The Kitt Peak Magnetograph
III. Automation and the 40-Channel Probe

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INTRODUCTION

In this paper we describe the 40-channel magnetograph primarily as an example of the automated data system at the McMath Solar Telescope. The principles of the magnetograph itself have been recently given in paper I (Livingston and Harvey, 1970), while the reduction and interpretation of data is covered in paper II (Harvey and Livingston, 1970).

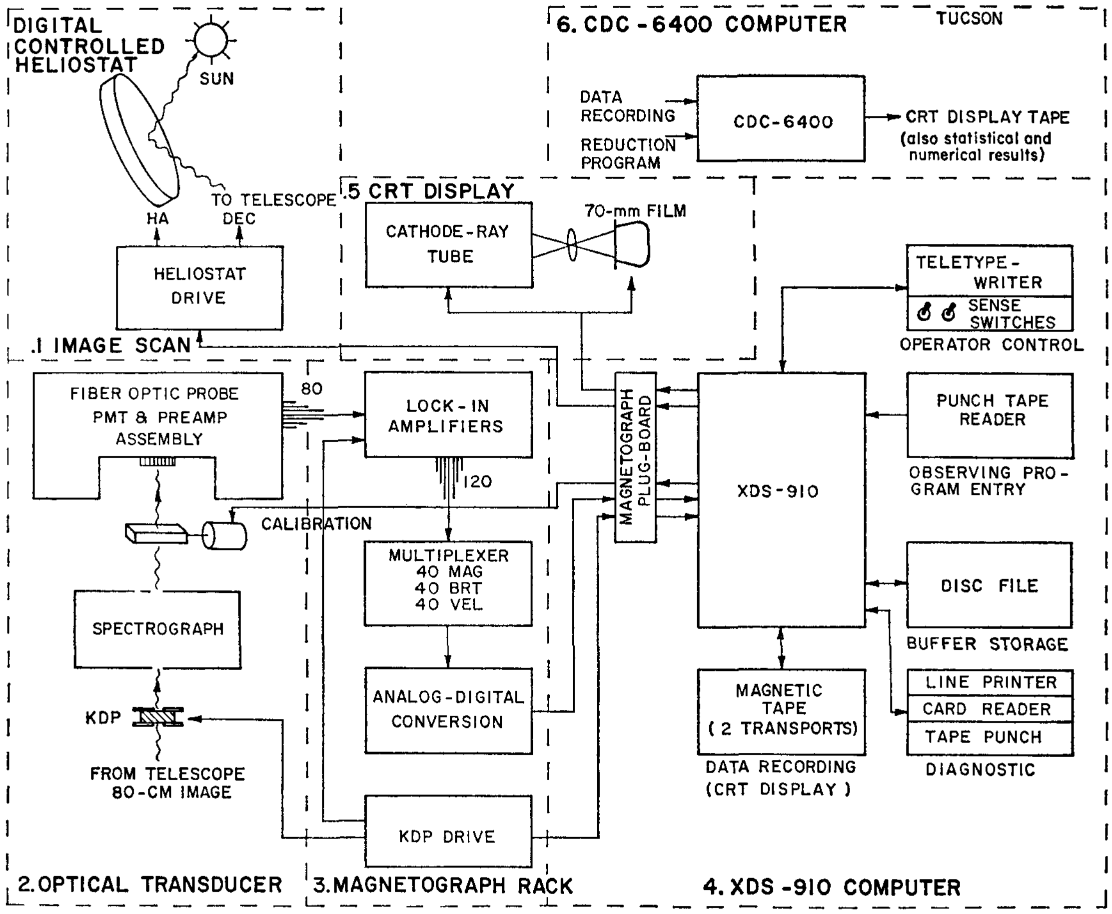

Fig. 1
Block diagram of the magnetograph computer system. The Line Printer, Card Reader and Tape Punch are not used in the observing process but are essential to program preparation and diagnostics.

The 40-channel magnetograph is an expanded version of a Babcock-type magnetograph. Our object is to record the magnetic, brightness and velocity data simultaneously from as many spatial elements as possible. Because the maximum scan speed of a photoelectric system is fundamentally limited by the photon flux, an expansion to a multi-element system is desirable to obtain better resolu-

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tion in the presence of imperfect "seeing". Examples will be given that show this aim is realized; photoelectric magnetograms having a resolution comparable to that of the photographic method are now obtained. Moreover, the sensitivity and quantitative aspects of the photoelectric method are preserved.

A few years ago such a 40-channel instrument would not have been practical. Today the availability of integrated circuit (IC) modules, miniature photomultipliers, fiber optics and all the associated computer equipment renders this design not only practical but actually conservative. Based on our experience with this instrument even larger arrays of photosensors can be considered.

THE MAGNETOGRAPH-COMPUTER SYSTEM

Figure 1 contains a block diagram of our system and indicates a logical decomposition into five, or possibly six units. Proceeding through the components we have (1) the *Digital Controlled Heliostat* which generates the image scan; (2) the *Optical Transducer* consisting of the fiber optic probe which dissects the spectral-line image and feeds the 80 photomultiplier tube (PMT) array; (3) the *Magnetograph Rack* which amplifies and digitizes the PMT signals; (4) the *XDS*-910 *Computer* which runs and orders the system; and (5) the cathode ray tube (*CRT*) *Display* which presents the reduced data in pictorial form. While the CRT can operate on-line as shown, the complexity of certain data display problems requires at present that the reduction of data and preparation of a display tape be done on the (6) *CDC*-6400 *Computer* located 80 km away in Tucson. If this step is included, the data recording, *i.e.* a magnetic tape, is taken to Tucson, processed, and returned to the mountain at a later date for display filming.

We now discuss each of these units in more detail.

Digital Controlled Heliostat

Solar image scanning is accomplished through the heliostat which can be moved in hour angle (HA) and declination (DEC) at various rates. The HA and DEC axes are each powered by a DC servo motor to which is connected a coaxial incremental digital encoder. The computer loads a rate R (arcsec s^{-1}) into a buffer register at time t_0. In response to this loading an oscillator then produces a continuous pulse train proportional to this rate which is fed to an up-down counter (Trumbo, 1969). Output from the (HA and DEC) heliostat encoders are also fed to the respective up-down counters. A voltage proportional to the instantaneous count is generated which drives the motors. Additional stabilization is by an auxiliary DC Velocity feedback which reduces overshoot about the desired rate. If at a later time t_1 the loaded rate R is set to zero the image position will finalize at a distance $R(t_1-t_0)$ arcsec from the starting point. For large rate changes it is necessary to wait for time periods of up to 1 sec for the feedback loop to correct overshoot introduced by the inertia of the telescope system. In both HA and DEC, $R_{max} = 100$ arcsec s^{-1}, and the minimum increment is $\Delta HA = .054054 \cos$ (DEC) arcsec and $\Delta DEC = .066666$ arcsec.

For observations where the image is to be moved only a short distance (<250 arcsec), or held fixed, the rate R can be supplied by limb guiders in place of the computer. These guiders are ordinarily set on a table above the spectrograph and can be translated with small motor drives at speeds up to 1 arcsec s^{-1}.

The highest data collection efficiency is realized in an open-loop condition called the "step-scan". In this mode the image is held in a fixed position, integration of the signals takes place for some selected time interval and then is terminated. The image is stepped one spatial element and the sequence is repeated. The sequencing frequency must be selected to avoid the mechanical resonant frequency of the heliostat.

Optical Transducer

The magnetograph operates as an accessory to the 13.7-metre vertical spectrograph (see Fig. 2). Above the entrance slit is an analyzer for circularly polarized light consisting of a KDP (potassium di-deuterium phosphate) electro-optic crystal, driven sinusoidally to a maximum retardation of $\pm\lambda/4$ at 10 kHz, followed by a (linear polarizer) polaroid. In the focal plane of the spectrograph, in place of the usual double exit-slit arrangement of Babcock, a fiber optic probe spans 0.50Å of each wing of a Zeeman sensitive Fraunhofer line, *e.g.* Fe I λ5233Å, and dissects the image into 1 mm sections perpendicular to dispersion. There are 40 such sections feeding 40 pairs of EMI 9524C PM tubes.

Immediately below this probe is a tipping glass plate that centers the line on the probe in response to the summed difference signals from the 40 PMT pairs. For field calibration this plate is placed under computer control. A D-A convertor generates a voltage which turns the plate through a small angle so as to introduce line displacements equivalent to known magnetic fields.

Besides the probe arrangement specified above, five additional probes are available providing higher spatial resolution and different equivalent slit widths (see Livingston and Harvey, 1970, paper IV, for details). The PM tubes are balanced in pairs across the spectrum line and normalized in gain to produce a 0.5 μA anode current when observing at the center of the solar disk. A small field-effect input operational amplifier provides a DC to 30 kHz bandwidth coupling between the photomultipliers and the electronics rack through a 10-metre interconnecting cable.

Magnetograph Rack

In the system as originally conceived the computer was to sample the PMT outputs directly in an appropriate manner to abstract the magnetic, brightness and velocity signals. The sample was to be taken synchronously and in constant phase with the 10 kHz KDP modulation. However, it was found that our "fast" computer was in fact about 100 times too slow for this task. Conventional analog amplification and detection was therefore employed.

Complete processing of the analog signals for each channel, including the phase-sensitive detection, is accomplished on 12×22 cm printed circuit cards of our own design and manufacture (Fig. 3). Each card contains 11 IC operational amplifiers, 2 reed-relays for remote change of gain or frequency, and 4 switching transistors. Since each IC Op-Amp contains 22 transistors, there are 224 per board, or $40 \times 224 = 8940$ in all. We comment that over the first six months of operation not a single component has failed!

As shown in Figure 1, output from the amplifier cards are directed within the rack to a multiplexer and also to summing amplifiers. (The latter are incidental to the operation of the Doppler correction servo). At the entry point of the multiplexer an RC filter effectively removes any unwanted high frequency pickup or extraneous noise. Besides the 120 data signals ($40 \times$ mag, brt, vel) other signals such as the position angle of the Doppler plate and servo error may be sampled, the multiplexer channel capacity being 144.

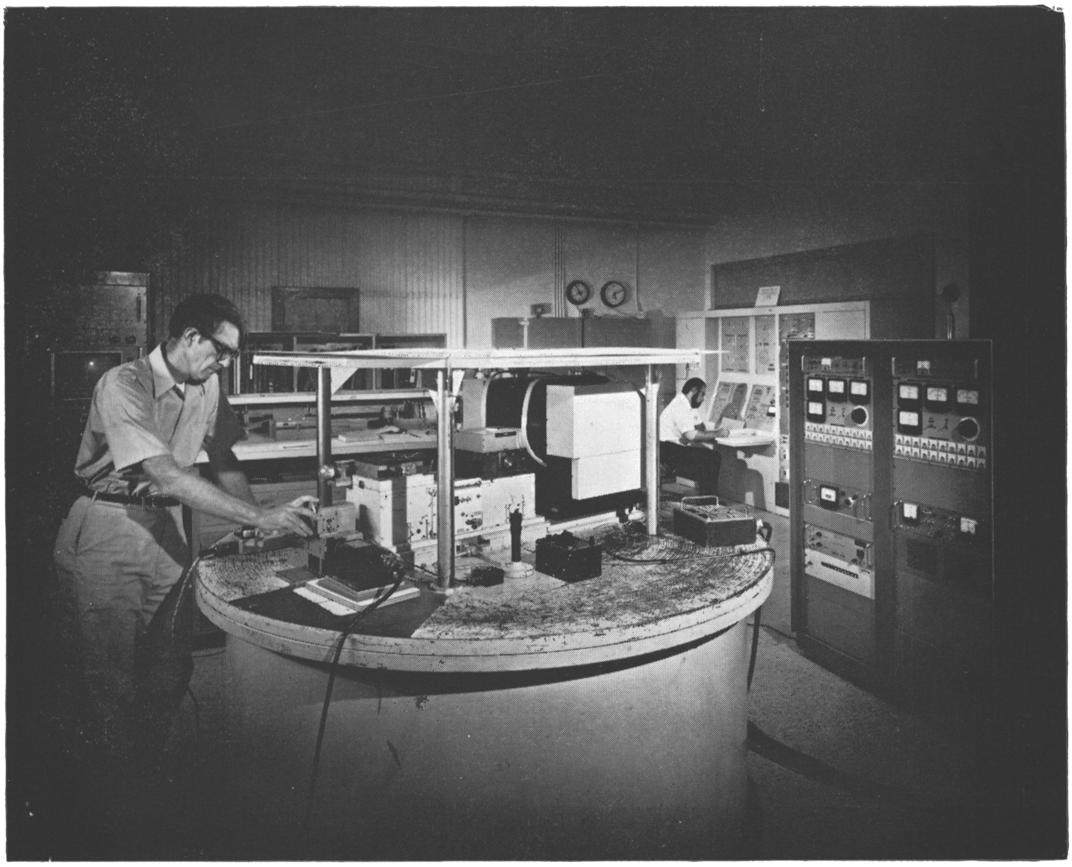
The multiplexer is followed by a 14-bit plus sign analog-to-digital (A-D) converter. A total of 36 lines interconnect the magnetograph and the computer.

XDS 910 Computer

The 40-channel system is completely controlled by the 910 computer and cannot be operated independently of it. The 910 is a general-purpose, stored program computer equipped especially for real time data acquisition. It has a 16 800–word, 24-bit core memory plus a 250 000-word Random Access Disk File. It was installed in the observing room in 1965 and plans for continued use extend into the indefinite future. Its reliability has been good and the main limitation is an 8 μs cycle time which can be considered slow as previously noted. Crucial to reliability has been (a) the installation of an inertial flywheel power converter that isolates the computer from line voltage surges (or interruptions < 1.5 s) and (b) the construction of a temperature-controlled enclosure. (Besides the magnetograph program the computer is central to many other observing tasks, particularly photoelectric photometry, and it is even used for photographic work where it can serve as a timer and sequencer. We will not attempt further description of the 910 system, but rather will now illustrate by example the way it is used with the 40-channel probe.)

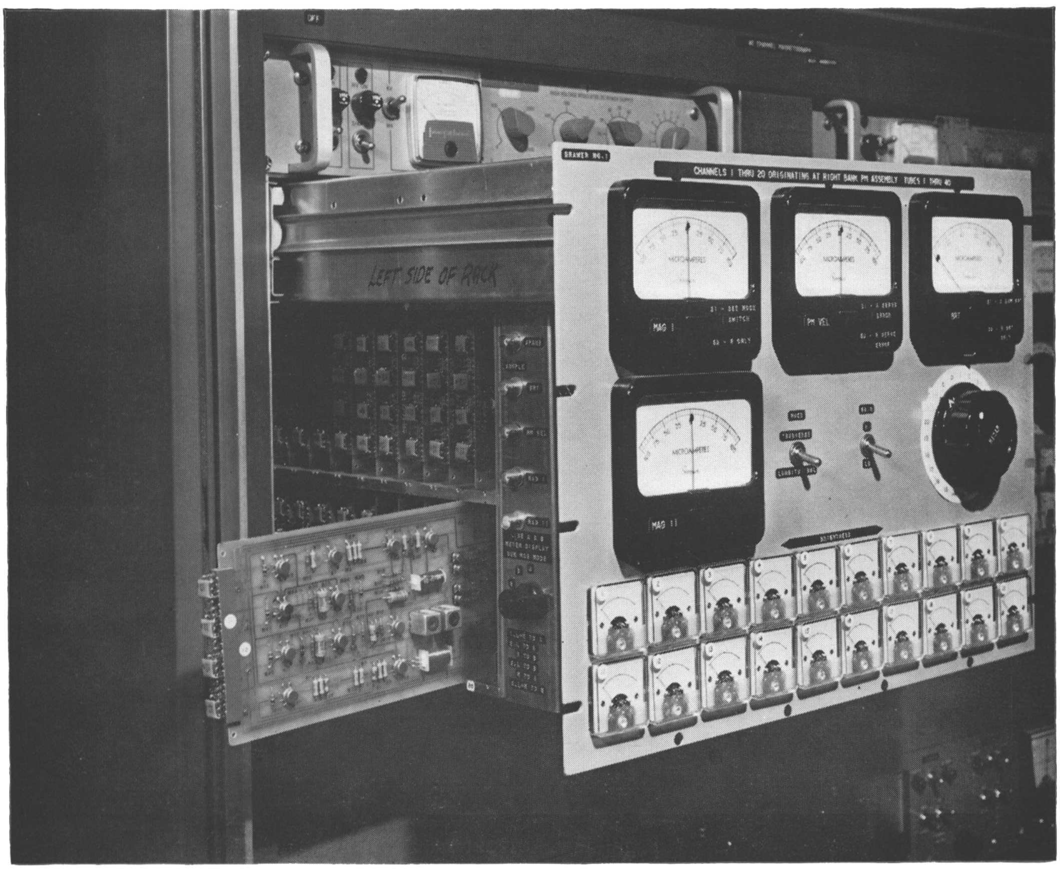
Assuming the magnetograph is in correct optical adjustment and that cables are connected, etc., an observation proceeds as follows. One turns on the computer power, mounts a reel of magnetic tape on the transport and loads the magnetograph program with a punched tape reader. Also a prewired plugboard is inserted, interconnecting the magnetograph signals to the computer. All further communication is via the typewriter and six "sense" switches mounted on it.

The program tests the Disk File and then types detailed instructions for making an observation. Figure 4 is an example of the communication between the observer and the computer, with the operator's replies underlined. Such a narration might become tiresome to one familiar with the process, but to the occasional observer it is an invaluable guide. From a beginning condition with the solar image centered, except for inserting and removing a circular polarizer during calibration the computer has full command, moving the image about, operating the tape transport, etc. When making a full disk



LIVINGSTON *et al.* Fig. 2

View of the arrangement of the optical transducer on the 13.5 m vertical spectrograph. The magnetograph rack is seen to the right and the heliostat master control is in the background.



LIVINGSTON *et al.* Fig. 3

Open drawer of magnetograph rack exposing a circuit board that holds the complete analog circuit for one channel. Capacitors fixing the output time constant are mounted on the printed circuit connector for interchangeability.

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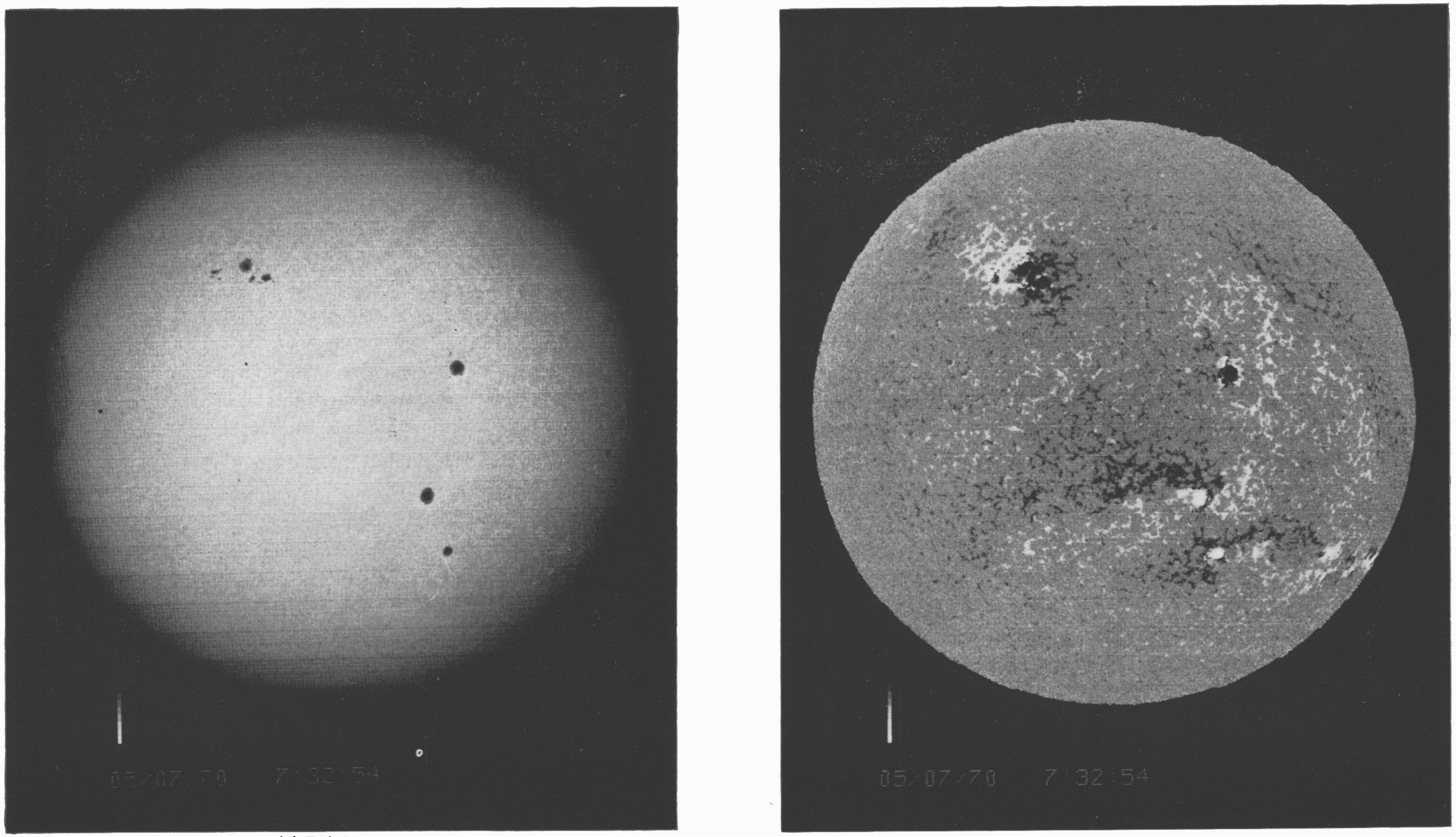

(a) Brightness. (b) Magnetic Fields.

LIVINGSTON *et al.* Fig. 5
Full Disk magnetogram for 7 May 1970.

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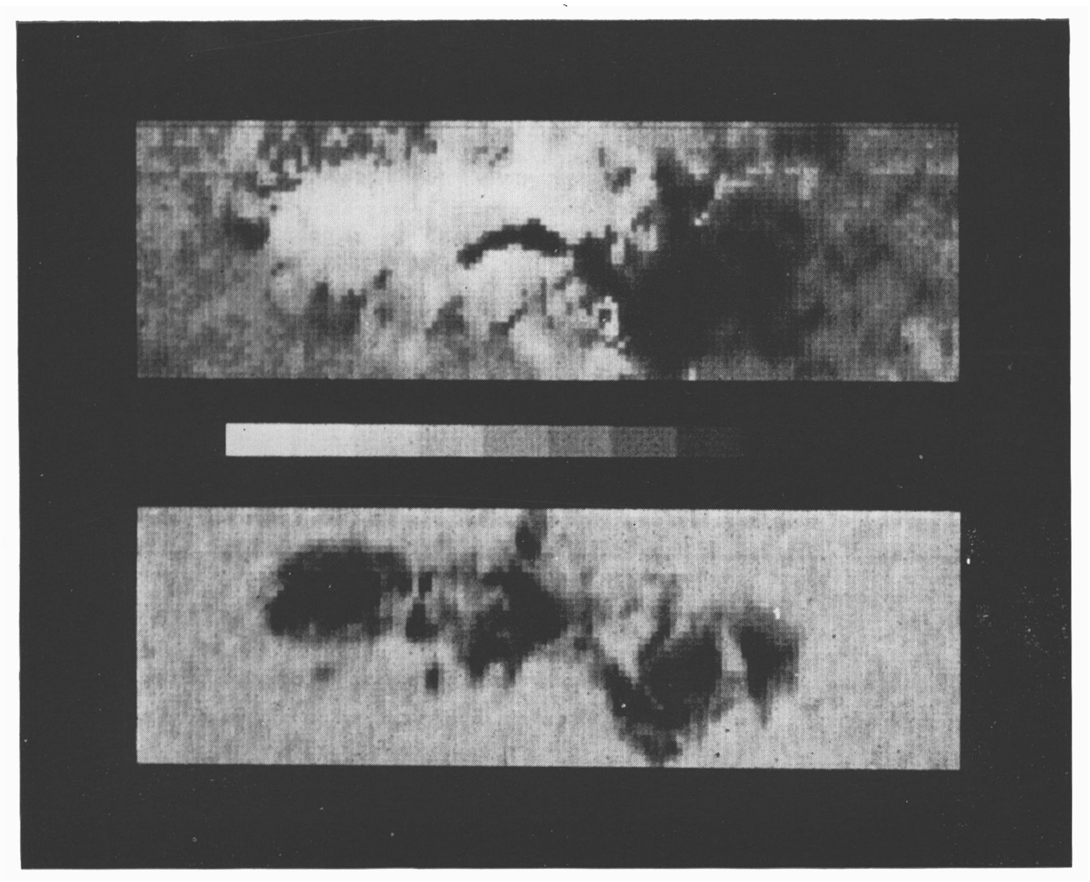
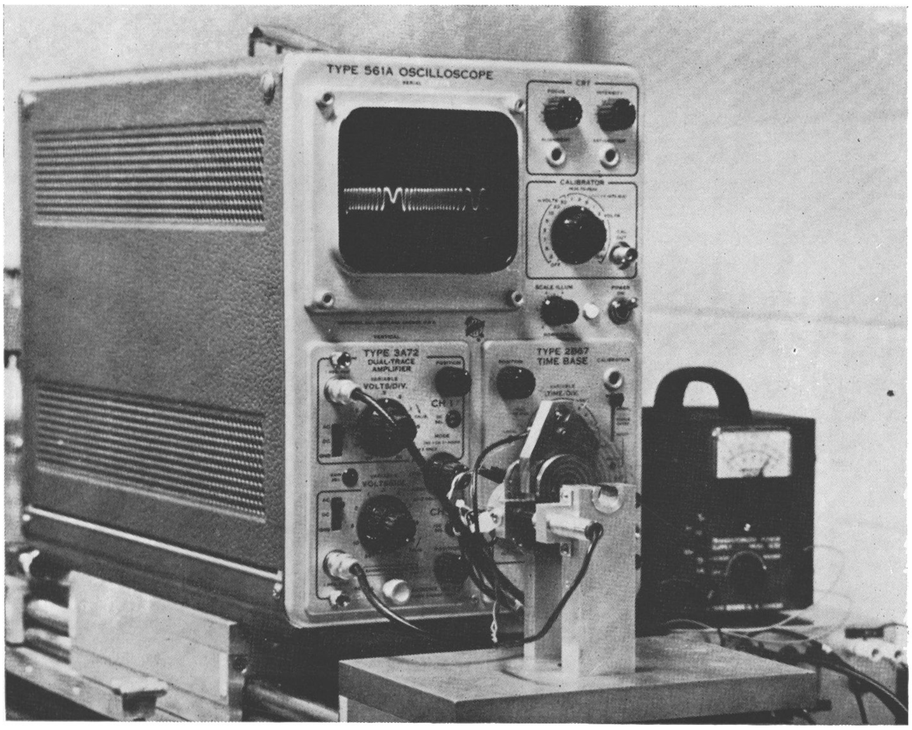


LIVINGSTON *et al.* Fig. 6
Low resolution "Step Scan", 40-channel swath, illustrating use of square-spot display, 15 May 1970.



VILLAMEDIANA AND FREDERICK Fig. 7

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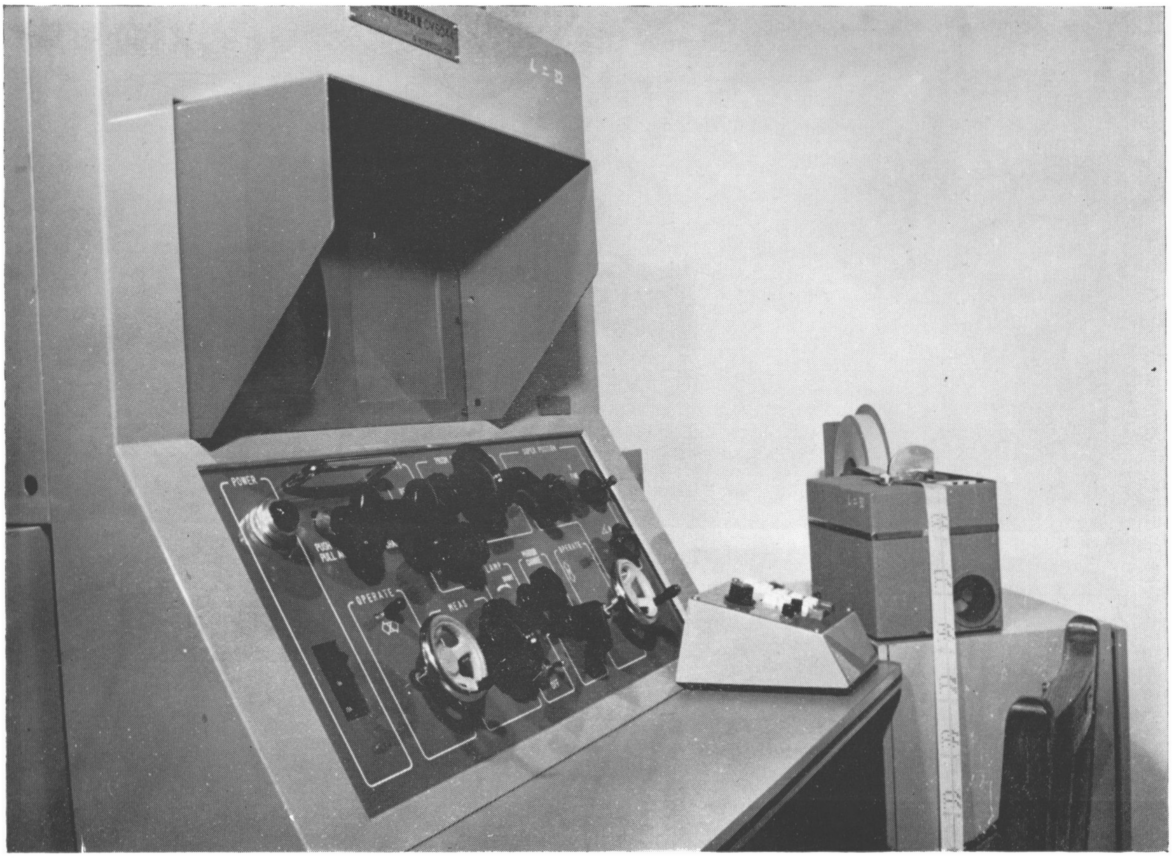

STRAND Fig. 1
A front view of the U.S. Naval Observatory automatic measuring machine.

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magnetogram the magnetic data are converted to gauss, and written directly onto the disk along with the brightness information. During the retrace, or "flyback", portion of the TV-type raster scan, the data are transferred to the magnetic recording tape.

The Full Disk observation has a running time of 40 min., yet, except during the flyback interval, the computer is occupied at 70 per cent of maximum capacity.

```
READY TAPE ON CHANNEL 0
DISC TEST IN PROGRESS
THE PROGRAM HAS THE FOLLOWING OPTIONS
        SWITCH 1 SET FOR FULL DISC
        SWITCH 3 SET FOR STEP SCAN WITH INTEGRATION, RESET TO END THE OBSERVATION
        SWITCH 2 STOPS THE SCAN AFTER EACH SWATH, IF SET, RESET TO CONTINUE
SW 1 OR 3 MUST BE SET BEFORE ANYTHING WILL PROCEED   Switch 3 was set
DISC TEST COMPLETED
SET SWITCH 6 TO ENTER DATE/TIME
TYPE GO WHEN READY  GO
ENTER DATE (MMDDYY)   061870
ENTER TIME (HHMMSS)   072700            Done while watching clock
RESET SWITCH 6 AT TIME                  with sweep-second-hand.
ENTER DECLINATION OF SUN (DD.D)23.4
TURN OFF KDP, CENTER IMAGE AND SET SS6 WHEN READY TO START AVERAGING
TURN ON KDP, INSERT CIRCULAR POLARIZER
TYPE GO WHEN READY  GO
TO OBTAIN MAGNETIC CALIBRATION ENTER VOLTAGE TO TURN DOPPLER COMPENSATING PLATE,
TYPE (V.VV)   0.20
THE ACCESSORY RACK DIGI-SWITCHES, (WORDS 6,7,8) HAVE THE FOLLOWING FUNCTIONS
        WORD 6 = THE NUMBER OF INTEGRATIONS AT EACH POSITION
        WORD 7 = THE NUMBER OF STEPS (LENGTH OF OBSERVATION)
        WORD 8 = THE STEP SIZE IN TENTHS OF MILLIMETERS
TURN ON DOPPLER SERVO, REMOVE CIRCULAR POLARIZER

POSITION IMAGE TYPE GO WHEN READY. GO
OBS AT  7 31  1 COMPLETED
POSITION IMAGE TYPE GO WHEN READY  GO
OBS AT  7 34 14 COMPLETED
```

04288

Fig. 4

Program narration with observer's reply from actual run.

CRT Display

Because of the large number of spatial elements involved (6×10^5 in the case of a full disk magnetogram) the data are most conveniently presented as "continuous" tone pictures rather than as contour maps or lists of numbers, Figure 5.

The display unit was designed and constructed at the observatory. It uses a 5-inch Westinghouse WX-4129 P11 CRT with magnetic deflection and an additional double axis electro-static micro-deflection. This micro-deflection is (optionally) operated at about 10 MHz to produce a square shaped spot. Low resolution pictures are improved in appearance with the square spot (see Fig. 6), and overlaying for correlation purposes is made easier. The unit has no internal compensation for pincushion distortion and focus error but depends on computer supplied correction voltages (from the 910 D-A). These corrections accompany position and brightness information for each point plotted. Obviously the CRT also cannot function without the computer.

A range of picture brightness is produced by varying the length of time the constant intensity spot, or square, is displayed. The ON time is quantized in units of one part in 256. The transfer characteristic is intrinsically linear. It can be altered by programming in the reduction process to produce an overall linear transfer including the film. Using Kodak 2492 emulsion about 15 clearly distinct levels of intensity can be produced.

Most commonly the CDC-6400 in Tucson prepares a CRT magnetic tape from the data record made at the telescope. However, for low-resolution simple displays the CRT can function on-line as the data are received. Rates up to 5 frames a sec are feasible, in which case a 35 mm pulse camera is used in place of the 70 mm magazine.

FURTHER COMMENTS

The performance of the 40-channel magnetograph has exceeded our expectations both as to quality and reliability. The surprise in quality comes about through the ability of the computer to

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normalize, adjust and make homogeneous the responses of the 40 individual channels. Reliability is largely a consequence of the nature of the integrated circuit. Evidently much larger arrays will prove useful in the future.

ACKNOWLEDGEMENTS

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DISCUSSION

J. RÖSCH: You showed us how computers can replace girls—I should have added to my speech this morning what girls can do and not computers!

R. B. DUNN: I'd like to ask Dr. Livingston if he'd do it any way differently now, or do exactly the same?

W. C. LIVINGSTON: Oh no, we'd do it differently. As indicated, our approach has been conservative. Continuing improvements in micro-circuit technology would make feasible larger arrays of channels.

P. J. TREANOR: How long does a complete scan of the Sun take?

W. C. LIVINGSTON: 40 minutes. We're limited at the moment in the speed at which the telescope can be moved with precision. If we moved the image any faster, of course, there'd be a sacrifice of signal-to-noise. We make a television-type raster, not boustrophedonic, so a lot of time is taken in flyback.