the step button is pressed, the controller steps the two heads alternately, while simultaneously reading or writing on the head not being stepped. This mode of operation is usually used with a step rate of 15 steps per second per head, so that up to 10 seconds of live video can be written on the disc.

The manual/auto switch is a 16 pole, double throw switch which selects either the control signals from the manual controller logic or the automatic controller, and passes them on to the output interfacing, and thence to the disc recorder.

The signals from the automatic controller reach the manual/auto switch through an eighteen pin connector on the back of the manual controller. Most of these are simply connected directly to the manual/auto switch. The only exceptions are the leads controlling the stepping of the movable heads. The outputs from the automatic controller are level outputs, but the step command lines require a pulse each time the head is to be stepped one track. The standard way of automatically stepping a head over several tracks is to turn on the appropriate output of the automatic controller for the same number of clock pulses as there are steps to be made. This means that circuitry must be provided to generate one step pulse for each clock pulse that occurs while the output of the automatic controller is held high. The step pulses must be generated in synchronism with the 30 Hz clock of the <u>automatic</u> controller, which is brought in through the eighteen pin connector for the purpose. The clock is run through a pulse delay circuit to bring its rising edge into the middle of the vertical retrace interval, and then run to four AND gates, one controlled by each of the step lines from the automatic controller. If one of these lines is held high, the delayed clock pulses will be allowed to pass through the AND gate controlled by the line. The outputs of the four AND gates are connected to the appropriate disc command lines through the manual/auto switch.

From the manual/auto switch, commands generated either by the manual controller or by the automatic controller are sent to interfacing amplifiers designed to provide the proper waveforms to drive the disc recorder logic. Most of these are simple RTL two stage pulse amplifiers using 2N3565 transistors. The interface amplifiers are run from a 5 volt power supply, and the output collector resistor is 300 ohms. The step pulses required to drive the Data Disc logic must have faster rise times than can be generated by the 2N3565 transistor final stages. Accordingly, the final stages of the step pulse amplifiers are Signetics N8481A inverters, used with an external 330 ohm collector resistor.

The disc recorder logic requires two signals to write on a video head. One of these is the "head select" command, and the other is the "write video" command. The disc command lines selecting the head to be written on are simply interfaced through a standard interface amplifier of the type described above. The "write video" command line is driven by a 5 volt RTL OR gate with one input in common with each of the four head select amplifiers. This configuration makes it unnecessary to generate a separate "write video" command in either the manual or automatic controller.

The track position of the two movable heads is monitored by two IDI up/down counters with Nixie tube readouts. A counter is set to "one" when a "homing" signal is received from the disc logic, indicating that the movable head is being moved to the outermost track. Thereafter, the counter simply keeps a running count of the step pulses sent to the movable head, counting up one when a pulse is sent over the "step in" command line, and down one when a pulse is sent over the "step out" command line.

Since the counter as supplied by IDI will not accept up and down pulses from two separate lines, some interface circuitry is required. This circuitry changes the input to the counter to pulses coming into the counter on a single line (they are simply ORed together) and a level on a count direction input that indicates whether a given pulse is to be counted as an "up" or "down" count. The count direction level is set by a set-reset flip-flop which is switched one way or the other by the pulses coming in on the two lines. Since the count direction level must be switched before the pulse to be counted reaches the counter, the output of the OR gate is sent through a delay circuit before being fed to the IDI counter.

The disc logic provides "in limit" and "out limit" signals to indicate when a movable head has been stepped as far as it will go in a particular direction. These signals are used to gate the pulses to the counter, so that it stops counting when the head reaches its limit.

The disc logic also provides a "home" signal for each movable head, which is on whenever the head is at its outermost position. These home signals from the two heads are run through an AND gate and a pulse delay circuit. The output of the pulse delay circuit is a one-shot pulse which is wired to one of the inputs on the automatic controller. It is used to inform the automatic controller that both heads of the disc are at track 1. This signal is usually used to cause a program to continue after waiting for the disc recorder heads to home, a process which takes a variable amount of time, depending on the position of the heads when the home command was given.

Controller Power Supplies

The automatic controller requires 3.6 volts at 8 amperes. The voltage is supplied by a standard 6.3 volt filament transformer driving a full-wave bridge, a capacitor input L-C filter, and a shunt regulator.

The manual controller requires 3.6 volts for RTL logic, 5.0 volts for TTL logic, and 200 volts for the Nixie tubes. The 3.6 volts is taken from the automatic controller supply. The other voltages are taken from a commercial power supply built by IDI.

The Sync Interface

The clock tracks on the disc have a 31500 Hz square wave recorded on one track, and a 30 Hz "once around" pulse recorded on the other. The format of the "once around" pulse is required for the proper operation of the disc line sync circuits, but unfortunately the 30 Hz frequency is too low for generating the 60 Hz vertical drive required by the television camera. The video sync and blanking signals required by the television cameras can be generated by the plug-in sync generator cards supplied by Philips with the television cameras. The Philips circuitry must be slaved to the disc to be used with the disc recorder. This is accomplished by modifying the Philips sync generator so that the generator can either run from its own clock, or from waveforms derived from the disc clock tracks.

To maintain proper phase relationships between the camera sweep circuits and the recorded picture on the disc, it is necessary to synchronize the vertical sweep drive with the once-around pulse, and to synchronize the horizontal sweep with the disc 31500 Hz clock track. The Philips sync generator requires a 31500 Hz 0 to -11 volt square wave, and a 60 Hz 0 to -11 volt clock with negative pulses 128 microseconds wide.

The 31500 Hz clock from the disc is sent directly to a two-stage capacitor coupled amplifier that converts the clock from TTL levels to the voltage range required by the sync generator. The 31500 Hz clock is also sent to a string of J-K flip-flops gated as a 525 divider. The divider output is sent to a one-shot, which produces the required 128 microsecond pulses. The resulting 60 Hz signal is sent through a voltage conversion amplifier identical to the one just described, and on to the sync generator. The 60 Hz signal is also run through a pulse power amplifier, and then used to synchronize the controllers with the disc. This signal is referred to elsewhere in this thesis as the "60 Hz clock".

The once-around pulse from the disc is ORed with the internally generated reset pulse of the 525 divider. Thus the divider is automatically slaved to the disc once-around pulse, since the string is reset with each pulse from the disc.

Subtraction, Averaging, and Multiplexing Circuit

There are two subtraction amplifiers and two averaging amplifiers which form the heart of this circuit. The subtraction amplifiers must be capable of subtraction to a part in a thousand over a bandwidth of 6 MHz. Although the circuitry is quite simple, special care must be taken in the geometrical arrangement of the circuit, and special testing and adjustment procedures must be followed to insure the required level of performance.

The subtraction amplifiers used in this circuit are type SN7510L differential video amplifiers. They have a fixed gain of 100. The system requires a gain of ten, so the amplifiers must be fed through voltage divider networks on the inputs. The dividers must be on the inputs of the amplifiers to avoid the problem of amplifier saturation with moderately strong difference signals. If the amplifiers were operated with the dividers on the output, a difference of only 3% of the standard 1 volt video signal would saturate the amplifier. With the dividers on the input, however, the saturation point is at about 30% of the video signal.

Placing the dividers on the inputs of the amplifiers requires careful matching of the resistors used, both in resistance values and capacitance. Only high quality resistors with a low temperature drift should be used. Avoid wire-wound precision resistors, since in an amplifier with a bandwidth of 5 MHz their inductance is not negligible. Metal film resistors often work well.

Resistor networks may be matched by the following procedure:

(1) Select two 51.1 ohm and two 464 ohm 1% precision resistors. Other values may be used so long as the lower value is about 50 ohms and the two values combined form a divider which reduces voltage by about a factor of ten. A ten percent departure from the 50 ohm value is tolerable.

(2) Wire the four resistors together in a Wheatstone bridge.

(3) Place a dc voltage from any convenient source between the junction of the two 51 ohm resistors, and the junction of the two 464 ohm resistors. This voltage should be high enough so that 1/10,000 th of its value can easily be measured by the instrument in step (4). Be careful not to overheat the resistors. Even if they are not burned out, their stability will be impaired by overheating.

(4) Using a VOM or other instrument, measure the voltage across the bridge. While monitoring the bridge voltage, clip a large (try 1 megohm first) potentiometer across one of the 464 ohm resistors.

If the bridge voltage gets larger, clip the pot across the other 464 ohm resistor. If the bridge voltage changes sign, use a larger potentiometer. (Check to see if the first potentiometer is set at maximum resistance first.) If neither of these things happen, adjust the potentiometer to balance the bridge. When the bridge voltage is as close to zero as possible, but in any event no larger than .001 times the applied voltage, remove the potentiometer and measure its value.

(5) Select a 1/4 W 5% carbon resistor with a value as close as possible to the value measured from the potentiometer. Carbon can be used here since a relatively large change in the value of this resistor will have little effect on the divider. More instability can thus be tolerated. Solder this resistor in place of the potentiometer, with its leads wrapped around the leads of the precision resistor close to the body of the precision resistor (See Figure A3).

(6) Find the largest value 1/4 W 5% carbon resistor available - large enough so that it won't disturb the balance of the bridge, and solder it across the other 464 ohm resistor. The purpose of this resistor is to balance the capacitive coupling across the two resistors.

(7) Make a final check to see that the bridge is still in balance.

The circuit board on which the amplifier is mounted must have all input leads laid out as symmetrically as possible in order to match the capacitance to ground at the amplifier inputs as well as possible.

Each of the input dividers has a 215 ohm resistor connected across it. This resistor serves to bring the total input resistance to both

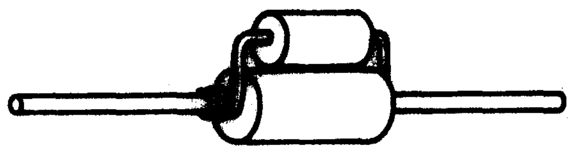


Figure A3. The method of preparing the bridge resistors.

subtraction amplifiers in parallel to about 75 ohms, the standard value for video equipment. The 215 ohm resistor should be a 1% resistor, but need not be adjusted more closely. The outputs of the disc recorder and television cameras are not closely matched anyway. However, if the dividers are not accurate, the differences will not subtract out properly.

The output of the SN7510L goes through a 5K potentiometer to ground, and the desired fraction of the output is picked off by the wiper of the potentiometer. The potentiometer provides a means of matching the gains of the two subtraction amplifiers. The gains must be matched to one part in a hundred.

After the amplifier is constructed, a common mode input should be applied from an r.f. oscillator, and the common mode rejection ratio measured. If necessary, it can be tweaked up by placing a small capacitor (1-2 pf) from one or the other of the input leads on the amplifier can to ground.

The averaging amplifiers are Fairchild μA702 operational amplifiers. The two input resistors to the summing point must be equal to at least one part in a hundred. The two resistors are matched by trimming with a shunt resistor as described previously. The trimming procedure is somewhat more involved than just matching a pair of dividers. After the bridge is balanced, the two resistors being made equal must be interchanged, and the bridge re-balanced. When the exchange of the two resistors does not affect the balance of the bridge, the two resistors are equal. In general, reaching this state will require several switches and readjustments. It will be necessary to trim at least two resistors in the bridge to reach the final state of balance.

The feedback loop in the averaging amplifiers consists of a 8200 ohm fixed resistor in series with a 25K potentiometer. The input resistors are 20K. The potentiometer allows the adjustment of the amplifier gain from less than 1/2 to about 1-1/2. One amplifier is wired in an inverting configuration, and the other is non-inverting.

The amplifier outputs are all A.C. coupled to the inputs of a General Instruments MEM2009 analog multiplexer. The output of the multiplexer is selected by a binary code (RTL logic levels) which is decoded by a BCD-DEC decoder. The outputs of the decoder are run through interfacing amplifiers to provide the proper voltage levels to the control gates of the multiplexer. The output from the multiplexer runs through an output amplifier consisting of a µA702 driving a one-transistor emitter follower power amplifier.

Inputs to the circuit as a whole are:

0, 0', A, B, C, D (video inputs)

1, 2, 4 (logic inputs).

There is one video output. Outputs that may be selected are:

0, 0', N(A+B), -N'(A+B), 10(C-D), 10(D-C).

N and N' are factors that may be adjusted by the potentiometers in the feedback loops of the two averaging amplifiers.

Signal Processing Circuit

The function of this circuit has been discussed in detail in the main text. The compensating waveform is produced by driving a one-shot with the 30 Hz clock from the automatic controller. The one-shot pulse, which is much shorter than the vertical retrace interval, turns on a transistor which allows a capacitor to rapidly charge. The capacitor then discharges through a variable resistor, producing the exponential waveform shown in Figure 6c of the main text. The time constant of the decay is adjusted by varying the resistor. An appropriate fraction of the signal is picked off by a variable resistor in parallel with the first, and the resulting compensation waveform is added to the video and a blanking signal from the camera sync generator. The addition amplifier is a μA702.

Delay Circuit

Due to the time lag effect discussed in the main text, it is necessary to delay the blanking waveform which is fed to the signal processing circuit and the sync pulses fed to the monitor, so that they are in proper phase with recorded pictures representing a high level of averaging. This is done by feeding the signal through an interfacing amplifier to convert it to RTL logic levels, and then running the converted signal and its inverse through a pair of matched variable pulse delay circuits. The outputs of the delay circuits feed a set-reset flip-flop, the output of which is a delayed reproduction of the input waveform. The delayed waveform is sent through another interfacing amplifier to convert it back to television voltage levels.

Logic for Peripheral Equipment

The 16 mm movie camera and the quarter wave plate are under automatic control.

The control circuit for the camera is quite simple. A control voltage from the automatic controller triggers a variable length one-shot. The output from the one-shot goes through a power amplifier to a solenoid which advances the film and holds the camera shutter open as long as the solenoid is actuated. When the one-shot pulse ends, a pulse is sent back to one of the inputs on the automatic controller to enable the controlling program to continue. The variable length one-shot provides a range of shutter speeds ranging from about 1/20 second to about 1 second.

The control circuit for the quarter wave rotator is similar in that a pulse from the controller also triggers a one-shot which remains on long enough for the filter to rotate, then sends a pulse back to the controller. In addition, the return pulse to the computer triggers a J-K flip-flop which changes the direction of motion of the rotator motor, so that when the motor is next turned on it will run the other way. The quarter wave plate thus rotates back and forth between two stops. There is no attempt to detect the stops. The quarter-wave plate is run by a slip-belt, and the one-shot is timed to over-run the stops slightly, thus pulling the belt tight. (It is actually a spring.) The spring action holds the plate holder firmly in position after the motor stops.

APPENDIX II - SYSTEM PARAMETERS

Overall Differential Sensitivity

Differential sensitivity is a somewhat subjective parameter. It can be specified objectively in terms of the light intensity difference required to produce an output signal equal to the output noise level. Such an approach, however, can be highly misleading. The acceptable output signal-to-noise ratio varies which the spatial frequency of the difference image to be observed, and with the precise character of the image contrast distribution. For example, a differential signal which covers a large area, and which has a sharp boundary, is easily visible if the difference signal is equal to the RMS output noise level. An example of this phenomenon may be seen by noticing how sharply defined the edges of the slide are in the first order subtractions (E and F) in Figure A4. The spatial frequency of the noise in the output picture is quite high, and this allows the eye to average over many noise elements to pick out a feature of low spatial frequency. On the other hand, a signal of many times the output noise level is required if its spatial frequency is about the same as that of the noise. Otherwise, it will be impossible to distinguish it from a noise peak.

Other psychological factors enter into the interpretation of the differential pictures. For example, the eye seems to more readily pick out extended features such as lines or networks than it does spots or blotches. The ultimate criterion for whether a certain sensitivity has been reached is whether or not most people can agree that a certain weak feature is in fact real, and not just some sort of noise.

Figure A4

This figure shows the results of a laboratory test of the differential video photometer in the single camera mode.

A: The background target.

B: The background target with a slide projected on it.

C: A as seen on the television monitor.

D: B as seen on the television monitor.

E: 10(B - A). The subtraction is of the form (head 1 - head 2).

F: 10(B - A). The subtraction is of the form (head 2 - head 1).

G: 1/2(E + F).

H: An average of 64 pictures of the type shown in G.

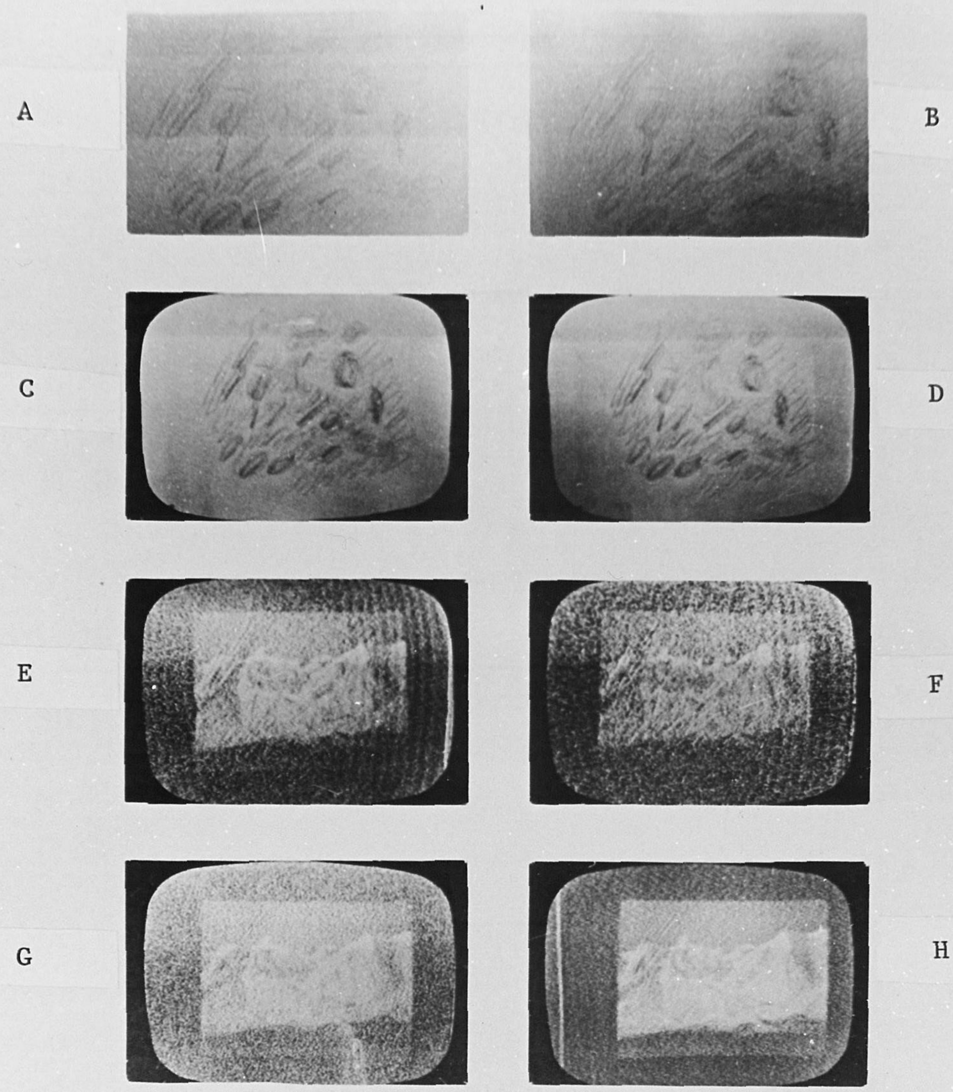


Figure A4. A laboratory test of the video photometer.

Accordingly, it is probably best to take the following quantitative measurements only as indications of the system's performance. Its usefulness as a magnetograph is best judged by looking at magnetograms.

The system sensitivity was tested in two different ways. The results of one of these tests is shown in Figure A4. In this test 128 pictures of a background target were recorded, and then subtracted from 128 pictures of the same target with a dim slide projected on it. The slide was sandwiched with a neutral density filter with a transmission measured at .080 ± .006. The illumination of the slide projector (without a slide in it) falling on the target was measured as about .77 ± .03 of the incident room light intensity. The relative intensities of the room light and the slide projector illumination were measured with a meter equipped with an all angle integrating hemisphere. Such a meter provides a more accurate reading of incident light from a diffuse source such as room light. The projector illumination is uneven, and this factor was taken into account in the reduction of data. The transmission of the slide was measured as .034 ± .013 for an average of 4 points measured just off the edge of the cardboard mount in the darkest part of the sky. A transmission of .38 ± .02 was measured in the snow highlights, and a transmission of .0117 ± .0005 was measured for a point near the lower left corner of the picture in the dark ground. (The point on the ground was not measured from the slide used for the video test, but from another slide taken of the same scene a few minutes earlier. This second slide gives the same values for the sky and snow within the error bars, so the value for the ground is probably quite good.)

Incident light intensities of light for the various parts of the slide as a percentage of incident room light are:

Sky:	0.24 ± 0.1%
Snow:	3.3 ± 0.7%
Ground:	0.07 ± 0.01%

The discrepancy between these values and the value of 0.1% given for the sky in a previous paper (Smithson and Leighton, 1971) is the result of a more accurate determination of the value at a later time. An even more accurate method has recently been devised, as is reflected in the measurement of the light intensity for the ground. It should be remembered, however, that none of these values must be taken too seriously. For one thing, the differences in spectral sensitivity between the television cameras and the photometer have not been taken into account. This could have some effect, although measurements made with a 1P21 photomultiplier should not be too far off. The plumbicon tube is more sensitive to red light and less sensitive to blue than the 1P21. The room lights are fluorescent, and the slide projector is incandescent, so there may be effects due to spectral sensitivity which would, in general, make the system appear more sensitive than it is. On the other hand, the blue light in the sky would tend to make the system appear less sensitive than it really is, since the plumbicon is less sensitive to blue than the 1P21.

In order to estimate the effects of spectral sensitivity differences, a comparison has been made between the relative values of room light and slide projector light as measured by the 1P21 photomultiplier and as measured using the plumbicon camera as a photometer. The response of the plumbicon camera is about unity gamma, so the relative light levels as measured by the camera were taken to be proportional to the output voltage levels measured with respect to the black level with the AGC and gamma correction circuits disabled. Black levels were set at the dark levels with the lens cap on. This setting proved to be the same as that obtained by using the dark room beyond the screen as a reference black level for the slide projector, so black seems to be well defined. The results of this experiment indicate that the results of the previous tests should be multiplied by a factor of 1.6 to correct for the differing spectral response curves of the camera and photometer.

In addition, the transmission of the slide was measured at the various points discussed above, also using the camera as a photometer. This revealed that corrections were also needed for the different colors in different parts of the color slide. The final corrected intensities of the various portions of the slide as a percentage difference signal with respect to room light are given below. The background target was made of yellow paper, and all measurements described in the last paragraph were made using a sheet of the same paper as a projection screen. The experimental set-up is diagrammed in Figure A5. Transmission measurements were made simply by selecting the particular point desired in the video signal and measuring the signal voltage at that point with and without a slide in the projector. The point in the raster scan corresponding to a particular picture element is easily picked out with a delayed sweep oscilloscope.
Results are:

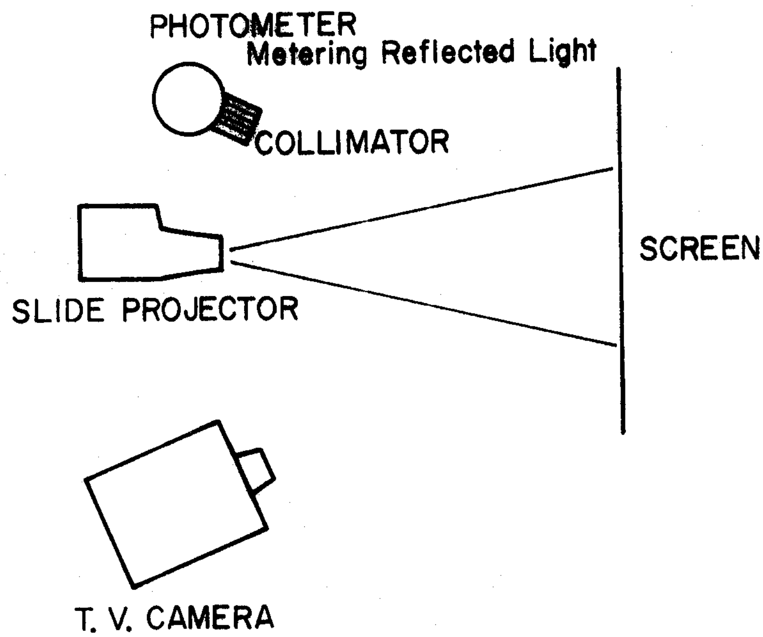


Figure A5. Using the television camera as a photometer for measuring light intensity in the projected slide, and for comparing 1P21 and plumbicon readings.

Sky: 0.28 ± 0.16%

Snow: 4.75 ± 1.12%

Ground: 0.18 ± 0.08%

Since the correction factors are obtained from the second slide of the pair of slides which were taken, not one used for the original video subtraction, these figures will only serve to give an indication of the reliability of the earlier values. The best thing to be said is that they give representative values for the difference signals displayed in the picture.

In Figure A4, A shows a direct photograph of the target under room light illumination; B shows the target with the slide projected on it; C shows the television monitor displaying a live picture of the target with the slide projected on it; D shows a live picture of the target with the slide projected on it; E shows a simple 10(head 1 - head 2) subtraction of a single recorded pair; F shows a simple 10(head 2 - head 1) subtraction of a single recorded pair; G shows an average of E and F (notice how the distortions due to differing response characteristics of heads 1 and 2 cancel out); H shows a composite average of all 128 subtracted pairs.

A second test was used to measure the system sensitivity and linearity. The experimental set-up is diagrammed in Figure A6. The projector was used to project a spot of light on a screen. The intensity of the spot of light was varied by inserting a neutral density filter in the projector slide holder. The neutral density filters used in the experiment had all been previously calibrated using the 1P21 photomultiplier photometer. The 128 pictures were

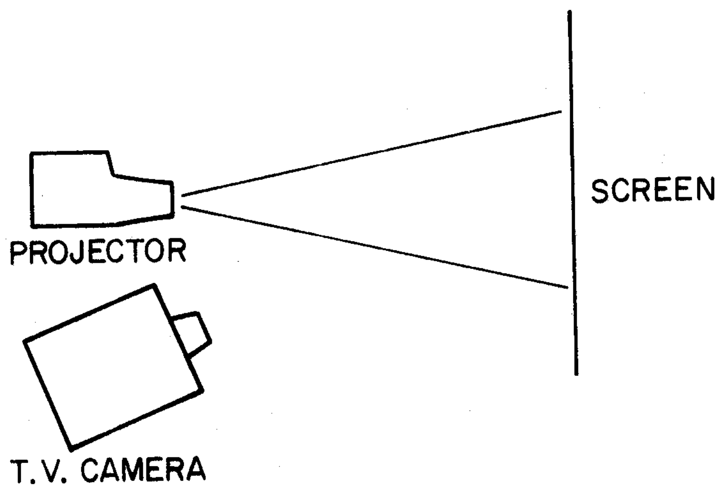


Figure A6. The system linearity and sensitivity test.

recorded of the blank screen illuminated only by room light, then 128 pictures were recorded of the screen illuminated by room light plus the spot from the projector. The pictures were subtracted and averaged, and the peak-to-peak value of the final differential signal was recorded. This procedure was repeated for several different neutral density filters so that a curve of ΔV out versus $\Delta I/I$ in could be plotted. The resultant curve is shown in Figure A7. Subtractions were made in both senses for each neutral density filter, so that a curve could be plotted for both positive and negative output signals.

The sensitivity of the system obtained from this experiment is probably the most reliable objective measurement of this parameter. The peak-peak output noise in the final average was 0.12 volts. The R.M.S. noise was .024 volts. The values of $\Delta I/I$ which produce a difference signal equal to these noise levels are 0.6% and 0.12%, respectively. These figures, however, are for a bandwidth of 50 MHz. When corrected to a bandwidth of 10 MHz (the bandpass of the Conrac monitor), the peak-peak noise becomes about .054 volts, and the R.M.S. noise about .011 volts. The corresponding values of $\Delta I/I$ are 0.27% and 0.05%, respectively. Since noise higher in frequency than 10 MHz will not be seen on the monitor, the corrected figures are probably the best to use. Figure A7 can be used to find the required value of $\Delta I/I$ for an output signal of any given multiple of the R.M.S. or peak-peak noise in the final difference picture.

The curve in Figure A7 holds true for any value of I which produces a camera signal with a signel-to-noise ratio of 40 db or better.

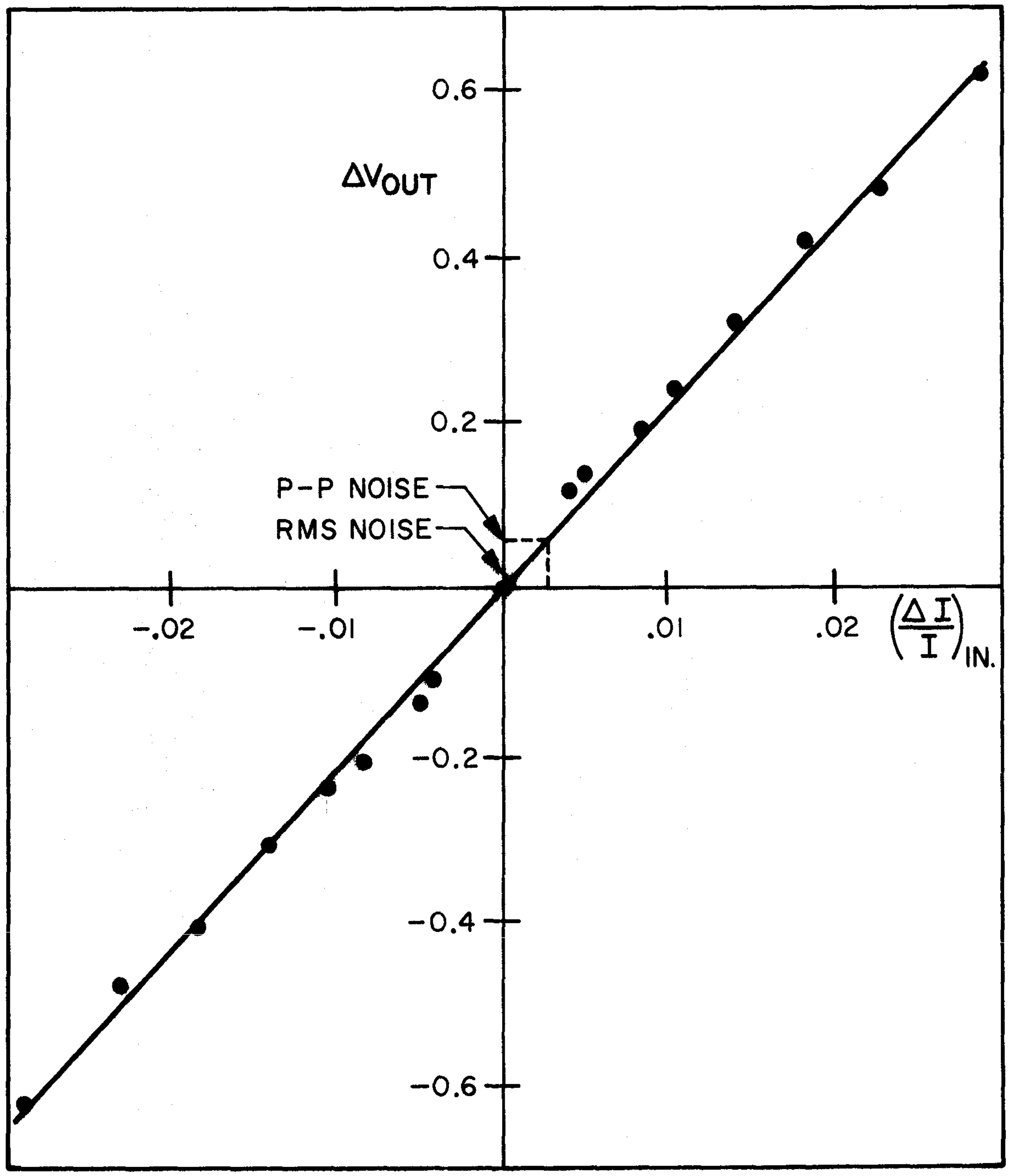


Figure A7. Results of the system linearity and sensitivity test. Peak and R.M.S. noise levels are shown.

To find this threshold value of I for the Philips cameras using the XQ1023R plumbicon tube, use Figure 5.

The curve in Figure A7 is uncorrected for spectral response characteristics close to that of the 1P21 photomultiplier, and so the values given for $\Delta I/I$ in the figure should probably be multiplied by about 1.6. This correction gives a 10 MHz sensitivity of 0.43% for peak-peak noise and 0.08% for R.M.S. noise.

A further improvement in sensitivity could be made by inserting a filter in the monitor video input to reduce its bandpass to 4 MHz, which is the bandpass of the disc recorder, but this has not yet been done.

Picture Averaging Effectiveness

It must be remembered that the measurements discussed in the previous section were made using an average of 128 subtracted pairs or 256 pictures in all. This section describes the results of experiments testing the effectiveness of the averaging technique in reducing noise, and gives results that may be used to estimate the results of averaging more or fewer pictures than this number.

In the first experiment, 256 noisy television pictures were recorded and averaged using the same program as that used to average pictures in the 256 picture subtraction and averaging routine. The improvement in signal-to-noise was about a factor of eight. A second experiment was done to see if this improvement was as expected. The video input to the disc recorder was shorted to ground,and the resulting zero level was written on two video heads. The recorded zero level was then read simultaneously from the two heads, and the two outputs were averaged. The output from the averaging amplifier was displayed on an oscilloscope which was triggered by the once-around clock from the disc recorder. The resulting trace could then be resolved into two noise components. The first component was random in time and represented noise generated by the averaging amplifier and the output circuits of the disc recorder. The second component did not fluctuate in time, and represented recorded noise generated by the disc recording circuits and then recorded as though it were a video signal. These two components will be referred to as n_R and n_F, respectively. n_R and n_F can be related to n_t, the noise introduced in reading two pictures from the disc, averaging them, and recording the average.

The noise in this experiment comes from three sources: the disc reading circuits, the disc writing circuits, and the averaging amplifier. (The averaging amplifier noise is referred to the amplifier input.) Let these components be n_r, n_w, and n_a, respectively (see Figure A8).

The noise to be expected in the output of the averaging amplifier can be written in terms of these parameters as:

$$n_{out} = \sqrt{\frac{1}{2}(n_r^2 + n_w^2) + \frac{1}{4}n_a^2}$$

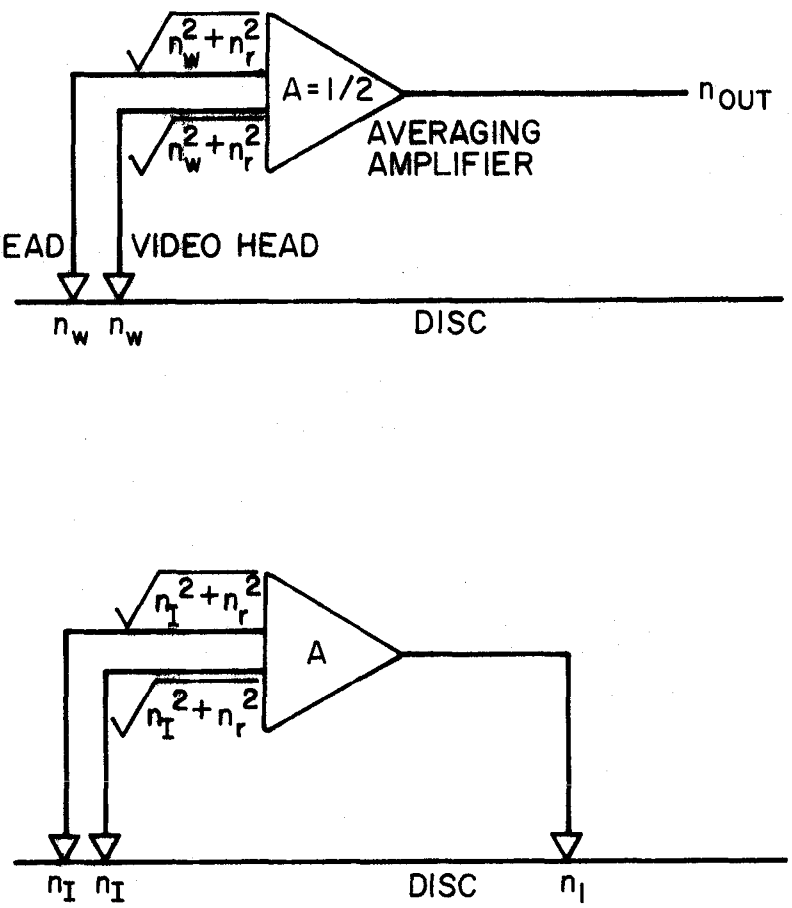
The fixed component of this noise is:

$$n_F = \frac{1}{\sqrt{2}} n_w$$

and the random component is:

$$n_R = \frac{1}{2}\sqrt{2n_r^2 + n_a^2}$$

A



B

Figure A8. A shows the noise components measured in the experiment described in the text. B shows the noise components appearing in the transfer process.

Now if two pictures are recorded on two tracks of the disc recorder, each with a recorded signal level of S_I and a recorded noise level of n_I, and if the two pictures are combined using the averaging amplifier with its gain set at A, and the averaged picture is written on a third track, the signal amplitude recorded on the third track is:

$$S_1 = 2AS_I$$

The noise level recorded on the third track is:

$$n_1^2 = 2A^2(n_r^2 + n_I^2) + A^2n_a^2 + n_w^2$$

$$= 2A^2n_I^2 + \left[A^2(2n_r^2 + n_a^2) + n_w^2\right]$$

$$= 2A^2n_I^2 + n_t^2$$

where n_t is defined by:

$$n_t^2 = A^2(2n_r^2 + n_a^2) + n_w^2$$

$$= 2n_F^2 + 4A^2n_R^2$$

so that $$n_t = \sqrt{2n_F^2 + 4A^2n_R^2}$$

If this "first level" average picture is averaged with another first level average picture to form a second level average (a composite of 4 initial pictures), then:

$$n_2^2 = 2A^2(2A^2n_I^2 + n_t^2) + n_t^2$$

$$S_2 = (2A)^2S_I$$

If 2^N original pictures are combined to form an Nth level average, then:

$$n_N^2 = (2A^2)^N n_I^2 + n_t^2 \left[(2A^2)^{N-1} + (2A^2)^{N-2} + \ldots + 1 \right]$$

$$= (2A^2)^N n_I^2 + \frac{(2A^2)^N - 1}{2A^2 - 1} n_t^2$$

$$n_N = \sqrt{(2A^2)^N n_I^2 + \frac{(2A^2)^N - 1}{2A^2 - 1} n_t^2}$$

$$= (\sqrt{2})^N A^N n_I \sqrt{1 + \frac{(2A^2)^N - 1}{(2A^2)^N (2A^2 - 1)} \frac{n_t^2}{n_I^2}}$$

$$S_N = (2A)^N S_I$$

Thus the signal-to-noise ratio of the Nth level average is:

$$\frac{S_N}{n_N} = (\sqrt{2})^N \frac{S_I}{n_I} \Bigg/ \sqrt{1 + \frac{(2A^2)^N - 1}{(2A^2)^N (2A^2 - 1)} \frac{n_t^2}{n_I^2}} \qquad \text{(A1)}$$

where: $n_t^2 = 2n_F^2 + 4A^2 n_R^2$

This equation can be used to determine the improvement in signal-to-noise ratio achieved by averaging any number of pictures with any gain in the averaging amplifier, and with any degree of noise in the initial pictures. Before this equation can be used for such a purpose, however, it is necessary to measure n_F and n_R so that n_t can be determined.

The experiment just described allows n_F and n_R to be measured directly. Unfortunately, however, it is difficult to devise a simple instrument which measures precisely the component of the noise spectrum which enters into the system transfer noise n_t. The fixed component presumably is correctly measured by a wide band oscilloscope, since it has already been recorded and read through the disc circuits, and thus contains no high frequency components which would be attenuated in the recording process. However, noise generated in the output circuits may contain high frequency components to which the disc recorder will not respond, and which would cause the measured value for n_R to be too high as measured with a wide band oscilloscope. A better figure can be obtained with an oscilloscope fitted with a filter with the same band-pass characteristics as the disc recorder, or by making a correction for the larger bandpass of the oscilloscope, assuming that the random noise component has a true "white noise" frequency distribution. The more accurate of the two methods would probably be to use a bandpass filter with the oscilloscope. It is easier to make an accurate measurement of the bandpass of the disc recorder than it is to do a spectrum analysis of the output random noise component, and the assumption of a white noise spectrum is probably not very good.

In interpreting the results of this experiment, it was decided to simply make a bandwidth correction to the measured value of n_R. This was done because the error involved in this approach is not large compared with the error made in estimating the noise from the observed pattern on the oscilloscope screen. In an ordinary noise measurement made by observing an oscilloscope pattern, where no attempt is made to estimate "stationary" and "moving" noise patterns, the usual rule of thumb is to turn the oscilloscope brightness all the way up and estimate the amplitude of the resulting bright band of noise. This amplitude cannot be measured exactly since the bright band fades out slowly rather than making an abrupt transition in intensity at the edge. In fact, if the noise were true white noise, the band would continue with diminishing intensity all the way to an infinite amplitude. The estimate made of the width of this band is what is referred to as the peak-to-peak noise level. The R.M.S. noise is taken to be about 1/5 of the peak-to-peak level as a rule of thumb. It is possible to obtain resistive noise meters that measure the heat generated when a noise voltage is placed across a resistor. These meters measure true R.M.S. voltages, but they cannot separate the two components wanted for this experiment.

The results of this experiment, which are quoted in Table 1 of the main text, should be considered accurate to perhaps $\pm$ 50% as absolute values. Their relative values, however, give a good idea of the relative performance of the various heads and tracks of the disc recorder at the time the test was made. It is usually quite easy to tell if one noise component or signal is larger than another. The results of the experiment are also presented in graphical form in Figure A9. Remember that these results were derived using two heads at once. Results are shown for the fixed heads together, and for the movable heads used together as a function of track position.

A more accurate way of determining an effective value for n_t for use in estimating the effects of changing averaging procedures is to

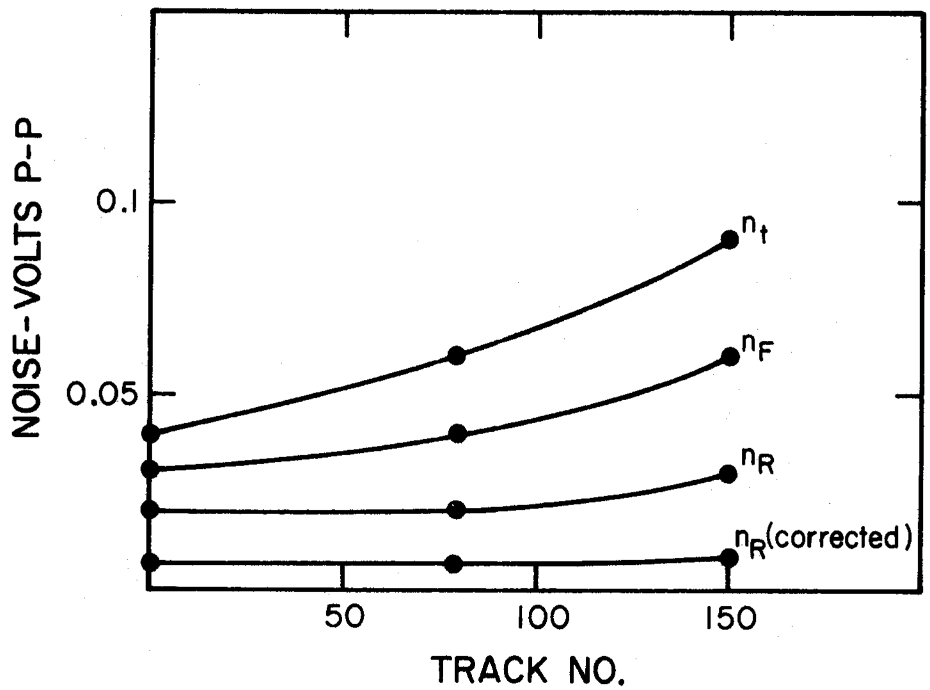


Figure A9. n_t, n_F, and n_R as a function of track position. Both movable heads were at the same track number for this test.

average several noisy pictures, compare the observed improvement in the signal-to-noise ratio with that predicted from equation A1, and thus deduce n_t. This method gives a sort of "average" value for n_t over the various heads and tracks used in the averaging process, and of course, only for the value of A used in making the average. This is not as great a drawback as it may seem, since the results shown in Figure A8 indicate that the value of n_R (corrected) is small compared to n_F, and since the random noise term is the only one dependent on A. Also equation A1 assumes that the value of n_t does not change for the various stages of averaging, so an "average" value of n_t is needed anyway.

The 256 noisy television pictures were recorded on the first 128 tracks of each of the two movable heads. The signal level of the initial pictures was 0.5 volts peak-to-peak, the initial noise level was 0.2 volts peak-to-peak, with a resulting initial signal-to-noise ratio of 2.5. Noise levels were estimated from the oscilloscope screen. The 256 pictures were averaged using the same averaging program normally used to process magnetograms, except that no subtractions were included. This was a test of the averaging process only. The final signal strength was measured and A was calculated. ($S_8 = (2A)^8 S_I$.) The final noise level was determined and the improvement in the S/N ratio was calculated. The S/N ratio had been improved by a factor of eight.

Equation A1 was plotted for the measured values of A, n_I, S_I and values of n_t from 0 to .2 volts peak-to-peak. The resulting curve is shown in Figure A10. The S/N enhancement factor of 8 can be seen to correspond to an effective n_t of about .03 volts peak-to-peak. Since

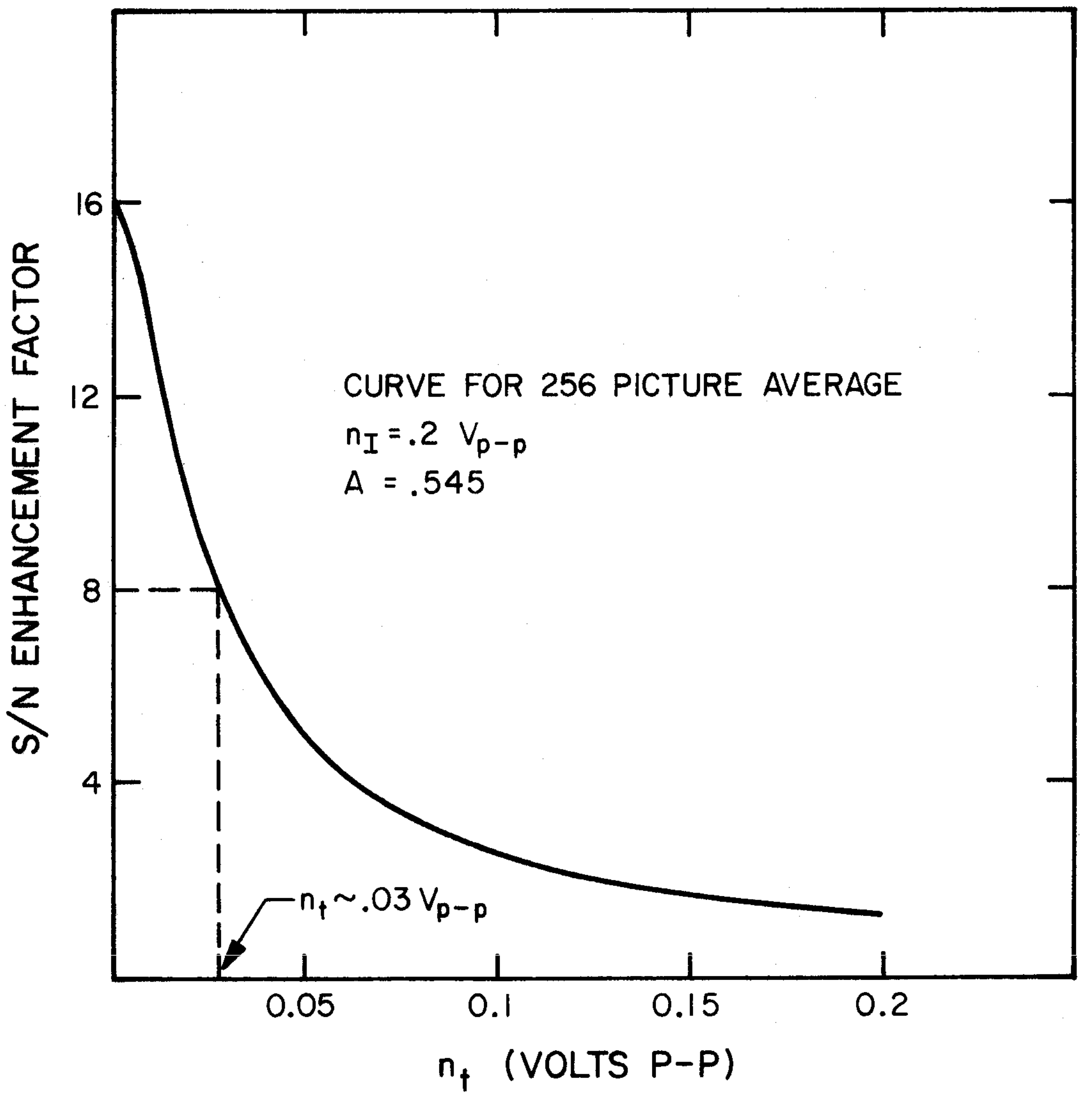


Figure A10. The expected S/N enhancement in a 256 picture average for various values of n_t.

the factor of eight is only accurate to about ± 25%, the actual value is probably somewhere between .02 volts and .04 volts. This is in reasonable agreement with the direct measurements of n_t. It must be remembered that half of the averaging steps are carried out on the fixed heads, and most of the rest near the outer tracks of the movable heads. Thus the effective value of n_t measured here should be near the low side of the range of values measured directly.

It would be possible to do this experiment extremely accurately using a resistance noise meter, but such an instrument was not available. It probably isn't worthwhile to carry these theoretical noise analyses too far since it is so simple to make a direct measurement of the system differential sensitivity, which is the parameter of real interest.

Camera Sensitivity

For the Philips cameras using the type XQ1023R plumbicon tube, a curve has been drawn up from data published by Philips showing the light intensity in microwatts/cm^2 falling on the plumbicon faceplate necessary to produce a video S/N ratio of 45 db. Since the disc recorder has a signal-to-noise ratio of about 40 db, the cameras will begin to contribute to the noise levels if much less light than the amount given is available, and since the system needs a starting picture with at least a 40 db S/N ratio as recorded in order to produce a subtraction sensitive to light differences of 0.1%, this curve can be taken to show the minimum light required for 0.1% sensitivity as a function of wavelength. The exact curve depends on the particular plumbicon used, and varies with the age of the tube. The curve is based on a 256 picture average. It is shown in Figure 5 of the main text.

Monitor Phosphor Response and the System Transfer Function

The monitor phosphor responds relatively linearly to changes in input video voltage levels over intermediate values of phosphor brightness. As the phosphor becomes extremely bright or extremely dim the response curve becomes non-linear. The monitor response curve is shown in Figure All. This curve was taken by varying the video input voltage relative to the black level, while measuring the monitor phosphor intensity. The video signal was produced by a television camera aimed at a target with a light source controlled by a variac. The video signal level was controlled by varying the target brightness and varying the gain of the video output amplifiers. The video signal voltage was measured at the input of the monitor by monitoring the signal with a delayed sweep oscilloscope. The oscilloscope was set to display a single horizontal television line running across the target, and the peak voltage of this particular line was measured relative to the video black level voltage. The phosphor brightness at the corresponding point in the picture was measured by a photometer equipped with a collimating tube.

It can be seen that the phosphor response curve (more precisely, the phosphor brightness versus video input to the monitor - the curve depends on the monitor circuitry, not solely on the phosphor characteristics) is quite linear over a wide range. The monitor brightness

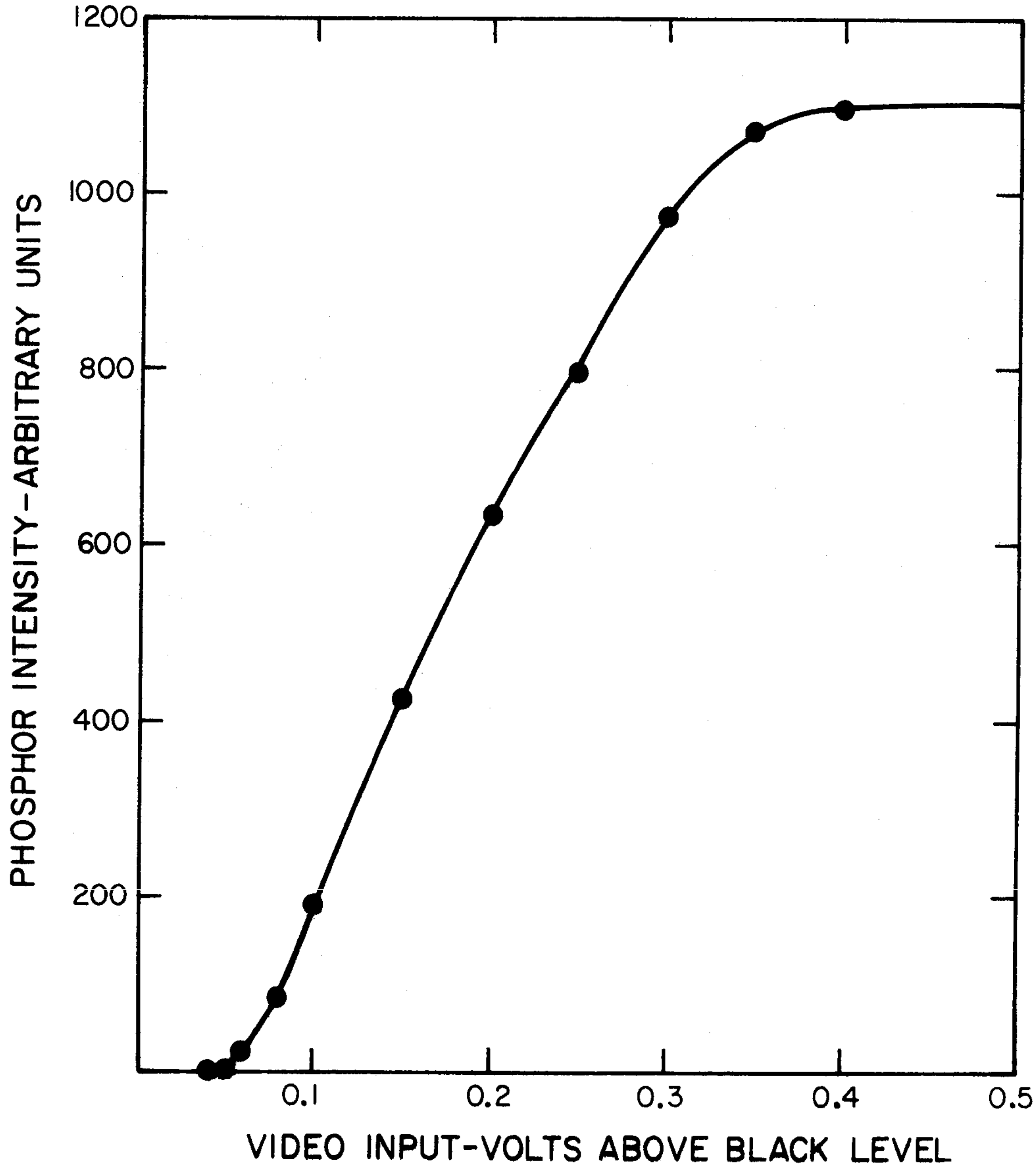


Figure A11. Conrac monitor phosphor response curve.

and contrast controls were set so that the monitor saturated at about .5 volts of video input signal. The precise scale and zero point of the response curve depends on the monitor control settings. The brightness control was adjusted so that with no video input there were no bright lines visible on the monitor face. Even under these conditions, there was a general background luminosity of the monitor screen. This background has been subtracted in plotting the curve.

Since the monitor response curve is so nearly linear, it is possible to consider the curve in Figure A7, which gives the output voltage of the subtraction system versus the differential input voltage, as proving that the overall system transfer function is in fact linear if the monitor brightness is kept in the linear portion of its response curve. The curve given as the system transfer function in Figure 7 of the main text is simply Figure A7 with the voltage axis relabeled I_{out} (arbitrary units). This interpretation of Figure 7 is quite accurate over most of the phosphor brightness range, and is as accurate as desired if the monitor is adjusted to display the range of available video over a limited portion of the phosphor response curve. This can always be done by setting the contrast and brightness controls.

Figure A11 is based on data taken using the original kinescope supplied with the monitor. Since the data were taken, the kinescope has been replaced by a different one. The result is that the monitor response curve is no longer linear. Instead, the phosphor brightness is roughly proportional to the square root of the input video voltage over most of its range. It has not yet been determined if this characteristic is designed into the tube in order to increase its dynamic range, or whether the new tube is faulty. In any event, the new tube cannot be considered linear over much of a brightness range. Since the magnetograms used in this thesis are not calibrated for field strength in any event, this is not a major weakness. However, it should be said once again that a direct form of absolute calibration should be used if the system is to be used to measure magnetic field strengths. (For example, a step wedge could be used to present a calibrated difference signal to the television camera.)

Geometric Linearity

The cameras are guaranteed linear to 1% of the picture height, and the monitor is guaranteed linear to 2% of the picture height. The disc recorder should not introduce any significant nonlinearities. Within these limits, the geometric fidelity of the system is quite good. Figure A12 shows a photograph of the monitor face when the monitor is being driven with a crosshatch pattern from a pattern generator. If the monitor were perfectly linear, the grid would consist of rectangles of equal size, 3 units high by 4 units wide. It is now standard practice to photograph this grid at the beginning and end of every magnetograph run so that the monitor nonlinearities may be corrected for in later data analysis. This was not done for the data used in this thesis, however, and therefore the nonlinearities must be dealt with in other ways.

At present, there is no way to easily monitor camera nonlinearities when the camera is mounted on a telescope. The method used to adjust

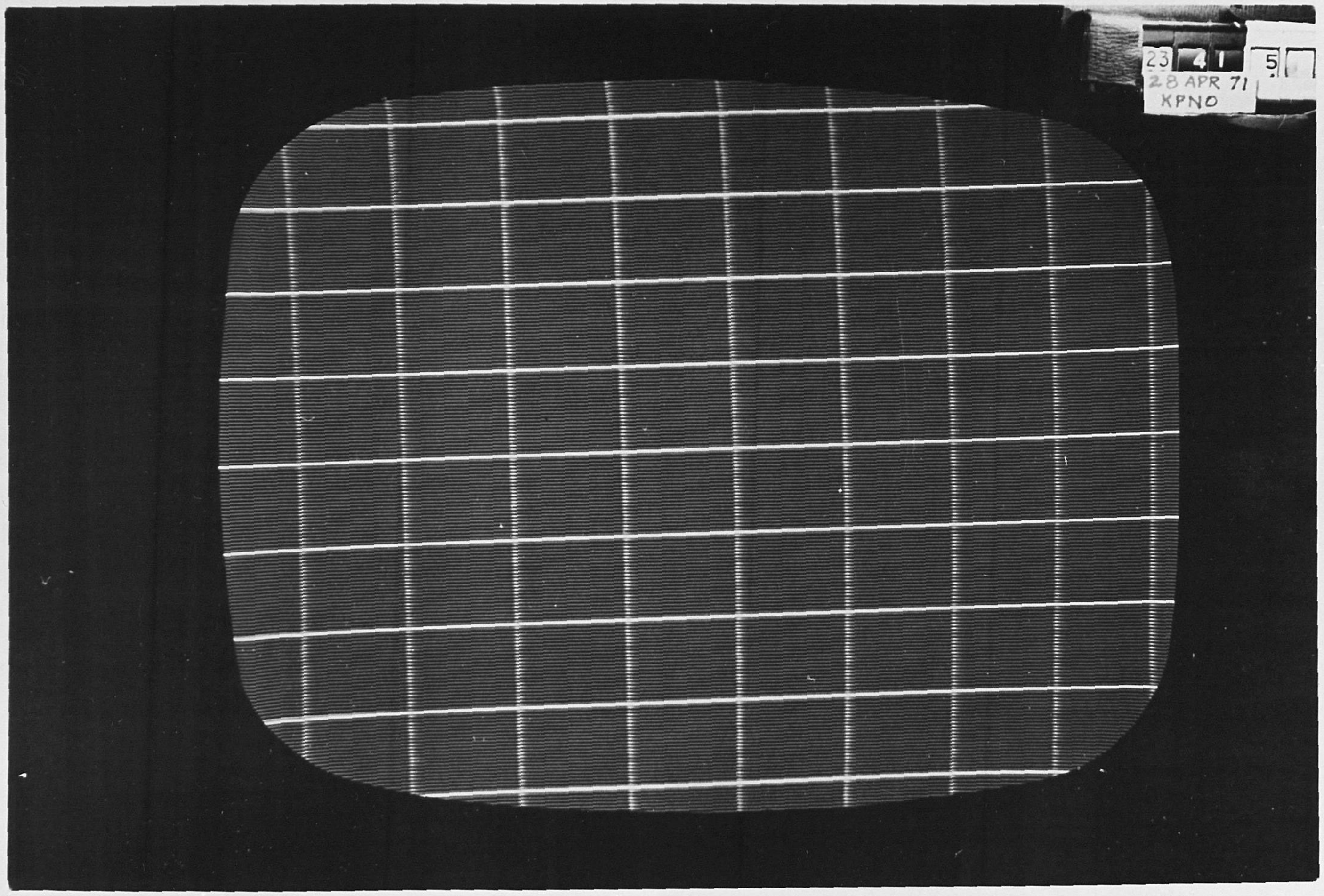


Figure A12. A cross-hatch pattern as displayed by the Conrac monitor. It would be perfectly uniform if the monitor had perfect linearity.

the camera at present is to remove it from the telescope, attach an ordinary lens to the camera, aim the camera at a suitable test pattern, and adjust the camera sweep circuits for a good display on the monitor. Of course, by this method, the camera and monitor cannot be adjusted independently, and any nonlinearity present in the lens will cause misadjustment of the system. Nevertheless, self-consistency tests involving the superposition of photographs of the monitor screen with the same object in different parts of the field of view, indicate the overall linearity of the system to be within the limits necessary for some types of geometric analysis of magnetograms. (See Part 2 of this thesis for a more complete discussion.) A reticle to be used while the camera is on the telescope is under investigation as a means of measuring overall system linearity.

Instrumental Parameters of the Birefringent Filter

The parameters of the Lockheed filter were not well known. The parameters of the filter recently purchased by Caltech will be measured soon on the large spectrograph at Kitt Peak.

APPENDIX III - PROGRAMMING THE AUTOMATIC CONTROLLER

Programming the automatic controller requires selecting the appropriate logic cards for the job at hand, plugging them into the controller, and interconnecting the cards with patchcords. It may be necessary to do some patchcord wiring on the logic cards themselves. The use of the logic cards is best understood by studying their function in simple programs. Figure A13 shows the program panels of the automatic controller.

The Sequence Card

The sequence card is the card around which all programs are built. It is the basic logical building block of the automatic controller.

The sequence card is diagrammed in Figure A14. The figure shows the various logical terminals used in programming. All socket terminals shown are brought to the logic panel of the controller when the card is plugged into one of the 16 pin sockets on the back of the logic panel. Terminals are also provided for logical wiring on the card. The nine numbered terminals are the outputs of the sequence card. These outputs are used to control external equipment and in the logical wiring of the program. The "end" terminal is used in logical wiring or as a pulse output to external equipment. The other socket terminals are logical inputs used to control the functioning of the sequence card.

When the sequence card has been "reset" by a high voltage on the "reset" input, all of the nine outputs are "off", ie. at a low voltage level. The card remains in this state until a high level is received

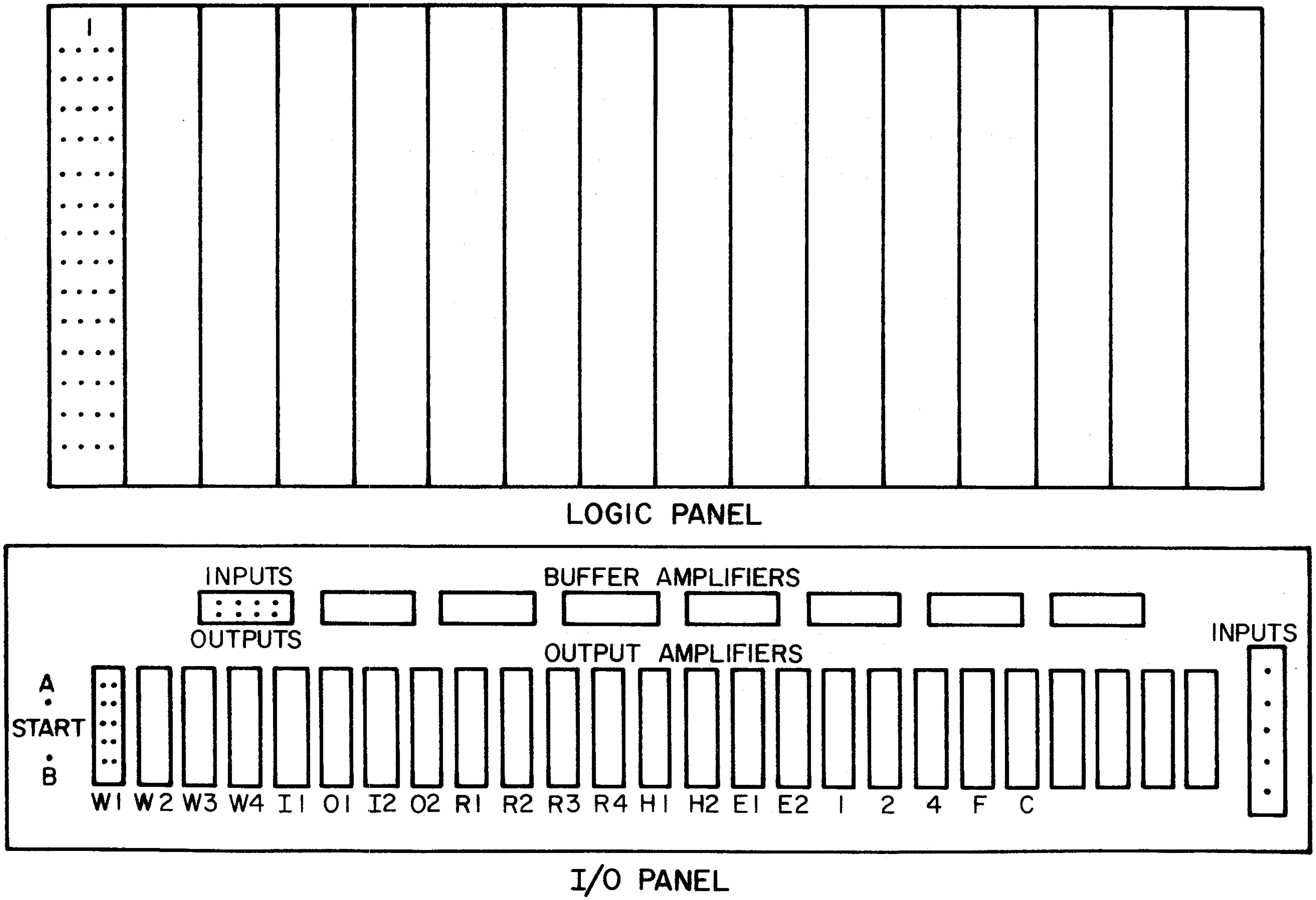
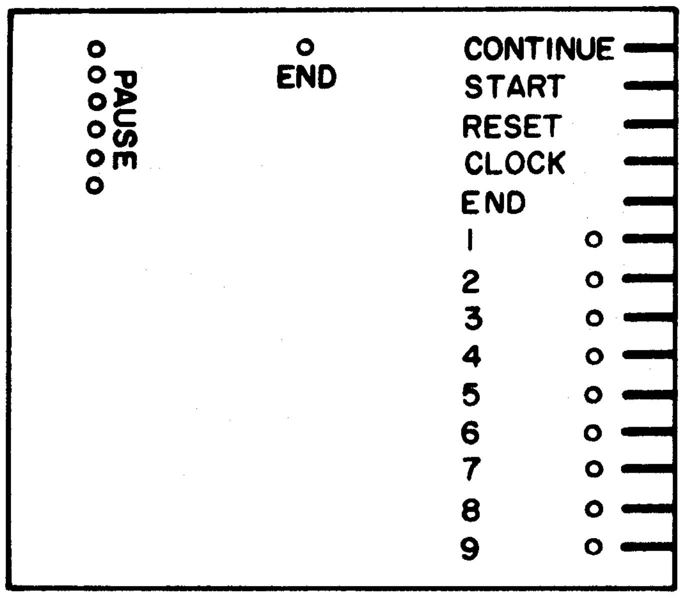


Figure A13. The programming panels of the automatic controller.



o – TERMINAL FOR PROGRAM WIRING ON THE CARD.

▬ – TERMINAL TO FIT 16-PIN SOCKET WIRED TO THE MAIN PROGRAMMING PANEL.

Figure A14. The sequence card.

at the "start" input. When a high level is received at the start input, the #1 output turns on instantaneously. The asynchronous nature of the start input means that if any circuitry is driven by the #1 output which must be synchronized to the system clock, a separate means must be used to insure that the output comes on at the proper time. This requirement is automatically satisfied by any logic control pulses generated by the automatic controller, but must be kept in mind where control pulses generated by external equipment are concerned.

The system clock is automatically supplied to the clock terminal of the card. It is not necessary to patch the clock in. The clock terminals on the front panel should be considered as outputs where the clock is available if needed. No signal is ever patched into a clock terminal.

After the first output of the sequence card has been turned on, the falling edge of the next clock pulse turns the first output off and the second on, the next clock pulse turns the second output off and the third on, and so on in sequence until the ninth output has been turned off. Only one output is on at a time, and the switch from one output to the next is made in synchronism with the falling edge of the system clock. When the ninth output has been turned off, no further outputs are activated by subsequent clock pulses unless a second start signal is received.

Any one (or several) of the outputs can be wired by means of a patchcord on the card itself, to a "pause" terminal. There are 6 pause terminals arranged in two groups of three. The three terminals within each group are completely equivalent. However, if adjacent outputs are wired to the pause terminals, the two adjacent outputs must be wired to different groups of three pause terminals.

If an output is wired to a pause terminal, then when the "paused" output is activated in the normal course of the sequence, it remains on regardless of subsequent clock pulses, and the other outputs remain off. The card remains in this paused condition until a high level is received on the "continue" input of the sequence card. On the next falling edge of the clock, the paused output goes off, the next output goes on, and the sequence continues normally.

Suppose the following program is required. The controller is to record a picture on the disc, then turn on a motor which changes a filter in front of the television camera. Then, when the filter is changed, the controller is to record a second picture on the disc. The patchcord wiring would be diagrammed as shown in Figure A15.

A diode is placed in each patchcord to permit a "wired or" function. That is, a given output amplifier or logical input can be driven by any of several outputs. For example, in the program shown in Figure A15, the output amplifier controlling the recorder is first activated by output #1 of the sequence card, then later by output #3. Notice that in this program the pause condition is used to allow the controller to wait while the filter is switched. The motor control circuitry sends back a pulse to let the controller know when the filter switching is complete. Such a return pulse must be designed into the interface circuitry between the motor and the controller.

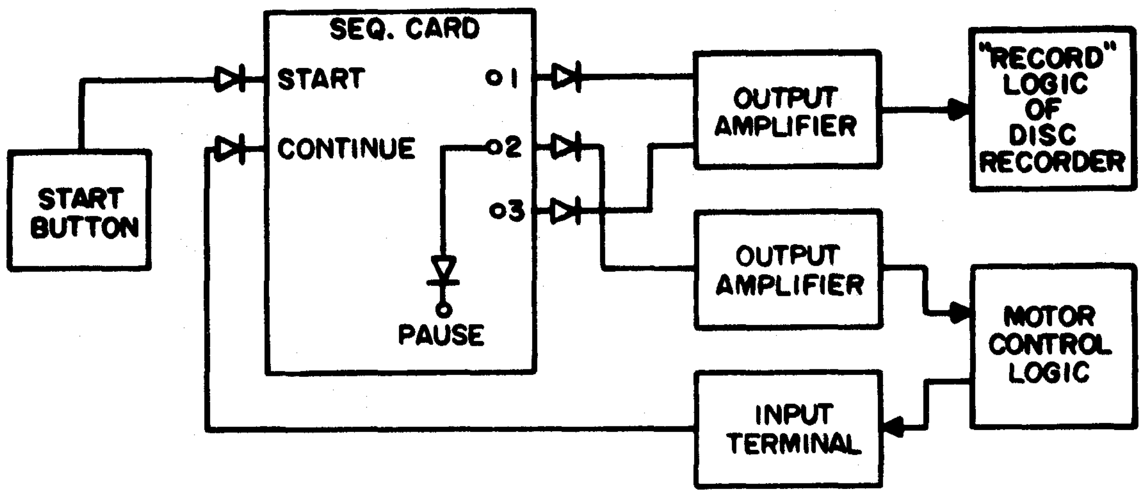


Figure A15. A sample program using the sequence card.

A second and very important use of the pause terminal is shown in Figure A16 (only relevant logic wiring is shown). This is known as "subroutining". There is a sequence of 6 steps which is repeated 3 times in the program. Rather than wiring the sequence into sequence cards 3 separate times, a subroutine is used. The 6 step sequence is controlled by one sequence card which is in turn controlled by a second sequence card which pauses while the subroutine is being executed. The operation of this program should be self-explanatory.

The sequence card alone can be used for quite complex programming. Subroutines can be nested inside one another, and cards can be cascaded if a longer sequence than nine steps is needed. When two cards are cascaded, the ninth output of one card is connected to the start input of another. This permits a 17 step sequence. Since the first output of the second card comes on instantaneously when the start input goes high, the ninth output of the first card and the first output of the second card come on simultaneously, and therefore cannot be used as two independent outputs. Thus only 17 steps are available instead of 18.

The most convenient output to use as the ninth step in a cascaded sequence is the first output of the second card. This is because if the program is to pause at that step, and if the output is taken from the first card, then pause and continue commands must be wired to <u>both</u> cards. Otherwise the second card, which was activated by the first, will move to the next steps in the program while the first card is still pausing. If the ninth step does not require a pause then either card may be used to supply the output. On the other hand, if a pause is required and the second card is used to supply the output, the first

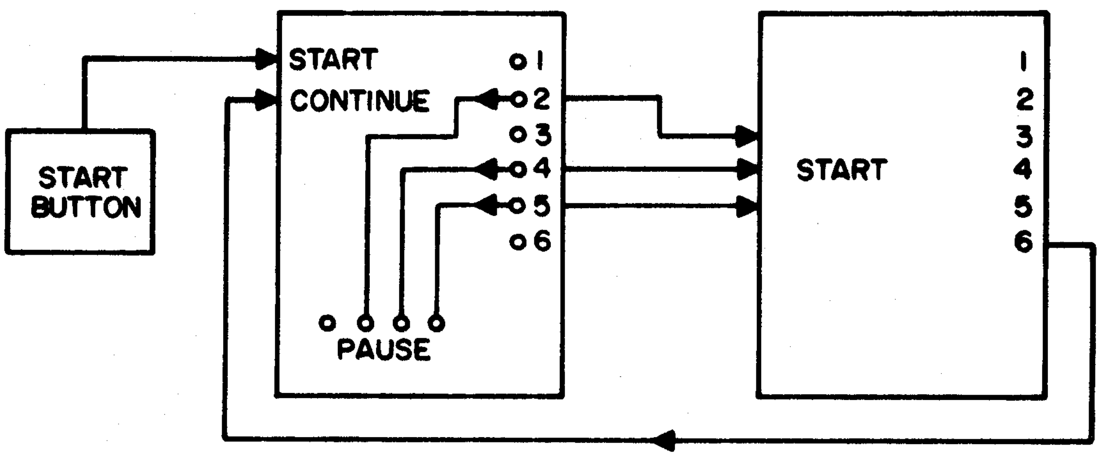


Figure A16. Subroutining

card will merely start the second, and then on the next clock pulse the ninth output will go out, while the second card remains paused. Since the ninth output of the first card is not controlling anything, this has no consequences so far as the program is concerned.

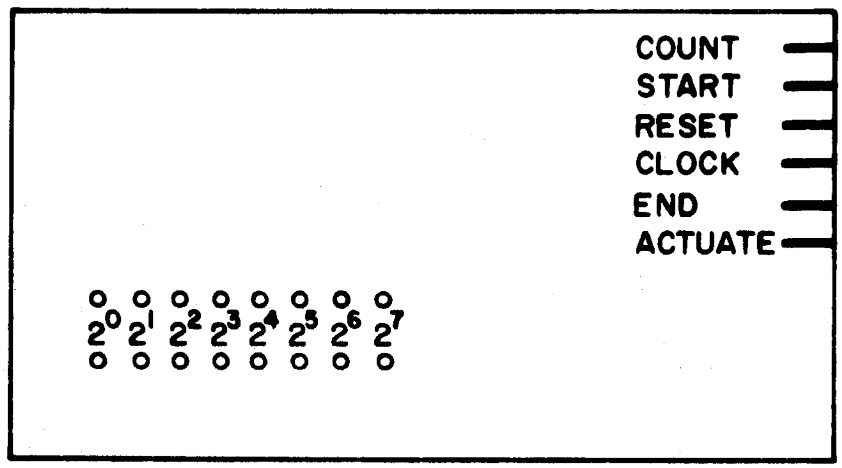
Of course, if fewer than nine steps are needed for a sequence, the unused outputs at the end of the string are simply left disconnected. They go on in sequence after the program has passed on to another card, but since they are not connected to anything, this has no consequences.

A sequence card can be started as often as necessary, and it is possible to have more than one high level propagating down the string of outputs. That is, it is possible to have several outputs high at one time if the sequence card has been restarted while a high level is still on the card. It is not, however, possible to have two adjacent outputs high at one time under program control. (This condition can occur as a result of transients or when the controller is first turned on. It is impossible to introduce adjacent high levels through the start input.)

The Loop Card

Quite complex programs involving cascaded cards and nested sub-routines can be produced using the sequence cards alone, so long as they do not involve the repetition of the same sequences many times over. Multiple repetitions are the job of the loop card, which is diagrammed in Figure A17.

A loop card can control up to 256 repetitions of the same sequence. The desired number of repetitions is coded onto the card



o – TERMINAL FOR PROGRAM WIRING ON THE CARD.

▬ – TERMINAL TO FIT 16-PIN SOCKET WIRED TO THE MAIN PROGRAMMING PANEL.

Figure A17. The loop card.

by means of wire jumpers (not patchcords). Wire loops must be used to connect a combination of the pairs of terminals shown so as to form in binary the number of repetitions desired, minus one. A loop card cannot be used to form a single-iteration loop. The sequence under the control of a loop card must always be repeated at least twice. A loop card in use is shown in Figure A16.

The program in Figure A18 repeats the 4 step sequence A twenty-five times, and then begins sequence B. The loop card sends out an "actuate" signal each time it receives a "count" input and increases its counter until the preset number is reached. An "end" pulse is then sent out to begin the next part of the program. The loop is initiated by a high level on the start input of the loop card. This start input is asynchronous, so the first sequence card under the control of the loop card is started instantaneously when the start input to the loop card rises to a high level. Subsequent actuate signals, however, are synchronous, occurring at the next falling edge of the clock after the count input goes high.

Loop cards can be nested to form loops which are products of the numbers set on the nested cards. A continuous progression of loop lengths is possible by cascading several loop cards. It is possible to control a single sequence by several different loop cards, and a different loop card is needed every time the number of repetitions of a sequence is changed.

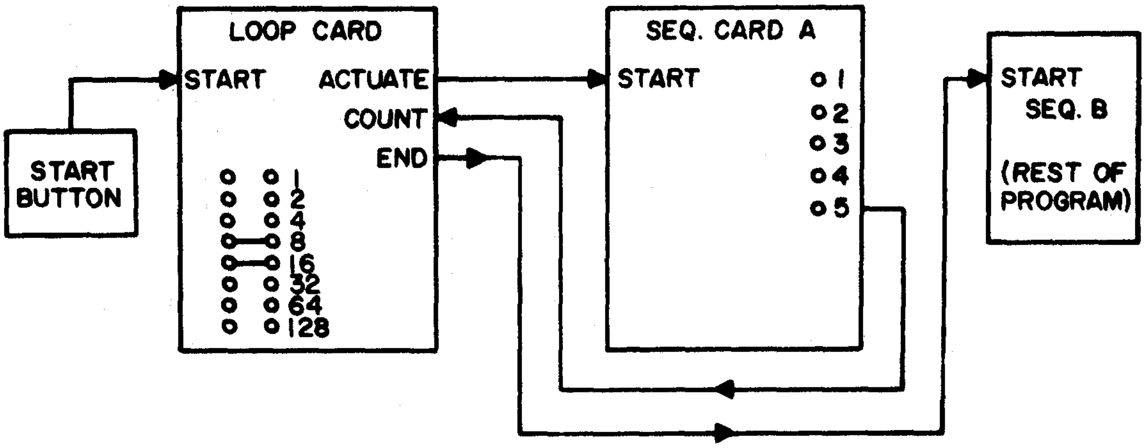
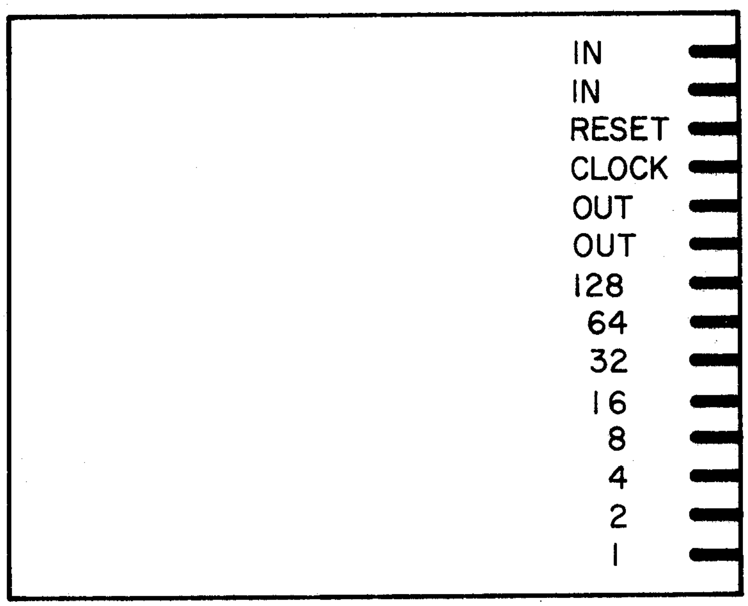


Figure A18. A loop card program.

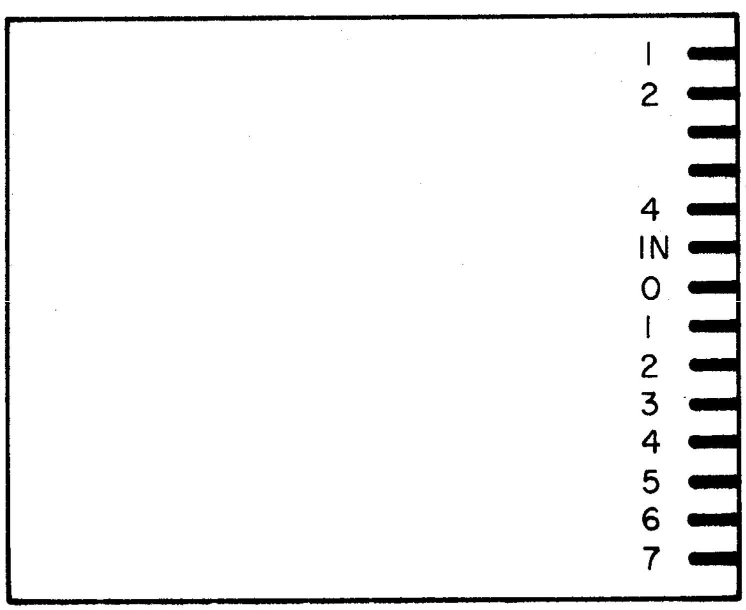
The Multi-Length Pause Card

It is very often the case when programming the disc recorder that the movable heads of the recorder must be stepped in or out a large number of steps. The recorder interfacing is designed so that a head steps in or out making one step at each clock pulse as long as a control voltage from the automatic controller remains high. Thus, from the programmer's point of view, the job of stepping a movable head over five tracks is that of providing an output which remains on for five clock pulses, then goes off. Such an output could be provided by using a paused sequence card to start a loop with the same number of repetitions as steps desired (minus one), and using the end pulse from the loop card to cause the paused card to continue. The count input of the loop card would be wired to the clock. The main problem with such an arrangement is that a different loop card is needed every time the number of steps is varied, and in a typical subtraction and averaging program there is enough variation that there isn't enough room in the controller for all the loop cards that would be required. Accordingly, a special card, called a "multi-length pause card" (MLPC) has been designed. The card is diagrammed in Figure A19.

In use, the MLPC is given a high level from a paused sequence card output. The high level is fed to one of the two "in" terminals on the MLPC and to a combination of the various binary inputs that forms the number of steps desired minus one. When the required number of clock pulses has passed, a continue pulse is sent out by the MLPC, and the sequence card moves to the next step in the program. If two



MLPC



VAC

Figure A19. The MLPC and VAC cards.

successive steps in a program are to be controlled by a MLPC, they must be wired to different inputs. The same MLPC can be used by many different sequence cards. Although a "continue" pulse is received by every card to which the output of the MLPC is wired, the pulses have no effect unless the card is in a paused condition. Since normally the only paused card is the one which is currently in use to step the disc recorder heads, the various cards wired to the same MLPC will not interfere with each other. There is one important exception to this rule. A step in a subroutine cannot be controlled by a MLPC which is also controlling a step in the sequence card which called the subroutine. If such programming is attempted, the pulse from the MLPC will not only cause the subroutine to move to the next step, it will also cause the card which called the subroutine to prematurely move on to the next step. In such a case there are two cards paused at the same time.

The Variable Address Card

In many cases, two very similar subroutines are needed, for example, a number of complicated steps involving stepping movable head 1 in and out may be performed, and then later the identical sequence of steps, but this time stepping movable head 2. The two sequences can be combined as a single subroutine by using the "variable address card" or VAC. The VAC is diagrammed in Figure A19.

The VAC card has one input and eight outputs numbered 0 through 7. There are also three control inputs. When a binary code is patched into the control inputs, the output gate corresponding to the binary code is selected. As long as the binary control code is present, the VAC routes any information sent into the input to the selected output. Notice that when no binary code is present, any signals sent into the input will be routed out of the output numbered 0.

The VAC is normally used by connecting an output of a sequence card in a subroutine to the input of the VAC, instead of directly to the output amplifier it is to control. Then, for example, the #1 output of the VAC could be connected to the output amplifier which steps movable head 1, and the #2 output to the output amplifier which steps movable head 2. Suppose that the first time the subroutine was called it is desired to step head 1, the second time, head 2. Then when the sequence card controlling the subroutine is paused to allow the subroutine to finish (see the section on the sequence card), the paused output is patched to the #1 binary control input of the VAC the first time the subroutine is called, and to the #2 input the second time. Since the paused output of the controlling sequence card is on during the entire period the subroutine is operating, this programming scheme provides proper routing of the subroutine control signals.

A single VAC can be used in more than one subroutine, as long as no two subroutines are operating at the same time, and as long as the total number of output combinations to be driven by the VAC does not exceed eight.

Loading Rules

A logic card output cannot drive an infinite number of inputs. The total number of inputs which can be driven by the various outputs used in the automatic controller are given in Table A1. All inputs driven by an output must be counted, including output amplifiers, pause terminals on the sequence cards, and all logical control inputs. Reset inputs on sequence and loop cards count as 3 inputs, as do buffer amplifier inputs.

Table A1: Loading Factors

Sequence Card:			
	Output #1	12	
	Output #2	16	
	Outputs #3-8	7	
	Output #9	10	
	End	16	
Loop Card:			
	Actuate	16	
	End	11	
MLPC:			
	Output	80	(both outputs combined - the sum of the loads on both outputs must not exceed 80)
VAC:			
	All outputs	16	
Start Buttons:			
	Outputs	13	
Buffer Amplifiers:			
	Outputs	80	

If it is necessary to drive more inputs than the number specified in Table A1 the output concerned can be routed through a buffer amplifier.

Those buffers have the capability of driving 80 inputs, and should be sufficient for any programming need. There are 8 buffer amplifiers provided.

General Programming Considerations

The main objective in programming the automatic controller is to use as few logic cards as possible to accomplish a given end. There is space for a total of sixteen cards on the controller, and most programs for the videomagnetograph require at least 14. This means that some care must be taken to program in a way that is economical of cards. Some tricks have been discovered that may be of use in saving cards and patchcords. Several general rules should be followed:

1. Do not rewire the same series of steps into a program more often than once unless absolutely necessary. Make full use of both ordinary subroutines and variable address routines.
2. Often, two output amplifiers are always activated together in the course of a program. For example, both movable heads may always be "homed" together. In such a case, it is convenient to wire the two amplifiers together with a piece of hook-up wire. (The pin jacks on the I/O panel will accept #20 wire.) Then only a single patchcord needs to be used to activate both outputs. This saves quite a few patchcords.
3. It is ordinarily necessary to use a separate loop card each time a particular sequence is repeated a different number of times than it was in previous loops. It is sometimes possible, however, if the sequence is short, to simply wire it in directly

if it is to be looped both N and N+1 times in the course of a program. This saves one card.

It is possible to wire one of the two start buttons to the continue input on a sequence card. In this way the program can pause to allow operator intervention. The program can be caused to continue by pressing the start button.

When the controller is first turned on, the various flip-flops in the logic cards come on in a random way. Pressing the clear button will reset all the program cards so that the program is ready to operate.

The controller should always be switched on with the manual/auto switch on the manual disc controller in the manual position. This will avoid damage to the disc due to improper commands being generated.

The patchcords have a built-in diode. The diode is located at one end of the card, giving that end a bulky appearance. Signals must always flow along the cord from the small end to the bulky end.

Programming for the disc recorder and the magnetograph configuration:

When the differential video photometer is in use as a magnetograph, the output panel of the automatic controller controls the following system functions. (In this section, "output" and "input" refer to the outputs and inputs of the automatic controller itself, i.e., to and from external equipment.)

W1, W2, W3, W4: These four output amplifiers control writing with the four video heads of the disc recorder. Only one of these functions should be actuated at any one time. It is not possible to write on more than one head at a time. No write function should be on for more than about 5 seconds, or damage may result to the disc recorder. The recorder writes video on the selected head as long as the output amplifier is kept at a high level. The usual way of writing video is to actuate the output for one clock cycle (that is, from an unpaused sequence card output). This results in exactly one frame of video being written. W1 and W2 control the two movable heads, W3 and W4 the fixed heads.

I1, O1, I2, O2: These outputs control the stepping of the movable heads in and out. A high level to one of these outputs causes the controlled head to step once for each clock pulse that occurs while the output is held high. Thus, these outputs are normally controlled by a sequence card which is paused for the same number of clock pulses as desired steps. I1 and O1 step head 1 in and out respectively. I2 and O2 control head 2.

R1, R2, R3, R4: These control reading video with the heads of the disc recorder. Heads 1 and 3 cannot be read simultaneously. Neither can heads 2 and 4. All other combinations are possible. Do not attempt to read and write on the same head simultaneously. Video will be read from the recorder as long as the output amplifier is kept at a high level. Video may be read continuously for any period of time without danger to the disc recorder.

H1, H2: These two outputs control the "homing" commands for the two movable heads. A high level on one of these outputs causes the head under control to run to its outermost track. A short time after the outermost track is reached, a pulse is sent back from the manual controller to inform the automatic controller that the head is at "home". The home outputs are normally actuated by a paused output on a sequence card. The sequence card continues to the next step in the program when the return pulse is received. At present, the manual controller is designed to return a pulse only when both heads are in the home position. Since both heads are always homed simultaneously in the programs in use up to now, it is necessary to make sure that both heads have reached the outermost track before continuing. The two home outputs are usually wired together to save patchcords.

E1, E2: These two outputs control the erasure of recorded images on the two movable heads. No erasure is possible on the fixed heads, successive frames being merely written over each other. For complete erasure of a frame the erase output amplifier need only be held high for a single clock cycle. No erase output should be held high for more than about 5 seconds.

1, 2, 4: These three outputs provide the binary code which selects the output of the multiplexer which feeds video to the disc video input. Whatever video is selected by this code is what is displayed on the monitor and what is written on the disc if a write command is given. The code is given in Table A2. (See also Figure 4 of the main text.)

TABLE A2

Code	MPXR OUTPUT
0	0
1	N(A + B)
2	10(C - D)
3	10(D - C)
4	-N'(A + B)
5	0'

F: This output causes the filter to switch. In the magnetograph, the "filter" is actually a quarter wave plate. On each rising edge fed to this output, the quarter wave plate rotates by 90^{o}. A return pulse tells the controller when the plate has finished rotating.

C: This output controls the camera which photographs the monitor. A rising edge here causes the camera to take one picture. A return pulse tells the controller when the picture has been taken.

Notice that it is often necessary to activate several outputs at a single step in a program. For example, if it is desired to read pictures off heads 1 and 2, average them, and write the result on head 3, the following outputs must be activated: R1, R2, 1, W3. Similarly, if it is desired to read pictures from heads 3 and 4, subtract them, and write the result on head 1, the outputs R3, R4, 1, 2 and W1 should be activated simultaneously. If the subtraction is desired in the opposite sense, the required outputs would be: R3, R4, 2, and W1.

Appendix IV gives a typical subtraction and averaging program for the magnetograph.

Debugging Programs:

Programs should be debugged with the manual/auto switch in the manual position. This is a precaution to avoid activating the write and erase outputs too long, and damaging the disc recorder.

A special high speed clock (about 1 KHz) is available for debugging. This clock should be plugged into the automatic controller in place of the system clock if much debugging is to be done. It allows the operator to run through the program much more rapidly, a considerable advantage when long programs are being debugged.

The usual method of debugging a program is to throw the interrupt switch, and step through the program one step at a time with the single-step button. In this way the particular step in the program giving trouble can be found. Apart from wiring errors, the most common sources of trouble are loose circuit cards and bad patchcords. A problem arising from one of these sources will always arise at the same point in the program. The progress of the program can be monitored by watching the readout lights, which will indicate which outputs are energized at any time.

Usually, when the program requires return signals from external equipment, these signals may be supplied during debugging by temporarily moving the patchcords which carry these pulses from their usual position at one of the input jacks to one of the start button terminals. Pressing the start button will then simulate the return pulse. (When the interrupt switch is thrown, it is necessary to hold down the start button and press the single-step button once while the start button is depressed in order to generate a pulse at a start terminal.)

Occasionally, the program will operate improperly while it is actually running the system, but will check out properly under debugging conditions. This usually means that some part of the system, such as a camera solenoid, or a head stepping motor, or a relay, is generating transients which are interfering with the program. In such a case, the source of the transients must be found and removed. In most cases the source is quite obvious from the point in the program at which the trouble occurs.

Transients generated outside the system will occasionally cause the program to operate improperly. Such transients will usually occur at irregular points in the program.

APPENDIX IV - A TYPICAL SUBTRACTION AND AVERAGING PROGRAM

The following program records 256 pictures on the movable heads of the disc recorder, 128 in right-hand circularly polarized light, 128 in left-hand circularly polarized light. The pictures are subtracted and averaged, taking care that the differences in response between heads 1 and 2 are subtracted out. The final result is displayed on the monitor and photographed.

This program has been used to make most of the magnetograms produced by the system to date. It is a program for the single-camera mode. In this system configuration, the camera is connected to multiplexer input 0, and multiplexer inputs A and C are shorted together, as are B and D. A and C are connected to the recorder output for heads 1 and 3, and B and D to the output for heads 2 and 4. Thus, a coding of R1, R2, 2, W3 would cause 10(head 1 - head 2) to be written on head 3. A coding of R1, R2, 1, W3 would cause N(head 1 + head 2) to be written on head 3. The effect of other codings should be evident.

The program has two major subroutines, one a variable address subroutine, the other not. The subroutines are:

Subroutine A:

Step	Coding
1.	W1, I2
2.	W2, I1

These two steps are repeated 63 times.

Cards required: 1 sequence card, 1 loop card.

Subroutine A includes a loop card which causes the given two step sequence to repeat 63 times. The subroutine writes a frame on one movable head while simultaneously stepping the other in one track. The frame comes from the television camera, since the multiplexer code for that source of video is zero.

Subroutine B:

Step	Coding
1.	R1, R2, W3, VAC1
2.	VAC2, I1, I2, Pause
3.	R1, R2, W4, VAC1
4.	R3, R4, 1, W1
5.	VAC2, I1, I2, Pause
6.	R1, R2, W3, VAC1
7.	VAC2, I1, I2, Pause
8.	R1, R2, W4, VAC1
9.	R3, R4, 1, W2
10.	VAC2, I1, I2, Pause

The coding VAC means that the output from that step goes to the input of one of the VAC cards associated with the subroutine. There are two, designated VAC1 and VAC2. The coding for the VAC outputs is given below:

VAC1:

Output	Coding
0	1
2	2
4	1, 2

VAC2:

0	Cont.
1	MLPC in, MLPC 3
2	MLPC in, MLPC 15

The coding "Cont." means that the output is patched to the continue inputs of the two sequence cards which make up the basic 10 step sequence of the subroutine.

The coding "MLPC in, MLPC n" means that the output is patched to the "in" input on the MLPC, and to the binary code for n on the MLPC. The MLPC output goes to the continue inputs on the two sequence cards.

This is the basic subtraction and averaging subroutine of the program. For example, if the subroutine is called with a code 2 for VAC1 and a code 0 for VAC2, then step 1 will record 10(head 1 - head 2) on head 3, step 2 will step heads 1 and 2 in one track, etc. If the subroutine is called with a code 0 for VAC1 and a code 1 for VAC2, then step I will record N(head 1 + head 2) on head 3, step 2 will step heads 1 and 2 in 4 track, etc. If the subroutine must be repeated several times, it must be called through a loop card. The loop card is started by the sequence card calling the subroutine, and the subroutine is then actuated the required number of times by the loop card. The end pulse from the loop card serves as the return pulse from the subroutine.

The main program is listed below, with only output wiring coded, except that VAC and loop coding is shown when subroutines are called and pauses are shown when they are necessary for proper interaction with external equipment. A coding of the form "I1 (n)" means that head 1 is stepped in n tracks. A coding of VAC1 (n) means that a binary code of n is patched to VAC1.

Main program:

Step	Coding
1.	F, pause
2.	W1
3.	W2, I1
4.	Call S.R. A

(continued)

Main program (continued):

Step	Coding
5.	F, pause
6.	Call S.R. A
7.	W1, I2
8.	W2
9.	H1, H2
10.	I2 (64)
11.	Call S.R. B, VAC1 (2), VAC2 (0), loop 16 times
12.	H1, H2
13.	I1 (64)
14.	Call S. R. B, VAC1 (4), VAC2 (0), loop 16 times
15.	H1, H2
16.	I1
17.	I2 (3)
18.	Call S. R. B, VAC1 (0), VAC2 (1), loop 8 times
19.	H1, H2
20.	I1 (5)
21.	I2 (15)
22.	Call S. R. B, VAC1 (0), VAC2 (2), loop 2 times
23.	H1, H2
24.	I1 (21)
25.	I2 (63)
26.	R1, R2, 1, W3
27.	I1 (64), I2 (64)
28.	R1, R2, 1, W4
29.	R3, R4, 1, C, pause

The functioning of this program is roughly as follows: Step 1 places the quarter-wave plate in the proper initial position. Steps 2 through 8 record the initial pictures, steps 9 through 14 make the initial subtractions, steps 15 through 28 do the averaging, and step 29 photographs the result. Sequences like steps 19 through 21 are for the purpose of placing the movable heads in the proper initial position to find the recorded results of the last stage of averaging. Notice that all reading and writing with the movable heads is done after stepping <u>in</u> to the track which is to be read or written on. (The only exception is the #1 track.) This is because backlash in the movable head makes it necessary to always read a track after stepping into it in the same direction in which it was stepped into when the picture to be read was recorded. If this is not done, a high noise level will be seen in the picture.

When the program is used for time-lapse magnetograms, it is normally connected in an infinite loop. A 30th step is added which is coded H1, H2, and the 31st step starts the first step again, in which case the program runs automatically in an infinite loop, taking about one magnetogram per minute. (It takes about 1 minute for the program to run.) The return pulse from the 16mm camera can be replaced by a pulse from one of the start buttons, in which case the final magnetogram remains displayed on the monitor until the button is pushed.

APPENDIX V - TROUBLESHOOTING

Every so often the disc recorder refuses to write anything on the disc. When this happens, attempt to read the frame just "written". If a pattern of moving noise is seen, unplug the card containing the disc modulator circuitry. Plug it back in. Do the same with the card containing the 1x4 f.m. switch that distributes the output of the modulator to the various heads. If the trouble is not gone, repeat the procedure. If the trouble is still not gone, unplug and plug the cards containing the demodulators and their associated switches. The trouble here seems to be some sort of progressive corrosion on the p.c. contacts. Cleaning the contacts only helps temporarily.

If the disc refuses to step one of its movable heads in properly after the head has just been homed to the outside track, the rack and pinion that drives the head has probably rusted. These are reportedly made from stainless steel, but they rust anyway. Stop the disc, remove the disc from its hub (following carefully the instructions for this procedure in the disc manual), put a drop of light machine oil on the rack and pinion and work the carriage back and forth a few times. This will temporarily fix the trouble. Under no circumstances touch the heads or the disc surface, or get any oil on them. If there is no time to go through this procedure, it is usually possible to continue to make magnetograms by either interrupting the program every time the head is homed and waiting a second or two to allow the carriage to force its way past the obstruction, or by soldering a larger capacitor into the home delay circuit in the manual controller. (See Appendix I.)

If spots or lines of lost picture elements appear in the magnetograms the disc is dirty and needs to be cleaned. Follow the instructions in the disc manual for cleaning the disc and the heads. Cleaning the disc does not always remove the drop-out, but it will often go away of its own accord after a while. If it does not, the disc is probably scratched, and will have to be replaced. If the scratch is on one of the fixed head tracks the head can be slightly repositioned by carefully rotating its mount about an axis normal to the plane of the mounting board with a small crescent wrench. Never make any adjustment to the disc without first completely familiarizing yourself with the instruction manuals. Note carefully: Just because a scratch is visible in the vicinity of the head does not mean that the scratch is causing any harm. Most do not. Only if the dropout does not go away after several days of use should the head be repositioned.

Since most damage to the disc occurs when the unit is turned on and off, the unit should be turned on in the morning and left on until there is no further use for it that day. There is no reason to be hypersensitive about this, and if it gets cloudy, or the disc seems to be malfunctioning, turn it off. Still, switching the disc on and off should be kept to a minimum.

Keeping a write command on the disc for more than about ten seconds will cause it to blow a very inaccessible fuse. The major danger of this occurs when the automatic controller is put in a paused mode with a "write" light on. Extensive program troubleshooting should be done with the manual/auto switch on the manual controller in the manual position. The controller can then be interrupted as long as desired with no danger to the disc. To replace the fuse see the disc manual.

For other problems not mentioned here, see the disc manuals and schematics. Other things go wrong sufficiently often that it is wise to have someone around who can troubleshoot a complicated electronic gadget with the level of aid provided in the disc literature. If the trouble is mechanical, the field service division of Data Disc, Inc. should be called.

APPENDIX VI

STATISTICAL ANALYSIS OF THE TWO-DIMENSIONAL RANDOM WALK

The random walk which will be assumed in this treatment will be a two-dimensional random walk with independent motions in each of the two dimensions. The distribution functions in the x and y directions are assumed to be:

$$P(x)dx = \frac{1}{\sqrt{2\pi\alpha t}} e^{-x^2/2\alpha t}$$

$$P(y)dy = \frac{1}{\sqrt{2\pi\alpha t}} e^{-y^2/2\alpha t}$$

(In a one-dimensional random walk with characteristic step time τ and characteristic step length L, $\alpha = L^2/\tau$. $t = N\tau$ where N is the number of steps. If a particle undergoes a large number of steps, the discrete distribution function becomes the continuous function given above.)

The two-dimensional distribution function is:

$$P(x,y)dxdy = P(x)dx \quad P(y)dy$$

$$= \frac{1}{2\pi\alpha t} e^{-(x^2+y^2)/2\alpha t} \, dxdy$$

Converting to polar coordinates, we have:

$$P(x,y)dxdy = P(r,\theta)drd\theta$$

$$= \frac{r}{2\pi\alpha t} e^{-r^2/2\alpha t} \, drd\theta$$

Since we are interested in the magnitude of the displacement:

$$P(r) = \int_{o}^{2\pi} P(r,\theta)d\theta$$

$$= \frac{r}{\alpha t} e^{-r^2/2\alpha t}$$

$$P(r)dr = \frac{r}{\alpha t} e^{-r^2/2\alpha t} dr \qquad (1)$$

This is a Rayleigh distribution. It will be of interest to calculate the expectation values of various powers of r:

$$\langle r^n \rangle = \frac{1}{\alpha t} \int_{o}^{\infty} r^{n+1} e^{-r^2/2\alpha t} dr$$

This integral can be evaluated in closed form:

$$\langle r^n \rangle = (\alpha t)^{n/2} n!! \sqrt{\pi/2} \qquad (n \text{ odd})$$

$$\langle r^n \rangle = (2\alpha t)^{n/2} \left(\frac{n}{2}\right)! \qquad (n \text{ even}) \qquad (2)$$

Let us now calculate the variance of r^2

$$\sigma_{r^2}^2 = \langle (r^2 - \langle r^2 \rangle)^2 \rangle$$

$$= \langle r^4 \rangle - \langle r^2 \rangle^2$$

$$= 8\alpha^2 t^2 - 4\alpha^2 t^2$$

$$= 4\alpha^2 t^2$$

Thus the standard deviation of r^2 is:

$$\sigma_{r^2} = 2\alpha t \qquad (3)$$

Also, from (2),

$$\langle r^2 \rangle = 2\alpha t \qquad (4)$$

Now consider a sample of n points with displacements r_i from an infinite population with distribution (1)

$$\text{Let } \overline{r^2} = \frac{1}{n} \sum_{i=1}^{n} r_i^{\,2}$$

then

$$\langle \overline{r^2} \rangle = \langle r^2 \rangle \text{ , so}$$

$\overline{r^2}$ can be used to estimate $\langle r^2 \rangle$.

$$\text{Let } S_{r^2}^{2} = \frac{1}{n-1} \sum_{i=1}^{n} (r_i^2 - \overline{r^2})^2 \text{, then}$$

$$\langle S_{r^2}^{2} \rangle = \sigma_{r^2}^{2} \text{ so } S_{r^2} \text{ can be used to estimate } \sigma_{r^2}.$$

Now the standard deviation of $\overline{r^2}$ is given by:

$$\sigma_{\overline{r^2}} = \frac{1}{\sqrt{n}} \sigma_{r^2} = \frac{\langle r^2 \rangle}{\sqrt{n}}$$

$$\cong \frac{\overline{r^2}}{\sqrt{n}}$$

Let $r_{RMS} = \sqrt{\overline{r^2}}$.

The standard deviation for r_{RMS} is given approximately by:

$$\sigma_{RMS} \cong \sigma_{\overline{r^2}} \frac{dr_{RMS}}{d\,\overline{r^2}}$$

$$= \frac{\sigma_{\overline{r^2}}}{2r_{RMS}} \qquad \text{or}$$

$$\sigma_{RMS} = \frac{r_{RMS}}{\sqrt{4n}} \qquad (5)$$

σ_{RMS} can be measured directly as:

$$\sigma_{RMS} = S_{r^2}/2r_{RMS}\sqrt{n} \tag{6}$$

We now derive a statistical test for the significance of an observed departure of the measured value of σ_{RMS} from the value given by equation (5). This test is due to Dr. G. Lorden (Lorden, 1971).

Let $r^2 = x^2 + y^2$ where x, y are independent random variables with normal distributions with mean 0, variance σ^2.

Let $W = (r^2 - \langle r^2 \rangle)^2$

then $\langle W \rangle = 4\sigma^4$

$\langle W^2 \rangle = 144\sigma^8$

Var $(W) = 144\sigma^8 - (4\sigma^4)^2 = 128\sigma^8$.

If we now consider the variables $(r_i^2 - \langle r^2 \rangle)^2$ we see that they are independent with mean $4\sigma^4$ and variance $128\sigma^8$. We can thus appeal to the central limit theorem to find a limiting distribution as $n \to \infty$.

<u>Central Limit Theorem</u>:

If x_i are independent variables with mean a and variance σ^2 then as $n \to \infty$ $\frac{1}{n}\sum_{i=1}^{n} x_i$ follows the normal distribution with mean a and variance σ^2/n.

Now $(r_i^2 - \langle r^2 \rangle)^2$ are independent variables with mean $4\sigma^4$ and variance $128\sigma^8$ $\therefore$

$$\frac{1}{n}\sum_{i=1}^{n} (r_i^2 - \langle r^2 \rangle^2 \equiv q$$

follows a normal distribution with mean $4\sigma^4$ and variance $\frac{1}{n}128\sigma^8$ as $n \to \infty$ $\therefore$

$$Q' = \frac{q-\langle q\rangle}{\sigma(q)}$$

$$= \frac{\frac{1}{n}\sum_{i=1}^{n}(r_i^2-\langle r^2\rangle)^2-4\sigma^4}{\frac{\sqrt{128}\,\sigma^4}{\sqrt{n}}}$$

$$= \frac{\sum_{i=1}^{n}(r_i^2-\langle r^2\rangle)^2-4n\sigma^4}{\sqrt{n}\,\sqrt{128}\,\sigma^4}$$

$$= \frac{\sum_{i=1}^{n}(r_i^2-\langle r^2\rangle)^2}{\sigma^4\sqrt{128\,n}} - \frac{4\sqrt{n}}{\sqrt{128}}$$

has a standard normal distribution.

Now if we replace $\langle r^2\rangle$ by $\overline{r^2}$ where

$$\overline{r^2} = \frac{1}{n}\sum_{i=1}^{n} r_i^2$$

we have an error:

$$e = \sum_{i=1}^{n}(r_i^2-\langle r^2\rangle)^2 - \sum_{i=1}^{n}(r_i^2-\overline{r^2})^2$$

$$= \sum_{i=1}^{n} 2r_i^2(\overline{r^2}-\langle r^2\rangle) + \langle r^2\rangle^2 - \overline{r^2}^{\,2}$$

Now:

$$\langle e \rangle = \langle \frac{2}{n} \sum_i \sum_j r_i^2 \, r_j^2 \rangle - 2n\langle r^2\rangle^2 + n\langle r^2\rangle^2$$

$$- \langle \frac{1}{n} \sum_i \sum_j r_i^2 \, r_j^2 \rangle$$

$$= \frac{2}{n} \left[(n-1)n \, \langle r^2\rangle^2 + n\langle r^4\rangle\right]$$

$$\frac{1}{n} \left[(n-1)n\langle r^2\rangle^2 + n\langle r^4\rangle\right]$$

$$- \; n\langle r^2\rangle^2$$

$$= (n-1)\langle r^2\rangle^2 + \langle r^4\rangle - n\langle r^2\rangle^2$$

$$= \langle r^4\rangle - \langle r^2\rangle^2$$

$$= \mathrm{Var}(r^2) = (32-4)\,\sigma^4 = 28\,\sigma^4$$

So we want

$$Q' \rightarrow \frac{\sum_{i=1}^{n} (r_i^2 - \overline{r^2})^2 + 28\,\sigma^4}{\sqrt{n}\;\sigma^4\,\sqrt{128}} - \sqrt{\frac{n}{8}}$$

$$= \frac{\sum_{i=1}^{n} (r_i^2 - \overline{r^2})^2}{\sqrt{n}\,\sigma^4\,\sqrt{128}} - \sqrt{\frac{n}{8}} + \frac{28}{\sqrt{128n}} \rightarrow$$

$$\frac{\sum_{i=1}^{n} (r_i^2 - \overline{r^2})^2}{\sqrt{n}\,\sigma^4\,\sqrt{128}} - \sqrt{\frac{n}{8}} \quad \text{as} \quad n \rightarrow \infty$$

Now $\overline{(r^2)}^2 = \frac{1}{n^2} \sum_i \sum_j r_i^2 \, r_j^2$

$$\langle \overline{(r^2)}^2 \rangle = \frac{1}{n^2} \left[n(n-1) \langle r^2 \rangle^2 + n \langle r^4 \rangle \right]$$

$$= \frac{n-1}{n} \langle r^2 \rangle^2 + \frac{1}{n} \langle r^4 \rangle$$

$$\rightarrow \langle r^2 \rangle^2 \quad \text{as } n \rightarrow \infty$$

$$\langle r^2 \rangle^2 = 4\sigma^4$$

$$\therefore \quad \frac{\overline{(r^2)}^2}{4} = \sigma^4 \quad \text{for large n.}$$

thus define:

$$Q = \frac{\sum_{i=1}^{n} (r_i^2 - \overline{r^2})^2}{\overline{(d^2)}^2 \sqrt{8n}} - \sqrt{\frac{n}{8}} \qquad (7)$$

Now for $n \gtrsim 50$, Q has a standard normal distribution, and the significance of any departure from the expected value of σ_{RMS} may be assessed by computing Q.

Finally, the probability of finding n or fewer points out of a sample of N in a circle of radius r_o, if the points belong to an infinite population with the distribution function (1) is given by:

$$\sum_{i=1}^{n} \frac{N!}{i!(N-i)!} \left[P(r< r_o)\right]^i \left[P(r> r_o)\right]^N$$

where

$$P(r< r_o) = \int_o^{r_o} \frac{r}{\alpha t} e^{-r^2/2\alpha t}$$

$$= - e^{-r^2/2\alpha t}$$

$$= 1 - e^{-r_o^2/2\alpha t}$$

and

$$P(r< r_o) = 1 - P(r< r_o) = e^{-r_o^2/2\alpha t}$$

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