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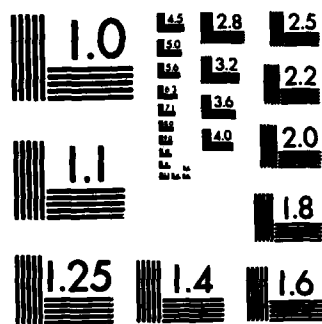
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VECTOR MAGNETIC FIELD ANALYSIS OF
LORENTZ FORCES ACTING IN THE
SOLAR ATMOSPHERE

K. Krall
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Huntsville, AL 35899

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AIR FORCE GEOPHYSICS LABORATORY
AIR FORCE SYSTEMS COMMAND
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transfer to the chromosphere. Noise within the data is found to be insignificant, while calibration uncertainties are large. An algorithm list is provided. Keywords included: Flares, and Energy buildup.

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1. INTRODUCTION

Evaluating the role of electric currents in the energy storage process within coronal and chromospheric magnetic fields has been limited mainly to comparing field lines extrapolated from observed longitudinal photospheric values to emission features assumed to be field-aligned (Tanaka and Nakagawa, 1973; Hagyard, 1976; Levine, 1976; Krall, et. al., 1978). These calculations have been done using arbitrary and overly simplistic constant- α ($= \mu_0 \underline{J}/\underline{B}$, where $\underline{J}$ is the current density, $\underline{B}$ the magnetic field, and μ_0 the permeability in free space) assumptions concerning current distributions. Measuring the transverse component of the photospheric field allows a unique opportunity to obtain information about α -distribution and thus the Lorentz forces exerted on the overlying layers. Unfortunately, utilizing an observationally deduced α -distribution to compute the force-free field in the region above the observing plane is in general an intractable, nonlinear boundary value problem. However, a method exists for determining net Lorentz forces and magnetic energy within a force-free region without explicit solution of the field equations (eg. Molodensky, 1974). The purpose of this paper is to examine the utility of such a method, within the limitations of available vector magnetic field observations, in determining energy exchange between photospheric fields and the overlying atmosphere. Such a method may be potentially useful in real time for identifying modes and levels of energy buildup in the preflare active region.

A discussion of pertinent equations is presented in Section 2. In order to properly evaluate the results, measurement and calibration uncertainties are discussed in sections 3 and 4. Although the interpretation

of transverse measurements is subject to significant uncertainty, correlative observations may be utilized to test the integrity and resultant conclusions of the measurements (e.g., photospheric proper motion may be found to be consistent with generation of the $\underline{J} \times \underline{B}$ forces inferred from the measured fields). Section 5 presents application of the previously discussed formalism to two sets of Marshall Space Flight Center Vector Magnetograph data, a flare productive and migrating delta-configuration spot on 6 April 1980 and a large but rather simple (beta-gamma) region on 15-16 September 1980.

2. Theoretical Formulation

The vector sum of all electromagnetic forces acting within a volume V above the photosphere can be written as:

$$\underline{F} = \frac{1}{c} \int_V \underline{J} \times \underline{B} \, dV \quad (2-1)$$

where c is the velocity of light and we assume electric fields to play a negligible role due to the high electrical conductivity. Using Maxwell's equations

$$\underline{J} = \frac{c}{4\pi} (\underline{\nabla} \times \underline{B}) \quad (2-2)$$

$$\text{and} \quad \underline{\nabla} \cdot \underline{B} = 0, \quad (2-3)$$

Equation (2-1) can be written

$$\begin{aligned} \underline{F} &= \int_V \frac{1}{4\pi} \left[(\underline{\nabla} \times \underline{B}) \times \underline{B} + \underline{B} (\underline{\nabla} \cdot \underline{B}) \right] dV \\ &= \int_V \frac{1}{4\pi} \left[(\underline{B} \cdot \underline{\nabla}) \underline{B} - \frac{1}{2} \underline{\nabla} B^2 + \underline{B} (\underline{\nabla} \cdot \underline{B}) \right] dV. \end{aligned} \quad (2-4)$$

The integral in Equation (2-4) can be identified as the divergence of the second rank Maxwell's stress tension $\overset{\leftrightarrow}{T}$,

$$\overset{\leftrightarrow}{T} = \frac{1}{4\pi} (\underline{B} \cdot \underline{B} - \frac{1}{2} \overset{\leftrightarrow}{I} B^2) \quad (2-5)$$

whose elements are

$$T_{ij} = \frac{1}{4\pi} \left(B_i B_j - \frac{1}{2} \delta_{ij} B^2 \right) \quad (2-6)$$

where

$$\begin{aligned} \delta_{ij} &= 1 & i &= j \\ &= 0 & i &\neq j. \end{aligned} \quad (2-7)$$

Thus, the volume integral Equation (2-4) can be replaced by an integral over the surface S containing V:

$$\begin{aligned} F &= \int_V \underline{\nabla} \cdot \vec{T} \, dV \\ &= \int_S \underline{n} \cdot \vec{T} \, dS \end{aligned} \quad (2-8)$$

where $\underline{n}$ is the outward direction unit normal to S. In a similar fashion, the net electromagnetic torque $\underline{\tau}$ acting within a volume can be shown to be

$$\begin{aligned} \underline{\tau} &= \frac{1}{c} \int_V \underline{r} \times (\underline{J} \times \underline{B}) \, dV \\ &= \int_V \underline{r} \times (\underline{\nabla} \cdot \vec{T}) \, dV \\ &= \int_S \underline{n} \cdot (\vec{T} \times \underline{r}) \, dS \end{aligned} \quad (2-9)$$

where $T_{ij} = T_{ji}$ is used to arrive at Equation (2-9) and $\underline{r}$ is the position vector of a lever arm. Thus, if a volume enclosing chromospheric coronal

fields is appropriately chosen to give zero contribution to Equations (2-8) or (2-9) on all but the photospheric surface, a complete specification of $\underline{B}$ on that level is sufficient to determine a lower limit (net) to the magnetic forces or torques exerted on the volume. The work done by the photospheric fields and any resulting magnetic energy buildup cannot, of course, be determined by this method. In the absence of chromospheric or coronal magnetic field data, these can only be inferred indirectly (e.g. by changing fibril structure or energy release).

The net forces and torques, and total magnetic energy (which is derived similarly) can be expressed in Cartesian coordinates using longitudinal (z direction) and transverse (x-y plane) field measurements.

$$\text{horizontal force } F_x = \frac{-1}{4\pi} \sum_{x,y} B_z \cdot B_x \cdot \Delta S$$

$$\text{and } F_y = \frac{-1}{4\pi} \sum_{x,y} B_z \cdot B_y \cdot \Delta S, \quad (2-10)$$

$$\text{vertical force } F_z = \frac{-1}{8\pi} \sum_{x,y} \left(B_z^2 - B_x^2 - B_y^2 \right) \cdot \Delta S, \quad (2-11)$$

$$\text{torque about a vertical axis } \tau = \frac{1}{4\pi} \sum_{x,y} B_z \left(B_x \cdot \Delta y - B_y \cdot \Delta x \right) \cdot \Delta S, \quad (2-12)$$

$$\text{and energy } E = \frac{1}{4\pi} \sum_{x,y} B_z \left(B_x \cdot \Delta x + B_y \cdot \Delta y \right) \cdot \Delta S. \quad (2-13)$$

3. Measurements

The MSFC Vector Magnetograph utilizes a .125 μ Zeiss filter, tunable to 10 m μ increments within the FeI 5250.2 μ line. All observations discussed here are centered at $\lambda = 60, 90$ or 120 m μ in the blue wing of that line. The measured components of the magnetic field are assumed to be

$$B_z = k C_1(\Delta\lambda) P_V(\Delta\lambda) \quad (3-1)$$

$$B_T = \left(B_x^2 + B_y^2 \right)^{1/2} = k^{1/2} C_2(\Delta\lambda) P_Q(\Delta\lambda) \quad (3-2)$$

where the fractional circularly-polarized intensity

$$P_V = \left(I_1 - I_2 \right) / \left(I_1 + I_2 \right), \quad (3-3)$$

and linearly polarized intensity

$$P_Q = \left(U^2 + R^2 \right)^{1/2} \quad (3-4)$$

and

$$U = \left(I_3 - I_4 \right) / \left(I_3 + I_4 \right), \quad R = \left(I_5 - I_6 \right) / \left(I_5 + I_6 \right) \quad (3-5)$$

are functions of the MSFC Vector Magnetograph raw intensity counts described in Table I. The direction ϕ of the tranverse field where

$$B_x = B_T \cos \phi$$

and

$$B_y = B_T \sin \phi, \quad (3-6)$$

is found as

$$\phi = .5 \tan^{-1} (U/R). \quad (3-7)$$

The values for C_1 , C_2 were determined from theoretical calibration curves derived from the Kjeldseth Moe solutions to the radiative transfer equations (Kjeldseth Moe, 1968) for penumbral and umbral atmospheric models.

The parameter k represents a scaling factor which adjusts measured polarization for loss of contrast and was determined by scaling the maximum B magnitude with that of Mt Wilson measurements. Corrections for linear and circular crosstalk in the MSFC data are discussed in the following paragraphs.

Average background (quiet sun) measurements of P_V and P_Q are normally used to look for linear and circular polarization biases. Typically, no circular bias is present; however, random linear polarization biases are found and are attributed to the magnetograph's correlation tracker subsystem. Figure 1 a-d shows an example of the distribution of weak field polarization values used in determining these biases. Figure 2 a-d shows corresponding distributions after correcting for bias.

Circular crosstalk, the effect of coupling circular into linear polarization measurements in strong field areas, must also be considered in the calibration process to eliminate biasing ϕ . Figure 3 a,b are scatter plots of U and R vs P_Q , with the linear least squares fits showing the artificial correlation induced by crosstalk. A correction factor has been introduced in Figure 4 a,b to eliminate the correlation.

4. Error Analysis

The effects of signal to noise and calibration must be estimated in order to determine the integrity of the measurements. This section describes the treatment of noise in the linear and circular polarization measurements used to derive longitudinal and transverse fields.

The physical parameters to be evaluated are Equations (2-10) through (2-13) and direction of horizontal force:

$$\theta = \tan^{-1} \left(\frac{F_y}{F_x} \right).$$

Gaussian statistics are used to determine the standard deviation at each pixel i,j :

$$\left(\sigma_T^2 \right)_{ij} = \left\{ B_z^2 \left(\Delta y^2 \sigma_{B_x}^2 + \Delta x^2 \sigma_{B_y}^2 \right) + \sigma_{B_z}^2 \left(\Delta y B_x - \Delta x B_y \right)^2 \right\} \Delta S^2, \quad (4-1)$$

$$\left(\sigma_E^2 \right)_{ij} = \left\{ B_z^2 \left(\Delta x^2 \sigma_{B_x}^2 + \Delta y^2 \sigma_{B_y}^2 \right) + \sigma_{B_z}^2 \left(\Delta x B_x + \Delta y B_y \right)^2 \right\} \Delta S^2, \quad (4-2)$$

$$\left(\sigma_{F_x} \right)_{ij} = \left\{ B_z^2 \sigma_{B_x}^2 + B_x^2 \sigma_{B_z}^2 \right\} \Delta S^2,$$

$$\left(\sigma_{F_y} \right)_{ij} = \left\{ B_z^2 \sigma_{B_z}^2 + B_y^2 \sigma_{B_z}^2 \right\} \Delta S^2,$$

$$\left(\sigma_{F_z}^2 \right)_{ij} = 4 \left\{ B_z^2 \sigma_{B_z}^2 + B_x^2 \sigma_{B_x}^2 + B_y^2 \sigma_{B_y}^2 \right\} \Delta S^2, \quad (4-3)$$

$$\sigma_\theta^2 = \left[\frac{1}{1 + (F_y/F_x)^2} \right]^2 \left[\frac{1}{F_x^2} \sigma_{F_y}^2 + \frac{F_y^2}{F_x^4} \sigma_{F_x}^2 \right]. \quad (4-4)$$

Equations 3-1 through 3-9 are used to determine the field uncertainties:

$$\sigma_{B_z}^2 = \left(2C_1 k \right)^2 \left(\sigma_{I_1}^2 I_2^2 + \sigma_{I_2}^2 I_1^2 \right) / \left(I_1 + I_2 \right)^4 \quad (4-5)$$

$$\sigma_{B_x}^2 = \sigma_{B_T}^2 \cos^2 \phi + B_T^2 \sum_{i=3,6} \left(\frac{\partial \cos \phi}{\partial I_i} \right)^2 \sigma_{I_i}^2 \quad (4-6)$$

$$\sigma_{B_y}^2 = B_T^2 \sin^2 \phi + B_T^2 \sum_{i=3,6} \left(\frac{\partial \sin \phi}{\partial I_i} \right)^2 \sigma_{I_i}^2 \quad (4-7)$$

where

$$\sigma_{B_T}^2 = C_2^2 k \left(U^2 \sigma_U + V^2 \sigma_R \right) / 4 \left[U^2 + R^2 \right]^{3/2} \quad (4-8)$$

and

$$\begin{aligned} \frac{\partial \cos \phi}{\partial I_3} &= - \left[\frac{.5}{1+x^2} \right] \frac{2I_4 R^{-1}}{(I_3 + I_4)^2} \sin \phi \\ \frac{\partial \cos \phi}{\partial I_4} &= \left[\frac{.5}{1+x^2} \right] \frac{2I_3 R^{-1}}{(I_3 + I_4)^2} \sin \phi \\ \frac{\partial \cos \phi}{\partial I_5} &= \left[\frac{.5}{1+x^2} \right] \frac{U}{R^2} \frac{2I_6}{(I_5 + I_6)^2} \sin \phi \\ \frac{\partial \cos \phi}{\partial I_6} &= \left[\frac{.5}{1+x^2} \right] \frac{U}{R^2} \frac{2I_5}{(I_5 + I_6)^2} \sin \phi \\ \frac{\partial \sin \phi}{\partial I_i} &= \frac{\partial \cos \phi}{\partial I_i} \operatorname{ctn} \phi \end{aligned} \quad (4-9)$$

Appendix A lists the algorithm developed during this effort and used

on MSFC data to calculate Equations 2-10 through 2-13 and θ , as well as standard deviations 4-1 through 4-4. Input from data files are raw intensities I_1 through I_6 and processed fields B_z , B_x , B_y (i.e., after calibrations and elimination of the 180° ambiguity in transverse field direction).

The standard deviation in the raw data (σ_{I_i}) produces the spread in the zero-field distributions (σ_{P_Q} and σ_{P_V}) in Figure 2. Equations 4-5 through 4-7 can therefore also be written in terms of measured σ_{P_Q} and σ_{P_V} , and are written so within the present code.

5. Results

In an earlier calculation (Krall, et al. 1982), a small, migrating and flare producing portion of Boulder SESC AR2372 (Figure 5) was evaluated using the equations of Section 2.

For the 48 hour period containing the maximum photospheric proper motion and flare activity, Figure 6 shows the direction of horizontal magnetic force for the area containing the small westward moving positive spot. The calculated force was directed within 30 degrees of the observed motion of the spot during the time of maximum spot motion and flare activity, changing significantly (and decreasing somewhat) outside of that time period. This is as expected if the photospheric motions act to magnetically transfer forces to the overlying atmosphere. Such forces can of course be dissipated rapidly or stored in a higher energy magnetic configuration. The later possibility is more likely here due to the high flare activity of the period.

Although AR2372 was an extremely interesting region from the viewpoint of this analysis, several factors combined to complicate the interpretation:

1. There are possibly strong field saturation effects.
2. Region complexity made difficult the task of eliminating the 180 degree ambiguity in the direction of the transverse field component.
3. Inadequate observations at greater than 60 mÅ from the line center increased the possibility of magneto-optical effects (West and Hagyard, 1983).
4. There was insufficient time resolution for an analysis of magnetic energy buildup or dissipation for such a rapidly evolving region (During the period an M or X class flare occurred on the average every 5 hours and C class flare every 8 hours).

It was therefore decided that a region of less spatial and temporal complexity was needed to properly evaluate the potential of this type of analysis. Boulder SESC # AR2665 (Figure 7), a simple large spot region on its second disk transit, was well observed at 90 and 120 mÅ on September 15 and 16, had little indication of saturation at those wavelengths, and was by its single spot nature, relatively easy to treat for its transverse field direction ambiguity. Its most significant characteristics were a large leader spot (of positive polarity) and a lack of pronounced magnetic complexity.

During the first few days of its rotation across the visible disk, AR2665 did exhibit some complexity and some evidence of sheared B_T fields, and produced several relatively small flares near the weakly sheared neutral line. Flare history (Figure 8) and magnetic history (Figure 9) both reached maxima from September 11 - 13.

The region had been simplifying, and continued to simplify during the period of interest. Between 15/1349UT and 16/1359UT (Figure 7a and c) the B_L gradients along the neutral line had decreased, the field strengths (both B_L and B_T) had declined near the neutral line, and the B_T configuration had become more potential appearing (orthogonal to the $B_L = 0$ line) in orientation.

The more frequent flare activity occurred before the times of the Lorentz force evaluation (Figure 8), with only one C1 and 2 subflares without associated x-rays occurring during the 72 hours after the beginning of the analysis. AR2665 had been reported as a beta-gamma region (somewhat magnetically complex) but by the 15th, observations of the magnetic field indicated it to be a simple beta (simple bipole) magnetic configuration.

Figure 10 shows physical parameters (Equations [2-11] through [2-13]) for a 24 hour period during the decay of region AR 2665. Points to be emphasized are:

1. Signal to noise is seen in all cases to be small compared to time variation and observing wavelength variation.
2. Although wavelength variation is only available at one time point in Figure 10 (actually a twenty minute period at 2000 UT on 15 September), the results are consistent with a measurement degradation as one approaches line center, e.g., a negative vertical force at 60 mÅ requires unlikely submerging magnetic flux or upward counter-forces. Such degradation is consistent with magneto-optical effects; in fact, detailed analysis for this region shows that reliable transverse field directions may be obtainable only at $\Delta\lambda > 120$ mÅ (West and Hagyard, 1983). In addition, the tightening spiral configuration suggested by the divergence in torque with decreasing observation wavelength is also consistent with magneto optical effects.
3. In the declining phase of AR 2665, available energy is seen to decay by 10^{32} ergs/day. If this is not an observational effect, significant energy release over a relatively short time period (10^{32} ergs/few hours) might be claimed to have been observed.
4. Upward vertical force decreases during the 24 hours; this could be interpreted as a declining rate of emerging flux. A declining, yet always positive rate of emerging flux is to be expected during the demise of an active region. (This upward energy flux would be more than compensated for by dissipative processes during the decay phase, whereas the converse would be true during region growth.)

6. Concluding Remarks

We have developed and utilized a procedure for evaluating the potential role of 3-component photospheric magnetic field measurements for studying the magnetic energy buildup process within solar active regions. We have applied the equations to two regions and the results appear encouragingly consistent with expectations, both as a function of time (physical variations) and wavelength (observational variations). Further evidence is presented that these type observations must be made at or greater than 90 mÅ from line center.

Important questions as yet to be answered during the validation process are:

1. Does the measured vertical magnetic force increase during early active region growth (when emerging flux is most apparent), reach a maximum, and then decay within the proper time frame? This is probably not answerable within the lifetime of single active regions, but can be approached by studying regions in each phase of growth.
2. Do proper spot motions (or rotations) show up as increased horizontal magnetic force (torque), and can these motions now be more quantitatively linked to magnetic energy buildup and release?

7. Appendix: Algorithm Listing

```

C      THIS PROGRAM CALCULATES THE 3 COMPONENTS OF NET FORCE, TORQUE,
C      ENERGY AND THE SIGNAL/NOISE UNCERTAINTIES ASSOCIATED WITH THEM
C      INPUT FROM TAPE 9 IS THE OBSERVED PHOTOSPHERIC BX,PY AND BZ
C      INPUT FROM TAPE 10 IS I1,I2,...I6 RAW DATA CORRESPONDING TO FIELD
C      STRENGTHS FROM TAPE 9
C      DIMENSION SIGT(41,41),SIGE(41,41),R(3,41,41),IR(6),AM(10)
C      DIMENSION F(3),YORIGN(10),XORIGN(10)
C      DIMENSION C1OLD(6),C1NEW(6),C2OLD(6),C2NEW(6)
C      DIMENSION RTPHI(41,41)
C      REAL KNEW(6)
C      REAL KOLD(6)
C      REAL IT(6,41,41)
C      REAL KFACT
C      REAL I56,I34,I56P,I34P,I12,I12P

C
C      DATA YORIGN/19.,16.,16.,19.,15.,5*.0/
C      DATA XORIGN/25.,23.,24.,23.,25.,5*0./

C
C      DATA IR/1,2,3,4,5,0/
C      UMBRAL MODEL
C      DATA C1NEW/4374.,2707.,3195.,4374.,4374.,0./
C      DATA C1OLD/6690.,3182.,4311.,6690.,6690.,0./
C      DATA C2NEW/3628.,2568.,2910.,3628.,3628.,0./
C      DATA C2OLD/4437.,2591.,3191.,4437.,4437.,0./
C      DATA KNEW /7.18,9.16,8.56,7.03,6.72,0./
C      DATA KOLD /4.7,7.8,6.35,4.6,4.4,0./
C      DATA AM/1.,0.,0.,1.,0.,0.,4*0./
C      DS=2.5*725E5
C      PI=3.14159
C      DTOR=PI/180.
C      MAX PI/2 UNCERTAINTY IN DIRECTION
C      SPHIMX=PI/2.
C      FRPI=4.*PI
C      DEFINE SIGPQ, SET INITIAL GUESS ON SIG3**2
C      SIGPQ=.001
C      SIG32=170.

C
C      DO 10 KTAPE1=1,6

C
C      INITIAL TIME FOR FINDING INTENSITY VARIANCES,SUCEEDING TIMES FOR
C      CALC PHYSICAL SIGMAS
C      KTAPE=KTAPE1
C      IF(KTAPE1.GT.1) KTAPE=KTAPE1-1
C      IF(KTAPE.EQ.1) REWIND9
C      RESET VARIABLES
C      GO TO 100
109 CONTINUE
C      READ DATA
C      GO TO 120
129 CONTINUE
C      LOOP THROUGH DATA ARRAY, CALCULATING UNCERTAINTIES
C      GO TO 140
149 CONTINUE

```

```

C      DTDFY=F(2) / (F(2)**2 + F(3)**2)
      DTDFX=-F(3) / (F(2)**2 + F(3)**2)
      TAUTOT=TAU/TAUTOT
      ETOT=EN/ETOT
      FXTOT=F(2)/FXTOT
      FYTOT=F(3)/FYTOT
      TAU=TAU*DS*DS*DS/FRPI
      EN=EN*DS*DS*DS/FRPI
      DO 2 I=1,3
2      F(I)=F(I)*DS*DS/FRPI
      FHMAG=SQRT(F(2)*F(2) + F(3)*F(3))
C      ROTATE BACK TO X-Y COORDS
C      FX=F(2)*COS(20.*DTOR)-F(3)*SIN(20.*DTOR)
C      F(3)=F(2)*SIN(20.*DTOR)+F(3)*COS(20.*DTOR)
C      F(2)=FX
      THETA=F(3)/F(2)
      THETA=ATAN(THETA)/DTOR
      IF(ITP.EQ.0) GO TO 9
      SIGTH2=SIGFX*DTDFX**2 + SIGFY*DTDFY**2
      SIGDEG=SQRT(SIGTH2)/DTOR
      SIG32P= SIGPQ * SIGPQ * (ISTOP-ISTART+1) * (JSTOP-JSTART+1)/DPQDI2
      IF(KTAPE1.EQ.1) SIG32=SIG32P
      SIGT(10,J0)=SQRT(SIGT(10,J0))*DS*DS
      SIGE(10,J0)=SQRT(SIGE(10,J0))*DS*DS*DS/FRPI
      SIGFZ=SQRT(SIGFZ)*DS*DS/FRPI
      SIGFX=SQRT(SIGFX)*DS*DS/FRPI
      SIGFY=SQRT(SIGFY)*DS*DS/FRPI
9      CONTINUE
      WRITE(6,6)
6      FORMAT(///,50H TORQUE ENERGY FZ FX FY )
      WRITE(6,7) TAU,EN,(F(I),I=1,3)
      WRITE(6,7) SIGT(10,J0),SIGE(10,J0),SIGFX,SIGFY,SIGFZ
      WRITE(6,7) TAUTOT,ETOT,FXTOT,FYTOT ,FHMAG
      WRITE(6,8) SIGDEG,SIG32,SIG32P,THETA,SIGPQ
8      FORMAT(//
$      14H SIGMA THETA= ,E10.3,25H D SIGMA INTENSITY USED,E10.3,
$25H SIGM INTENSITY CALC=,E10.3,10H THETA=,F5.1,
$12H SIGM PQ=,E8.2)
7      FORMAT(5E10.3)
10     CONTINUE
      STOP
C      * * * * B L O C K 1 0 0 * * * *
C
C      INITIALIZE VARIABLES
C
100    CONTINUE
C      RESET VARIABLES
      ITP=IR(KTAPE)
      WRITE(6,107)
103    FORMAT(1H1)
      WRITE(6,102) KTAPE,ITP
102    FORMAT(2I10)
      SIG12=SIG32
      SIG22=SIG32
      SIG42=SIG32
      SIG52=SIG32

```

(BLKC)


```

SIG62=SIG32
C   IKNOWN=0 FOR K ONLY KNOWN, 1 FOR K,C1,C2 KNOWN
IKNOWN=1
KFACT=KNEW(KTAPE)
C   KFACT=4.
C   C1=1000.
C   C2=1000.
C1=C1NEW(KTAPE)
C2=C2NEW(KTAPE)
JG=XORIGIN(KTAPE)
IC=YORIGIN(KTAPE)
TAU=0.
EN=0.
SIGT(IC,J0)=0.
SIGE(IC,J0)=0.
SIGFX=0.
SIGFY=0.
SIGFZ=0.
SIGQ2=0.
DPGDI2=0.
DO 101 I=1,3
101 F(I)=0.
THETA=0.
SIGTH2=0.
ETCT=0.
TAUTOT=0.
FXTOT=0.
FYTOT=0.0
GO TO 109

```

* * * * B L O C K 1 2 0 * * * *

(BLKC)

```

C   120 CONTINUE
C   READ DATA FILES
C   READ(9) M,N,(((B(K,I,J),J=1,N),I=1,M),K=1,3)
C
C   WRITE(6,124)
124  FORMAT(1H1)
WRITE(6,123)((B(1,I,J),J=1,39,2),I=1,39,2)
123  FORMAT(20F6.0)
DO 125 I=1,M
DO 125 J=1,N
BTPHI(I,J)=ATAN(B(3,I,J)/B(2,I,J))/DTOR
IF(B(3,I,J).LT.0..AND.B(2,I,J).LT.0.) BTPHI(I,J)=BTPHI(I,J)-180.
IF(B(3,I,J).GT.0..AND.B(2,I,J).LT.0.) BTPHI(I,J)=BTPHI(I,J)+180.
125  CONTINUE
WRITE(6,124)
WRITE(6,123)((BTPHI(I,J),J=1,39,2),I=1,39,2)
WRITE(6,124)
C
C
C   PEWIND 10
IF(ITP.EQ.0) GO TO 122
DO 121 ITAPE=1,ITP

```

```

IF(AM(ITP).EQ.1.) READ(10)((IT(K,I,J),I=M,1,-1),J=N,1,-1),K=1,6)
IF(AM(ITP).EQ.0.) READ(10)((IT(K,I,J),I=1,M),J=1,N),K=1,6)

```

```

121 CONTINUE
122 CONTINUE
GO TO 129

```

***** BLOCK 140 *****

(BLK0)

```

140 CONTINUE
C LOOP THROUGH DATA ARRAY
C

```

```

ISTOP=M
JSTART=1
JSTOP=N
ISTART=1
ICLK=ISTART+3
JCHK=JSTART+3
RECOVER RAW DATA

```

```

DO 141 I=1,M
DO 141 J=1,N
DO 141 KCAL=1,6
141 IF(IT(KCAL,I,J).LT.0.) IT(KCAL,I,J)=IT(KCAL,I,J)+65536.

```

```

C
C
C USE CORRECT OR UPDATED CONSTANTS
C

```

```

COR1=1.
COR2=1.

```

```

COR2=SQRT(KNEW(ITP)/KOLD(ITP))*C2NEW(ITP)/C2OLD(ITP)
COR1=KNEW(ITP)*C1NEW(ITP)/(KOLD(ITP)*C1OLD(ITP))

```

```

C
C
C DO 148 I=ISTART,ISTOP
DI=I-ID
DO 147 J=JSTART,JSTOP
DJ=J-JD
B(1,I,J)=B(1,I,J)*COR1
B(2,I,J)=B(2,I,J)*COR2
B(3,I,J)=B(3,I,J)*COR2
BX= B(2,I,J)
BY=B(3,I,J)
BZ=B(1,I,J)

```

```

C
C
C CALCULATE PHYSICALS
GO TO 1000

```

```

1000 CONTINUE

```

```

C
C CORRECT SIGNS OF B IF NECESSARY( Y UP,BX TO RIGHT,BZ OUT OF PLANE)
BX=-(B(2,I,J)*COS(20.*DTOR)+B(3,I,J)*SIN(20.*DTOR))
FY=- B(2,I,J)*SIN(20.*DTOR)+B(3,I,J)*COS(20.*DTOR)
BZ=B(1,I,J)
RT=SQRT(BX*BX+BY*BY)
IF(ITP.EQ.C) GO TO 147

```

```

C      IF CALIBRATION CONSTANTS NOT KNOWN, CALCULATE THEM
C
1019  IF(IKNOWN.EQ.0.AND.I.EQ.ISTART.AND.J.EQ.JSTART) GO TO 1010
C      CONTINUE
C      CALCULATE INTENSITY DIFFERENCES,SUMS
      I56= IT(5,I,J)-IT(6,I,J)
      I56P=IT(5,I,J)+IT(6,I,J)
      I34= IT(3,I,J)-IT(4,I,J)
      I34P= IT(3,I,J)+IT(4,I,J)
      I12= IT(1,I,J)-IT(2,I,J)
      I12P= IT(1,I,J)+IT(2,I,J)
C      CALCULATE U,V,SIGU,SIGV
      U= I34/I34P
      V= I56/I56P
      UVMAG=U*U+V*V
      U2V2= (U/I34P)**2 + (V/I56P)**2
C      DPQDI2=DPQDI2 + 2.*KFACT*KFACT*U2V2 / (U*U+V*V)
      DPQDI2=DPQDI2 + 2. * U2V2 / (U*U+V*V)
      SIGU= (1.-U)**2 * (SIG32 + SIG42)/(I34P*I34P)
      SIGV= (1.-V)**2 * (SIG52 + SIG62)/(I56P*I56P)
C      IF(KTAPE.EQ.4)
C      $WRITE(6,144) I56,I56P,I34,I34P,I12,I12P,U,V,UVMAG,U2V2,SIGU,SIGV
144  FORMAT (12E10.3)
C
C      DETERMINE DIRECTION PARAMETERS
      GO TO 1020
1029  CONTINUE
C      GO TO 1050
C1059  CONTINUE
C      CALCULATE R SIGMAS
      GO TO 1030
1039  CONTINUE
C      CALCULATE PARAMETER SIGMAS, CHECK FOR LARGE TERMS
      GO TO 1040
1049  CONTINUE
147  CONTINUE
148  CONTINUE
      GO TO 149

C      * * * * B L O C K   1 0 0 0   * * * *
C
1000  CONTINUE
C
C      CALCULATE FORCES,ETC.
C      TORQUE = BZ * (BX * DY -PY*DX)
      T=BZ*(BX*DI-BY*DJ)
      E=BZ*(BX*DJ + BY*DI)
      F1=BZ*BZ-BX*BX-BY*BY
      F2=BZ*BX
      F3=BZ*PY
C      SUM OVER ARRAY
      EN=EN+E
      TAU=TAU+T
      F(1)=F(1)+F1
      F(2)=F(2)+F2
      F(3)=F(3)+F3
      ETOT=ETOT+ABS(E)
      TAUTOT=TAUTOT+ABS(T)

```

(BLK 140)

```

FXTOT=FXTOT+ABS(F2)
FYTOT=FYTOT+ABS(F3)
GO TO 1009

```

```

* * * * B L O C K 1 0 1 0 * * * *

```

```

(BLK 140)

```

```

C
C
1010 CONTINUE
IFLAG=0
VAR1=0.
VAR2=0.
1015 CONTINUE
C
C CALCULATE C1,C2,GIVEN KFACT
ICOUNT=0
JCOUNT=0
RATIO1=0.
RATIO2=0.
BLIM=500.
PLIM=10.
DO 1018 I10=1,M
DO 1017 J10=1,N
    FZC=B(1,I10,J10)
    IF(BZC.LT.BLIM.AND.BZC.GT.-BLIM) GO TO 1011
    BZP= KFACT *
1    (IT(1,I10,J10)-IT(2,I10,J10))/(IT(1,I10,J10)+IT(2,I10,J10))
    RAT1=BZC/BZP
    IF(IFLAG.EQ.1) VAR1=VAR1+(RAT1-C1)**2
C    WRITE(6,9011)I10,J10,RAT1,BZC,BZP,IT(1,I10,J10),IT(2,I10,J10)
C9011 FORMAT(2I5,7F10.3)
    RATIO1=RATIO1+BZC/BZP
    ICOUNT=ICOUNT+1
1011 CONTINUE
    BTC=SQRT(B(2,I10,J10)**2+B(3,I10,J10)**2)
    IF(BTC.LT.BLIM.AND.BTC.GT.-BLIM) GO TO 1012
    U=(IT(3,I10,J10)-IT(4,I10,J10))/(IT(3,I10,J10)+IT(4,I10,J10))
    V=(IT(5,I10,J10)-IT(6,I10,J10))/(IT(5,I10,J10)+IT(6,I10,J10))
    UVMAG=U*U+V*V
    BTP= SQRT(KFACT*SQRT(UVMAG))
    RATIO2=RATIO2+BTC/BTP
    RAT2=BTC/BTP
    IF(IFLAG.EQ.1) VAR2=VAR2+(RAT2-C2)**2
C    WRITE(6,9011)I10,J10,RAT2,BZC,BZP,IT(3,I10,J10),IT(4,I10,J10),
C    IT(5,I10,J10),IT(6,I10,J10)
    JCOUNT=JCOUNT+1
1012 CONTINUE
1017 CONTINUE
1018 CONTINUE
    C1P = RATIO1/(ICOUNT+1.)
    C2P=RATIO2/(JCOUNT+1.)
    WRITE(6,1013) KFACT,C1,C1P,C2,C2P,IKNOWN
1013 FORMAT(3X, 6H K = ,F5.2,13H C1(GIVEN)= ,F6.0,13H C1(CALC)=
    ,F6.0,13H C2(GIVEN)= ,F6.0,13H C2(CALC)= ,F6.0,10H IKNOWN= ,I5)
    IF(IKNOWN.EQ.1) GO TO 1014
    C1=C1P
    C2=C2P
1014 CONTINUE
    IF(IFLAG.EQ.1) VAR1=SQRT(VAR1)/ICOUNT
    IF(IFLAG.EQ.1) VAR2=SQRT(VAR2)/JCOUNT

```

```

IFLAG=IFLAG+1
IF(IFLAG.LT.2) GO TO 1015
WRITE(6,1016) VAR1,VAR2

```

```

1016 FORMAT(2E10.3)
GO TO 1019

```

```

C      * * * * B L O C K   1 0 2 0   * * * *
C

```

(BLK 140)

```

1020 CONTINUE

```

```

C
C      CALCULATE DIRECTION, DIRECTION VARIANCE

```

```

PHI=ATAN(BY/BX)
CHI=-TAN(2.*PHI)
DENOM=(I34/I56)*(I56P/I34P)
DFACT=.5/(1. + DENOM*DENOM)
DPD3= 2.*DFACT * IT(4,I,J)*I56P/(I34P*I34P*I56 )
DPD4= 2.*DFACT * IT(3,I,J)*I56P/(I34P*I34P*I56 )
DPD5= 2.*DFACT * IT(6,I,J)*I34 /(I56 *I56 *I34P)
DPD6= 2.*DFACT * IT(5,I,J)*I34 /(I56 *I56 *I34P)
SIGPHI = SIG32*DPD3*DPD3
$      + SIG42*DPD4*DPD4
$      + SIG52*DPD5*DPD5
$      + SIG62*DPD6*DPD6
SIGPHI=SQRT(SIGPHI)
IF(SIGPHI.GT.SPHIMX) SIGPHI=SPHIMX
GO TO 1029

```

```

C      * * * * B L O C K   1 0 3 0   * * * *
C

```

(BLK 140)

```

1030 CONTINUE

```

```

C
C      CALCULATE B SIGMAS
TA= C2*C2*KFACT*(U*U*SIGU+V*V*SIGV)/(4.*UVMAG*SQRT(UVMAG))
TB= (.5/(1.+CHI*CHI))**2.*(( SIG32+SIG42)/(I34*I34)
$      +(SIG52+SIG62)/(I56*I56) )

```

```

TB=1.
TC=SIGPHI*SIGPHI*BT*BT
SIGBX2 = TA * COS(PHI)**2 + TC*TB*SIN(PHI)**2
SIGBY2 = TA*SIN(PHI)**2 + TC*TB*COS(PHI)**2
SIGBZ2=
$4.*C1*C1*KFACT**2      * (SIG12*IT(2,I,J)**2 + SIG22*IT(1,I,J)**2)/
SI12P**2/I12P**2
GO TO 1039

```

```

C      * * * * B L O C K   1 0 4 0   * * * *
C

```

```

1040 CONTINUE

```

```

C      CALCULATE PARAMETER SIGMAS, CHECK FOR LARGE TERMS
CHECK=.5

```

```

ST= BZ*BZ*(DJ*DJ*SIGBX2 + DI*DI*SIGBY2)
1 + SIGBZ2* (DJ*BX - DI*BY)**2

```

```

C      ST= DJ*DJ * (BZ*BZ*SIGBX2 + BX*BX*SIGBZ2)

```

```

C      $      + DI*DI * (BZ*BZ*SIGBY2 + BY*BY*SIGBZ2)

```

```

SE= (BX*DI+BY*DJ)**2*SIGBZ2 + BZ*BZ*(SIGBX2*DI*DI+SIGBY2*DJ*DJ)

```

```

SFX= BZ*BZ*SIGBX2 + BX*BX*SIGBZ2

```

```

SFY= BZ*BZ*SIGBY2 + BY*BY*SIGBZ2

```

```

C
C      SFZ= 4.*(BZ*BZ*SIGBZ2 + BX*BX*SIGBX2 + BY*BY*SIGBY2)

```

```

C
C      IF(I.LT.ICLK.AND.J.LT.JCHK) GO TO 1041

```

```

CHKT= SIGT(10,J0) *CHECK
CHKE= SIGE(10,J0) *CHECK
CHKX= SIGFX          *CHECK
CHKY= SIGFY          *CHECK
CHKZ= SIGFZ          *CHECK
IF(CHKT.GT.ST .AND. CHKE.GT.SE .AND. CHKX.GT.SFX .AND.
S  CHKY.GT.SFY .AND. CHKZ.GT.SFZ ) GO TO 1041
WRITE(6,1042)1,J, ST,SE,SFX,SFY,SFZ,BX,BY,BZ
1042  FORMAT(2I5,36H FOLLOWING ARE T,E,FX,FY,FZ,VARIANCES,5E10.2,3F8.0)
WRITE(6,1043) SIGT(10,J0),SIGE(10,J0),SIGFX,SIGFY,SIGFZ
1043  FORMAT(46H          AND RUNNING TOTALS ARE          ,5E10.2)
1041  CONTINUE
      SIGT(10,J0)=SIGT(10,J0) + ST
      SIGE(10,J0)=SIGE(10,J0) + SE
      SIGFX= SIGFX + SFX
      SIGFY= SIGFY + SFY
      SIGFZ= SIGFZ + SFZ
      GO TO 1049
C  BLOCK 1050 $$$$
1050  CONTINUE
      PHI1=ATAN(-U/V)
      IF(V.LT.0.) PHI1=PHI1+PI
      PHI1=PHI1/(2.*DTOR)
      PHI=PHI1/DTOR
      WRITE(6,1051) PHI,PHI1,I,J
      PHI=PHI*DTOR
1051  FORMAT(2F10.3,2I5)
C  GO TO 1059
      STOP
      END

```

FIGURE CAPTIONS

- Figure 1. Distribution of polarization measurements for weak field picture elements of solar active region 2665, used for determining observational biases and uncertainties. Normalized frequency of occurrence is plotted against (a-b) two components of linear polarization, (c) circular and (d) total linear polarization. If no biases have been introduced, distributions should center and peak at zero. Small biases in transverse measurements probably are induced by gridding optics.
- Figure 2. Distribution of polarization measurements (See Figure 1) after minor correction for biases. Spread in distribution (σ_{PV} and σ_{PQ}) gives random uncertainties used in estimating noise effects.
- Figure 3a-b. Circular Crosstalk Determination. The measured circular polarization is compared with the two components of the linear polarization, with each plotted point representing a picture element. Only the weak fields are shown and, therefore, the relationship of linear to circular polarization should be random. The weak but systematic correlation (seen here) between the magnitude of the circular and linear polarization measurements implies circular crosstalk into the linear polarization measurements. In the case shown, the deviation of best fit straight lines from horizontal approximates the degree (percentage) of crosstalk observed. Although an infrequent problem, crosstalk testing and correction procedures are routinely incorporated into the MSFC data analysis programs.
- Figure 4a-b. Circular Crosstalk Correction. Same as Figure 3, after the estimated correction for percentage of circular crosstalk has been applied to the data. Linear polarization data now appear free of circular crosstalk influence. (Note that the best fit for the zero values approximates a horizontal line.)
- Figure 5. Contours of circular polarization measurements for AR2372 during the time of spot motions and greatest flare activity. In all figures, solid lines depict positive magnetic polarity, dashed lines are negative, and orientations are the same. Contours levels are ± 0.01 , 1.0, 2.5, and multiples of $\pm 5\%$ polarization.
- Figure 6. Measured direction of horizontal force (θ) for AR2372. Greatest spot migration occurred after data points on 5 April and before point on 7 April. Direction of proper motion of the migrating spot (from white light and magnetograms, Figure 5) agree well with data points on 6 April.

- Figure 7. Vector Magnetographs of AR2665. The line-of-sight component (B_L) is represented by contours of field strength, solid for positive values and dashed for negative values. The transverse component (B_T) is represented by azimuthal vectors where length is proportional to field strength. The minimum length represents 300 Gauss and the maximum length represents 1000 Gauss. Note the changes occurring in the vicinity of the line of B_L polarity reversal. Throughout the period under study, there is weakening of both B_L and the B_T components of the field. Continuing simplification is also shown by the increasing orthogonal nature (less shear) of the transverse component.
- Figure 8. Histogram of X-ray Flares for AR2665. Logarithmic plot with $C1 = 10^{-3} \text{ ergs cm}^{-2} \text{ s}^{-1}$, $M1 = 10 \times C1$. Note the decline in activity, with only minor flares after the 12th.
- Figure 9. Region History. The number of spots is indicated by the dark triangle in (a) and by the asterisks in (b). The solid lines represent sunspot area evolution. The flare histograms at the bottom of the plots indicate the number and magnitude of the x-ray flares; open histograms for class C, lined for class M. In its first disk transit (a), the region was very small and non-productive of flares. As AR2665 (b), early activity had declined by mid transit and the region exhibited a gradual decline in sunspots and sunspot area.
- Figure 10. Physical parameters (Equations 2-12, 2-11 and 2-13) for AR2665, determined using Lorentz equations and vector magnetograms obtained as a function of time and observing wavelength. Solid lines connect 120 mÅ observations, while simple 60 and 90 mÅ observations are also shown. Error bars are one sigma values determined as the square root of the sum over pixels of Equations 4-1, 4-3, and 4-2 respectively.

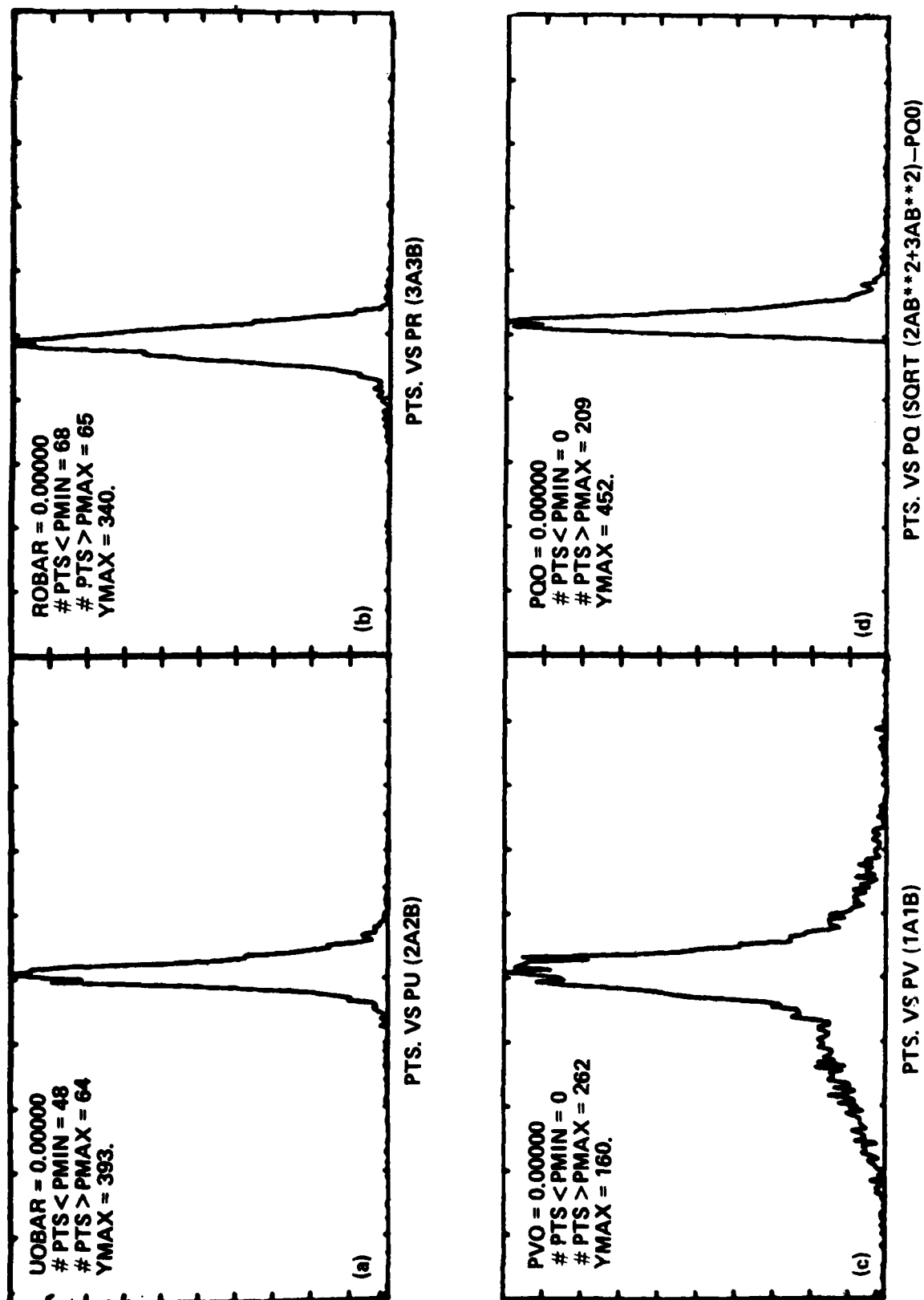


Figure 1 a - d

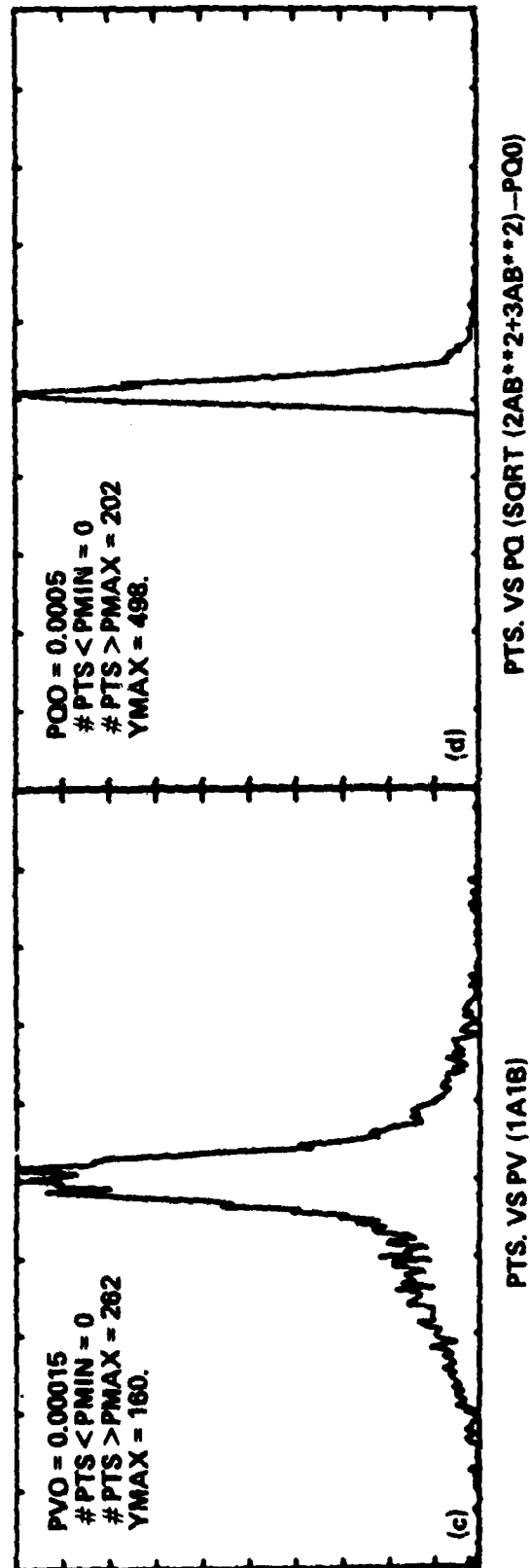
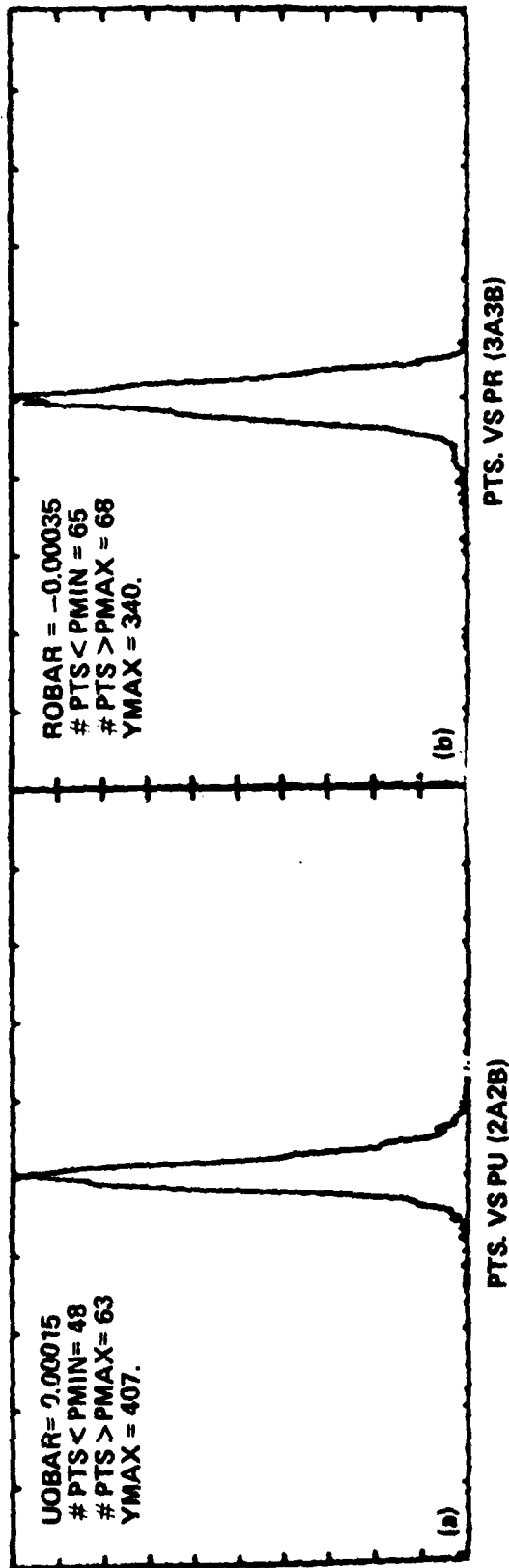
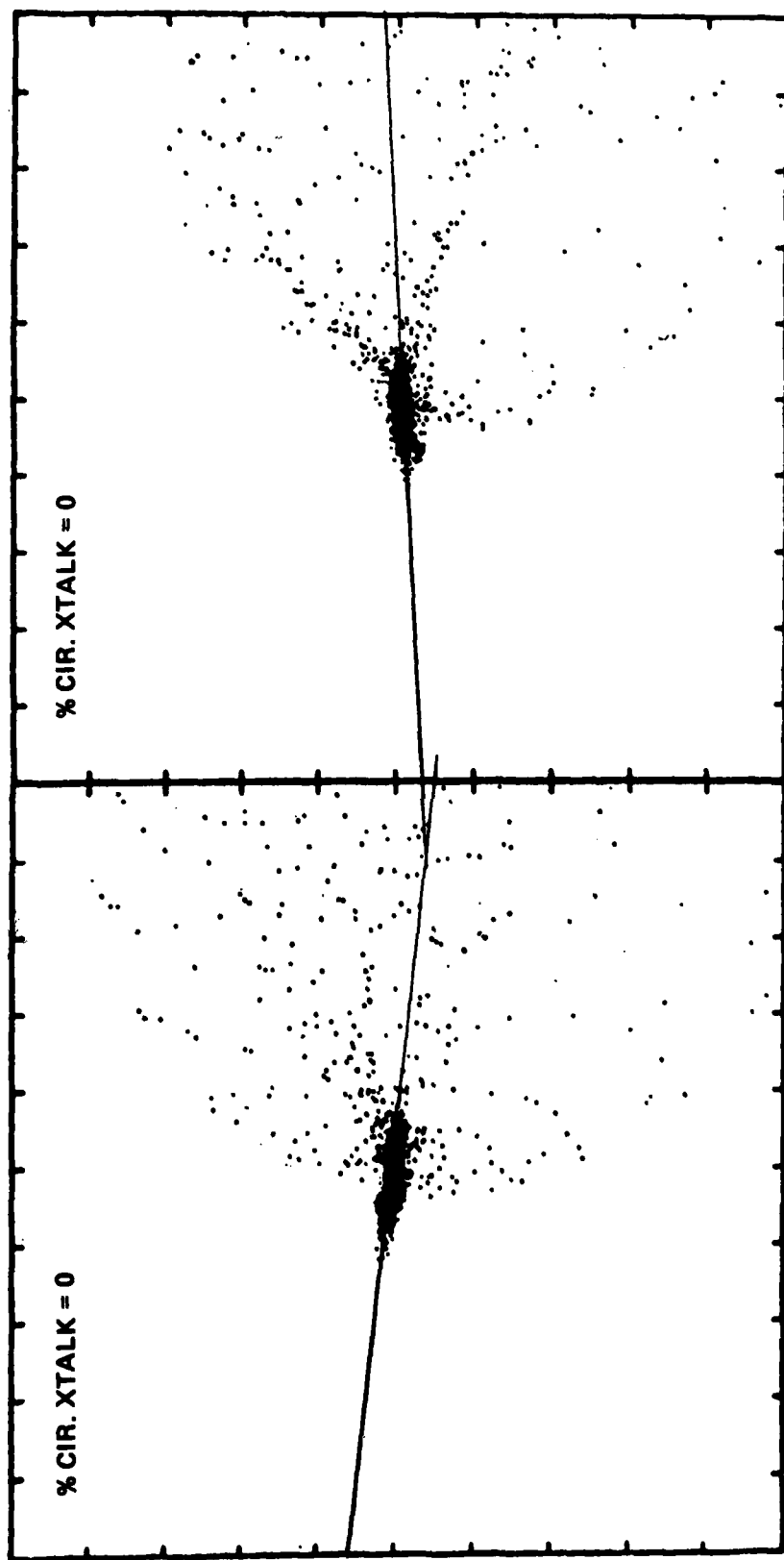


Figure 2 a - d

15/1359 U.T. SEPT., 1980

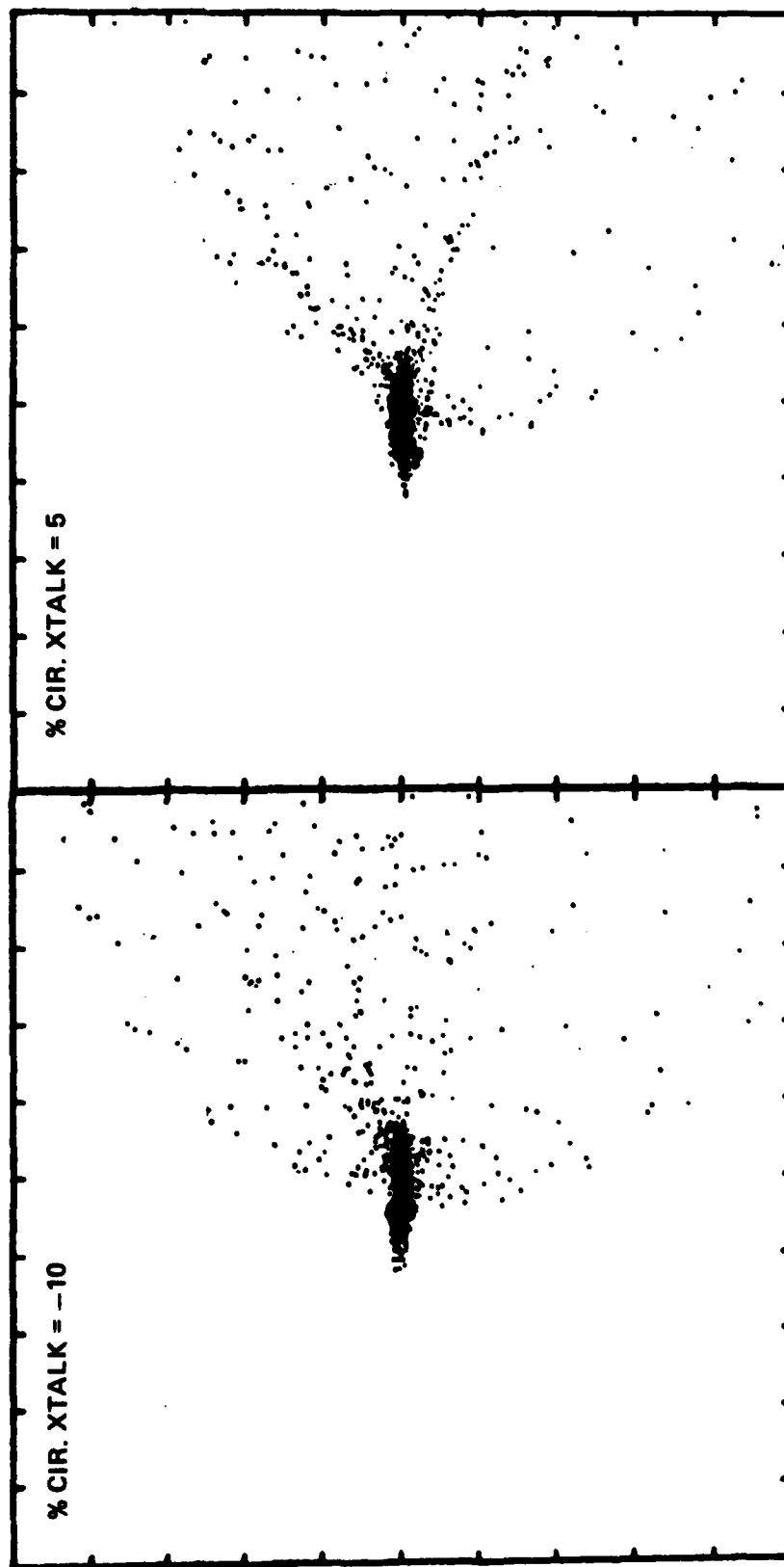


3A3B VS 1A1B

2A2B VS 1A1B

Figure 3 a - b

15/1359 U.T. SEPT. 1980



2A2B VS. 1A1B

3A3B VS. 1A1B

Figure 4 a - b

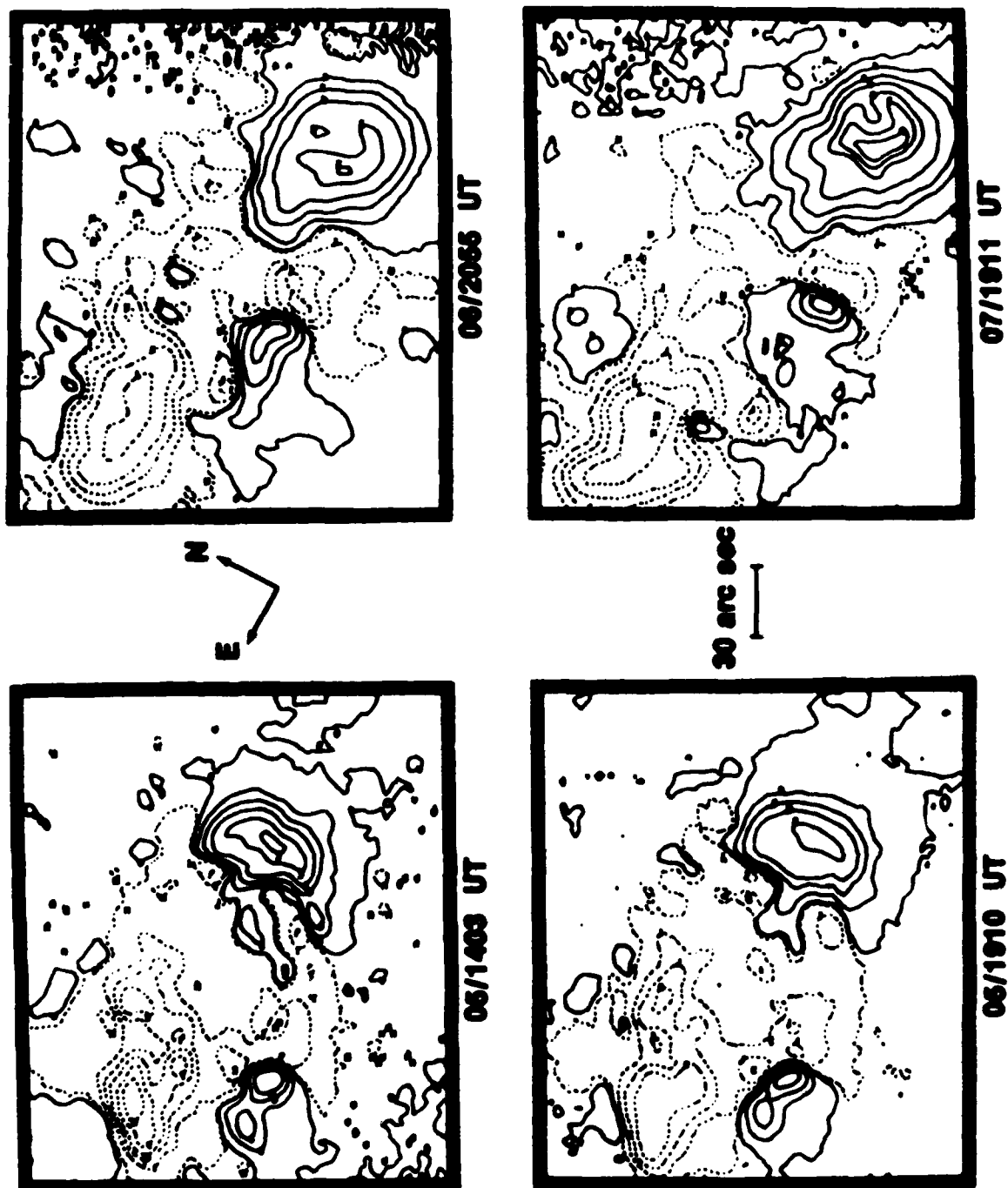


Figure 5

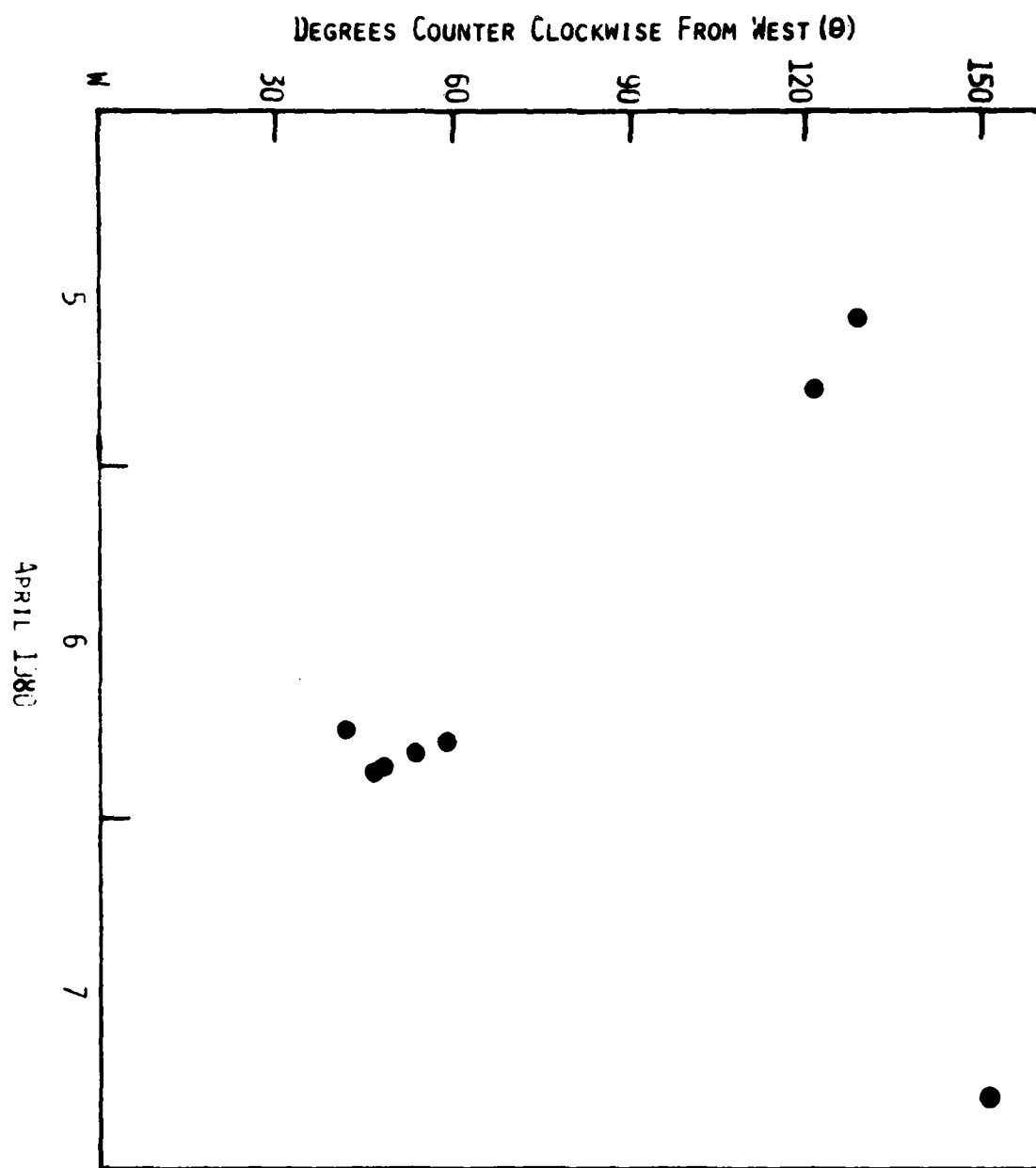
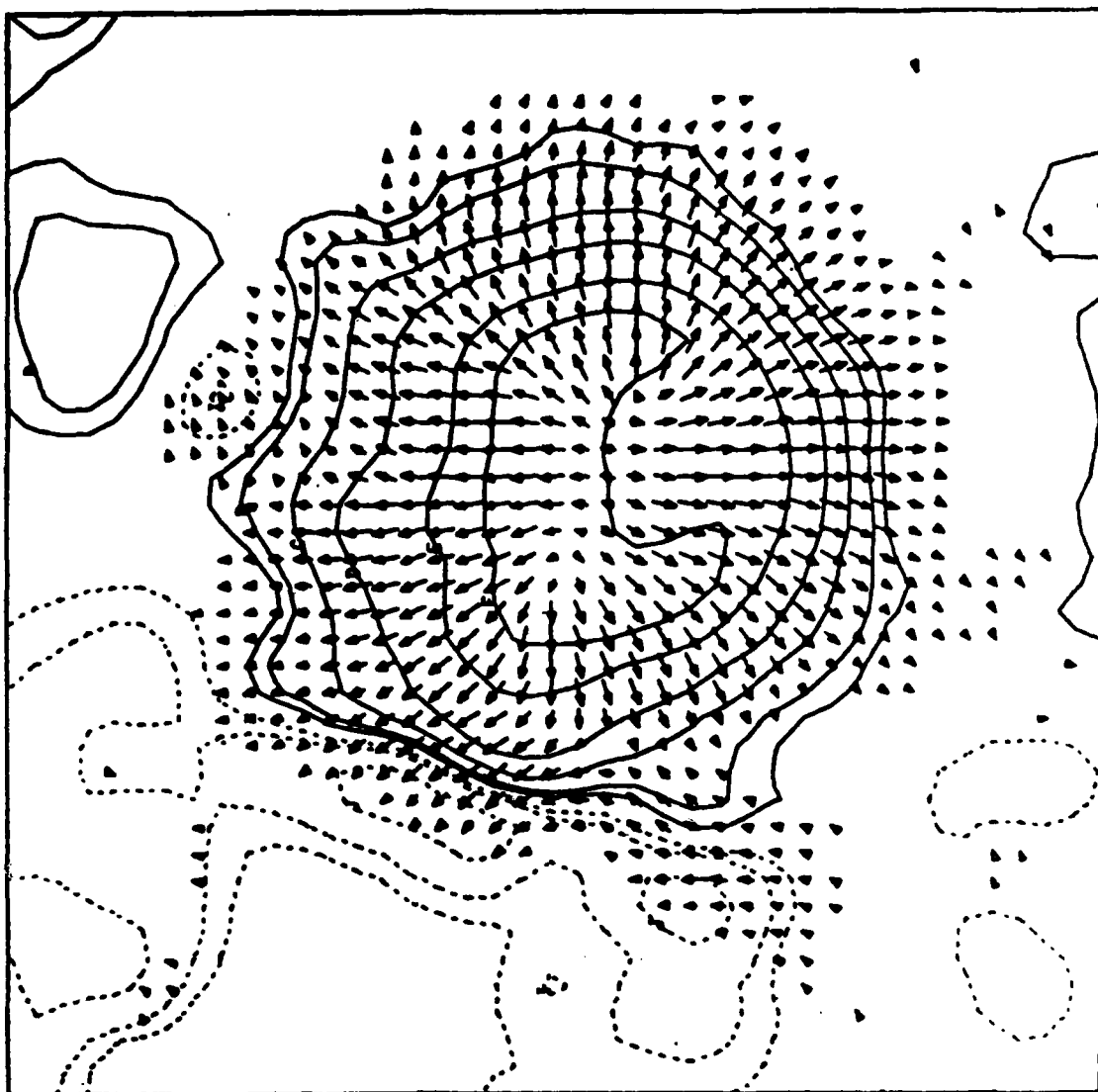
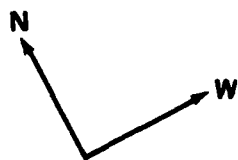


Figure 6

15/1349 U.T. SEPT. 1980



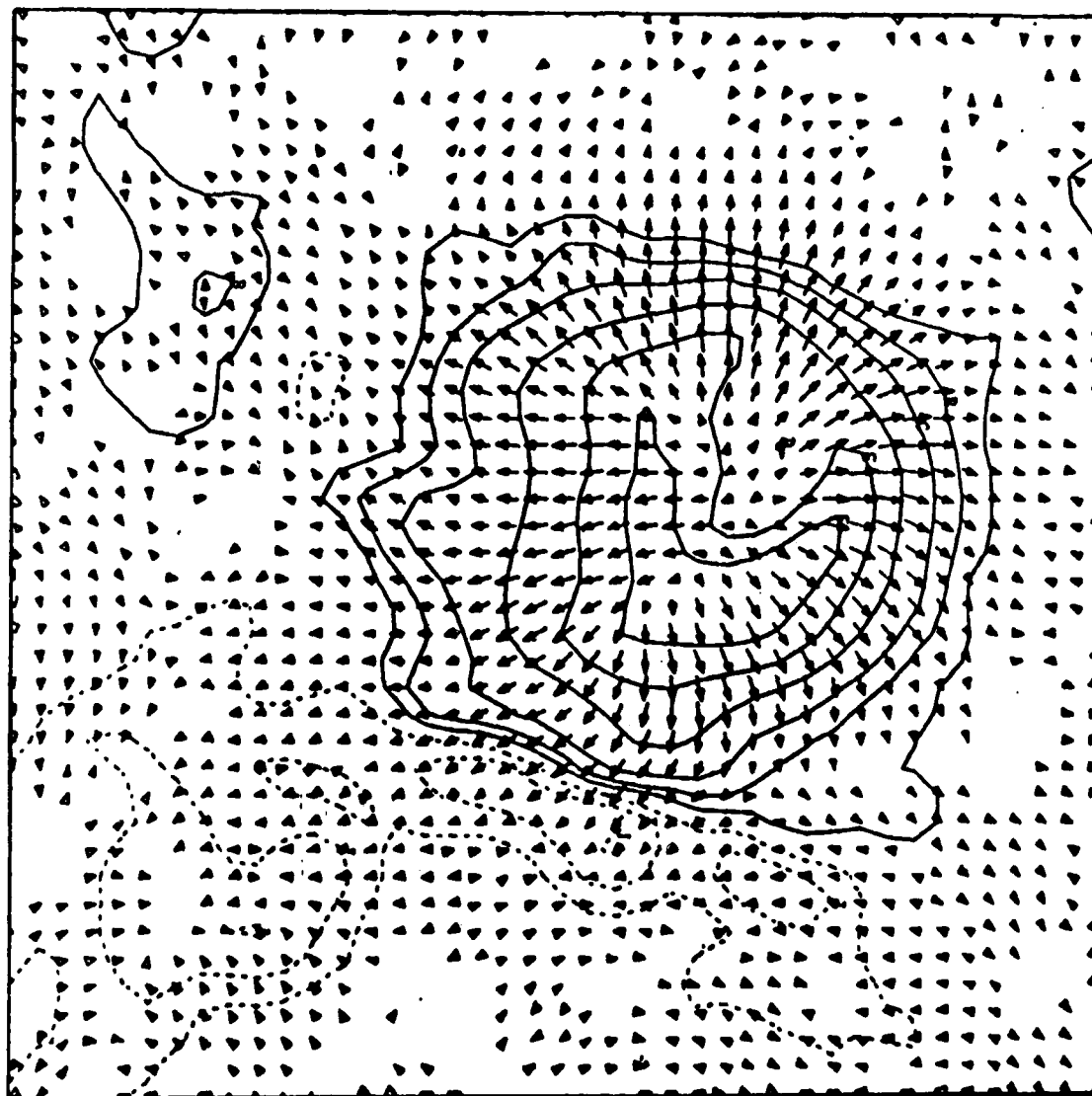
(a)



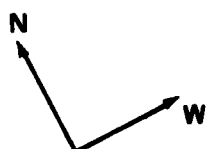
20 arc sec

Figure 7 a

15/2029 U.T. SEPT. 1980



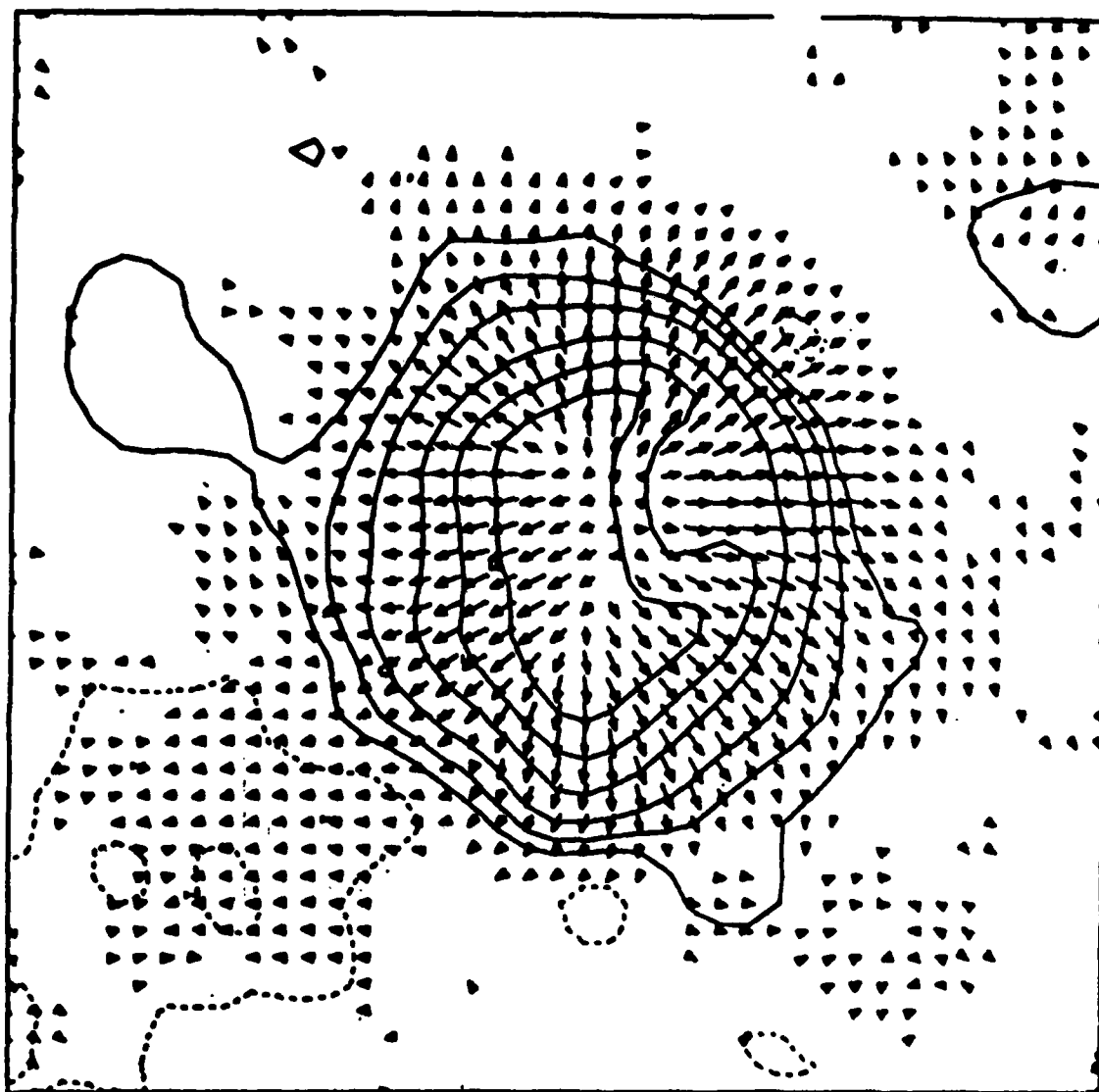
(b)



20 arc sec

Figure 7 b

16/1359 U. T. SEPT. 1980



(c)

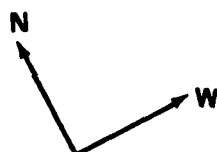

20 arc sec

Figure 7 c

AR 2665

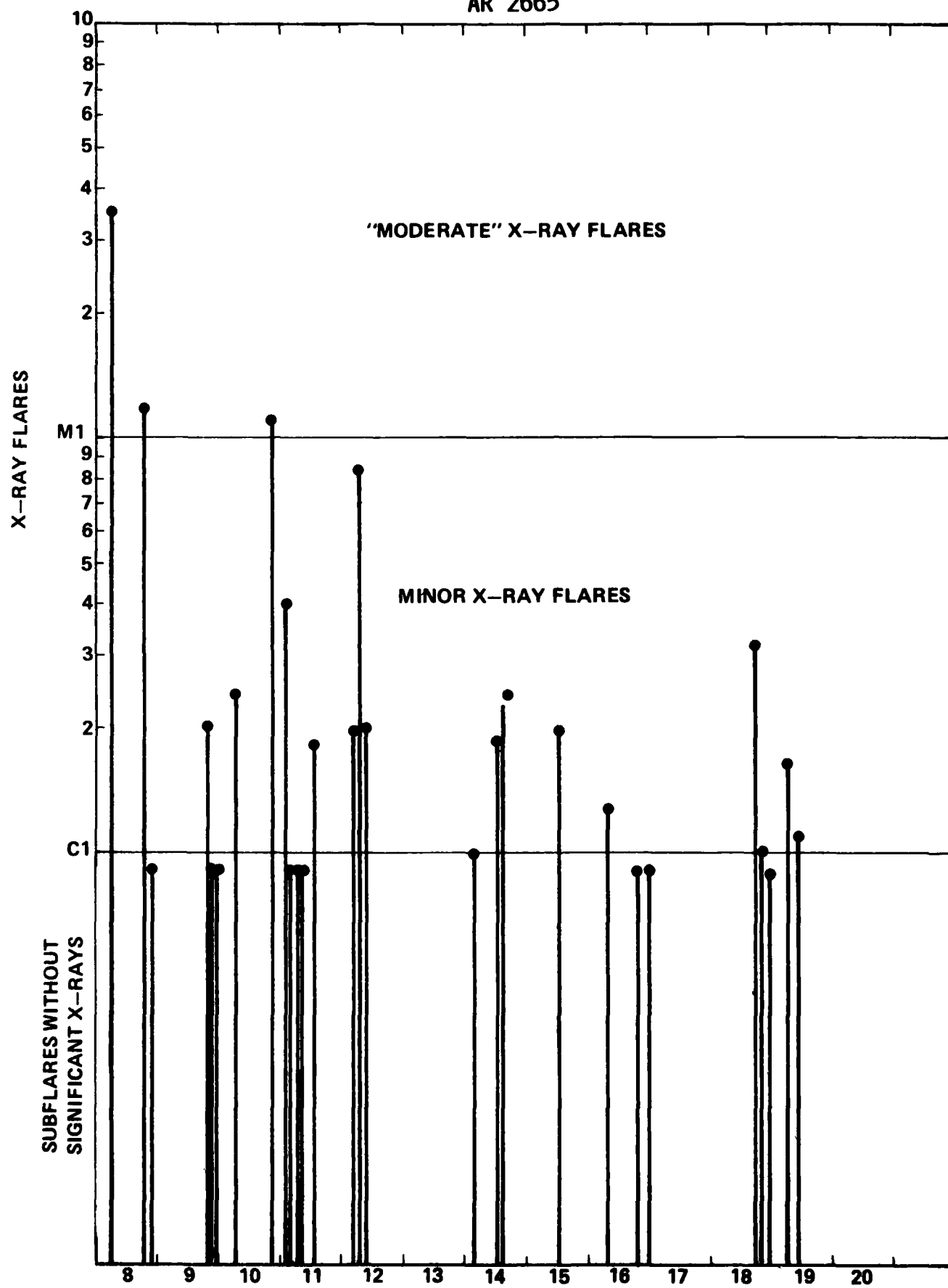


Figure 8

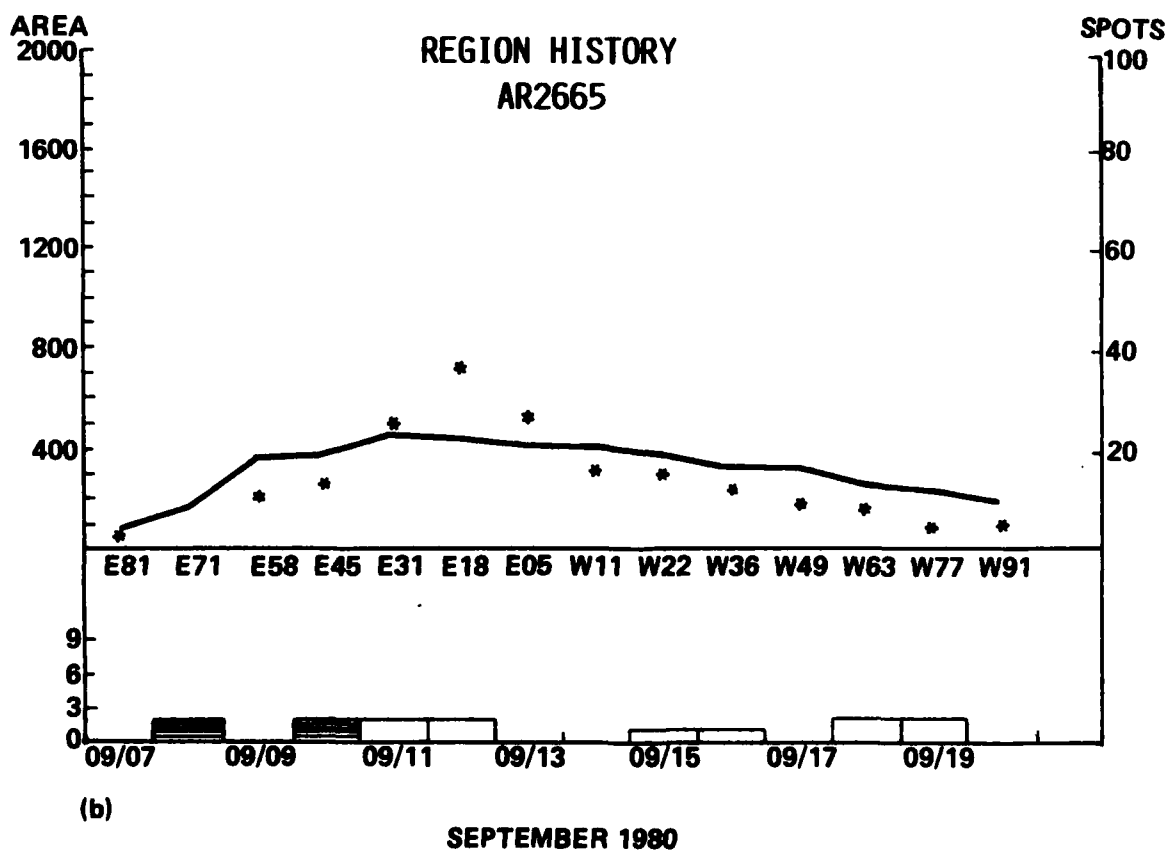
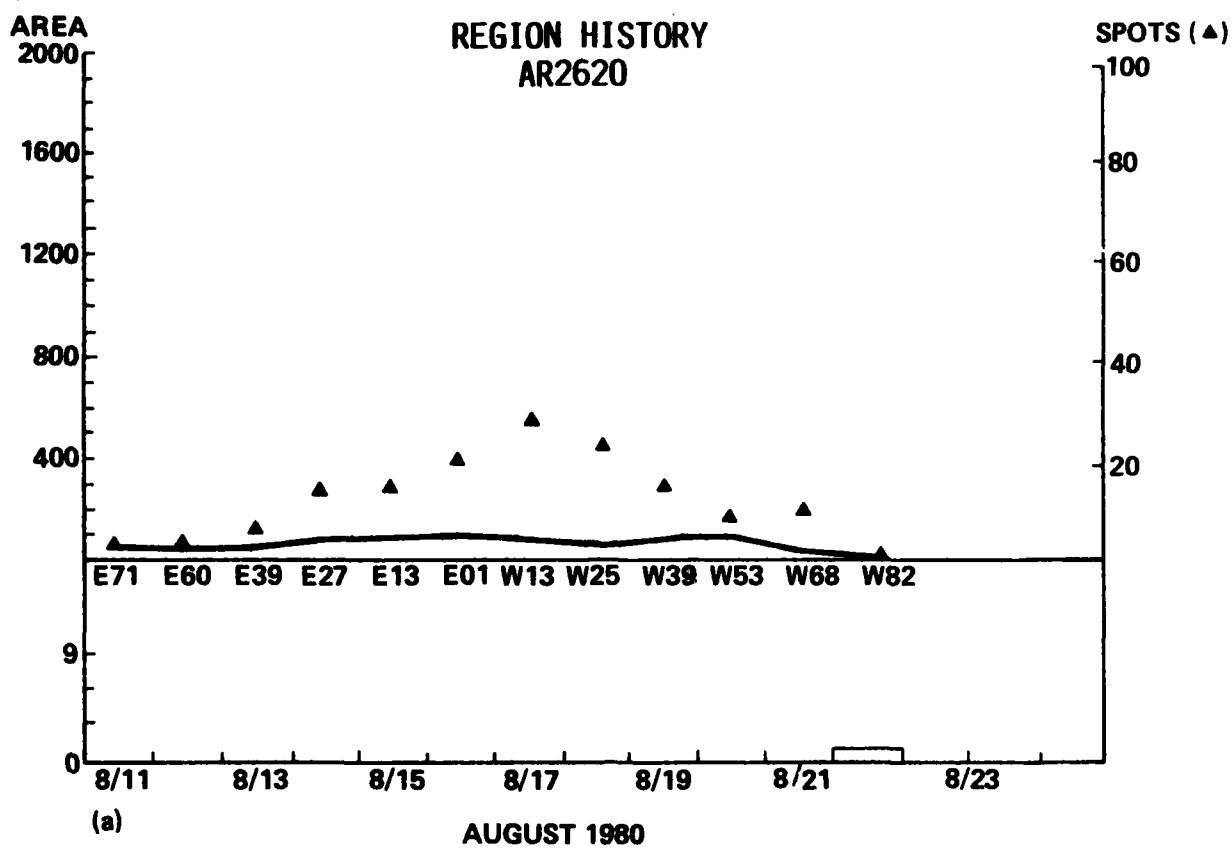


Figure 9

AR2665
SEPT. 1980

38 11

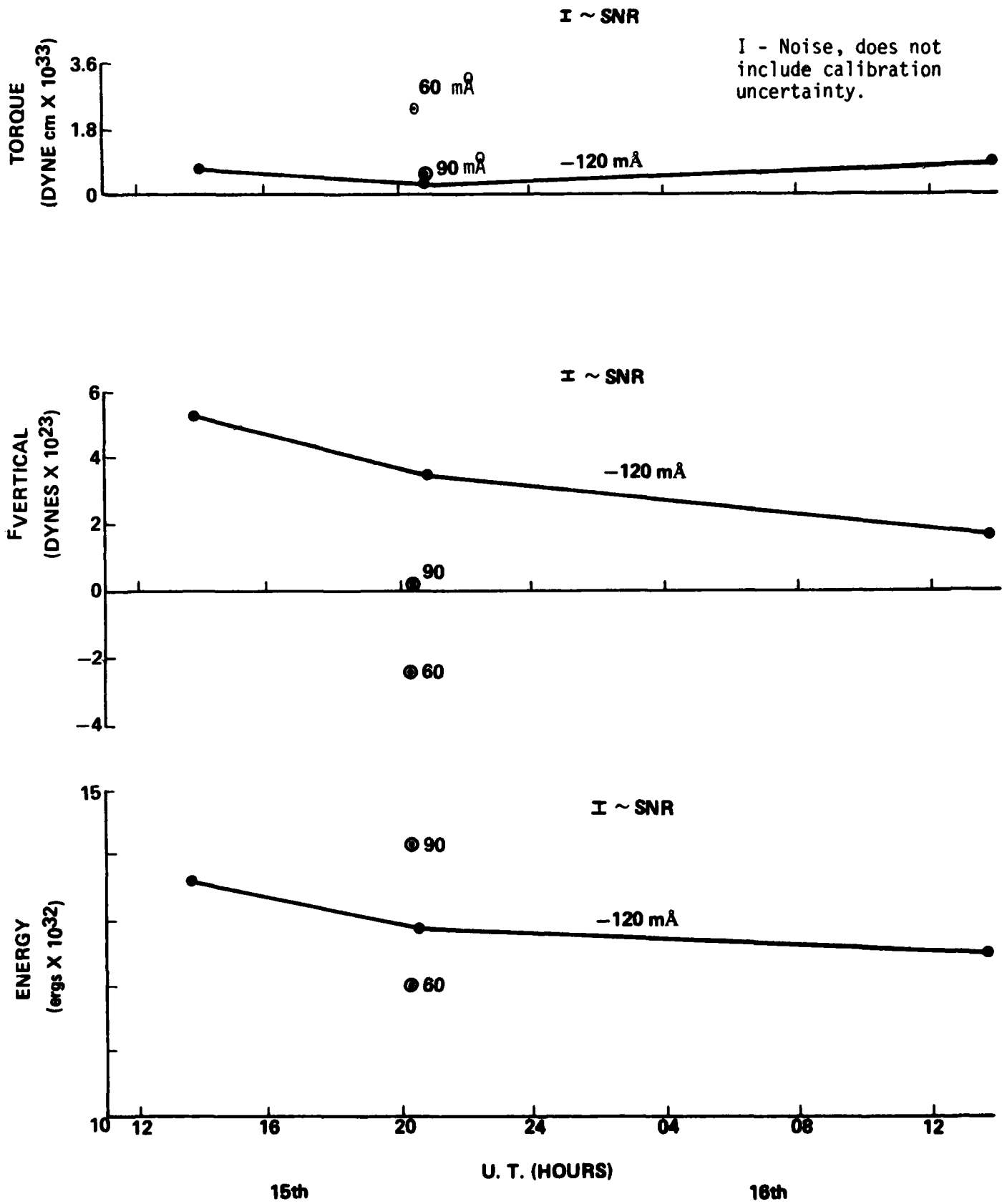
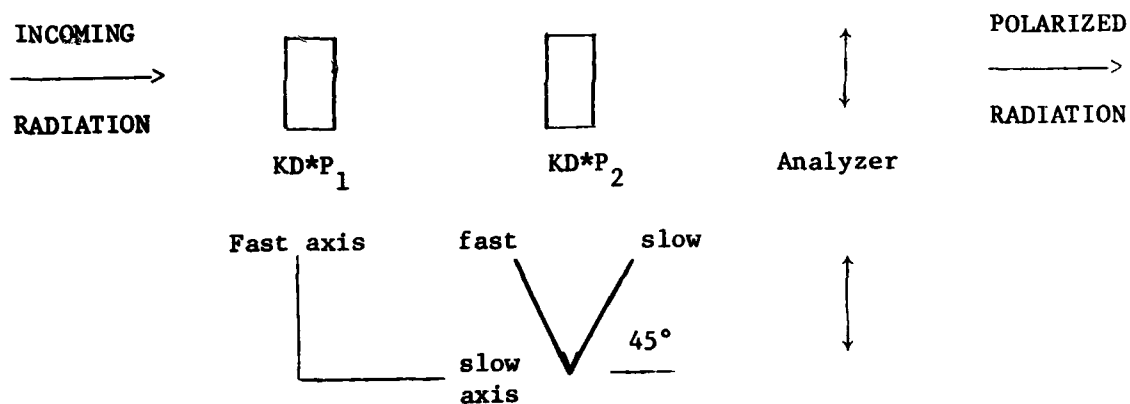


Figure 10

TABLE I. MSFC Magnetograph Optical Configuration For Measuring Circular And Linear Polarizations



Intensity

I1	0λ	+λ/4
I2	0λ	-λ/4
I3	λ/4	+λ/4
I4	λ/4	-λ/4
I5	0λ	0λ
I6	0λ	λ/2

Polarization

I + V	} P _V
I - V	
I + U	} U
I - U	
I + Q	} R
I - Q	

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