Procedures for Reduction of
FE XII 10747 Å Coronal Emission-Line Polarization Observations

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PREFACE

This note documents the reducing procedures used to obtain the best estimates of the coronal Stokes parameters from the raw measurements recorded in two spectral channels with the High Altitude Observatory--Sacramento Peak Observatory Coronal Emission-line Polarimeter (KELP). The original reduction programs written by C. Querfeld have been modified to survey the KELP data as a whole and to help determine whether corrections are needed for each scan.
ACKNOWLEDGMENTS

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The High Altitude Observatory - Sacramento Peak Observatory Coronal Emission-Line Polarimeter (KELP) has been especially constructed to measure the Fe XIII 10747 Å emission-line. The Stokes parameters I,Q and U were simultaneously measured in the “line-plus-continuum” channel, centered on the emission-line and in the “continuum-only” neighboring channel.

We describe in this note the corrections applied on the measurements. The first one is used to remove the skylight polarization, or at least in main part due to multiple scattering, which is, at a given time, constant in value and direction. The second one is used, when needed, to remove an offset signal often present on the measurements. For that one assumes that the minimum values around the scan of the parameters to be corrected are 0. One assumes also that the value of those parameters are the same for the first and for the last point of each scan (points measured near the north pole). As very small coronal signals exist in the polar regions, those approximations are, except in the polar regions, small in comparison with the value of the measured parameters.

The reduction programs used to survey the KELP data as a whole and to help determine whether corrections are needed for each scan are described.
I. KELP OBSERVATIONS AND CONTENTS OF DATA FILES

The Coronal Emission-Line Polarimeter (KELP) is a coronameter with two spectral channels especially constructed to measure the Fe XIII 10747 Å emission line (Querfeld, 1977). The Stokes parameters $I$, $Q$, and $U$ were simultaneously measured in the "line-plus-continuum" channel, centered on the emission line and in the "continuum-only" neighboring channel.

Circular scans of the corona, at given radial distance, $R$, were made around the center of the solar disk. Each height was generally scanned in 128 sequential measurements, equally spaced in position angle, the first measurement being made for the heliocentric direction corresponding to the north pole of the Sun.

A slightly different procedure was used for the heights in which simultaneous measurement lines were made with the Sac Peak photoelectric photometer for the Fe XIV 5303 Å. They were scanned in 120 sequential measurements, starting at the north point.

The data obtained for each scan were recorded on a magnetic tape data file, which also contains calibration and housekeeping data. Each measurement consists of elementary measurements integrated during a 0.2-s period; the resulting total integration time varies between 3 and 10 s. The mean values and the standard deviations of those elementary measurements are recorded for the following Stokes parameters:

1. $I_L - I_K$, the difference between the $I$ Stokes parameter for the "line-plus-continuum" channel (subscript $L$) and for the "continuum-only" channel (subscript $K$);
2. $Q_L$ and $U_L$ for the "line plus continuum" channel;
3. $I_K$, $Q_K$, and $U_K$ for the "continuum-only" channel.
Those files contain all the intensity and polarization calibration data (obtained on the center of the disk), as well as the instrument status and other information needed to obtain the calibrated Stokes parameters for the line and the continuum.
II. THE CORRECTIONS APPLIED

Corrections of Skylight Polarization

Skylight polarization is due to primary and multiple scattering by molecules and aerosols. The measured polarization varies largely from day to day, which precludes any a priori correction (Leroy et al., 1972). The main part of this polarization is due to multiple scattering and is, at a given time, constant in value and direction. Thus, the multiple scattering imparts a sinusoidal contribution to the tangential polarization for one scan around the sun, with a period double that of the scan.

This polarization is corrected with a so-called second harmonic correction: the second harmonic of the tangential polarization around the scan is computed and subtracted. This correction is systematically applied for all the scans to the continuum Stokes parameter $Q_K$. The Stokes parameters $Q_K$ and $U_K$ used herein refer to the local radius of the Sun. As the K-corona is tangentially polarized, $U_K$ is, in principle, equal to 0. It is actually low compared to $Q_K$ and can be neglected.

Instrumental Effects

The principal observed contamination of the measurements is an offset signal, and is generally slowly variable with time. Two different corrections are used to compensate for the offset, and are described below.

1. A "detilt" correction, based on the assumption that the physical parameters are the same for the first and for the last point of each scan. The actual differences in the measured values of the Stokes parameters are assumed to be due to an instrumental
linear drift. The entire scan is corrected for a drift computed to equalize its first and last values. This correction is almost systematically applied to the Stokes parameters corresponding to line intensity ($I_{LK} = I_L - I_K$), line polarization ($Q_{LK} = Q_L - Q_K$ and $U_{LK} = U_L - U_K$), and K-corona ($Q_K$ and $U_K$). The Stokes parameters used here are referred to the north-south axes of the Sun.

2. An "equilibrate" correction, used to correct the constant offset remaining in the signal after the detilt correction. To determine the value of this correction, one assumes that, at the point of the scan where the uncorrected values of $I_{LK}$, $pI = \sqrt{Q^2_{LK} + U^2_{LK}}$ (line polarization brightness), and $p_K I_K$ (K-corona) are minimal, the actual values of those parameters are 0. Actually, for $pI$, the procedure determines where the main value over three points is minimal (to reduce the influence of the noise). The offset correction needed to set the minimal value to 0 is applied to the corresponding Stokes parameters for all the scans. This correction is systematically applied to the line intensity when one of the two following conditions is filled: either $I_{LK}$ (min) < 0, or $I_{LK}$ (min) > 0.125 $I_{LK}$ (max).

Those conditions are based on the assumptions that negative values of $I_{LK}$ are physically meaningless; and that the variation of $I_{LK}$ around the Sun is at least the same as that for the K-corona. In systematic observations of K-coronameters, it is obvious that the ratio of the maximum value to the minimum value is, for any scan, generally largely greater than 8. So, if the variation of $I_{LK}$ around the scan is less than 8, it is likely due to a spurious signal.

The decision of whether to use the equilibrate correction is made for each scan after examination, independently for the line polarization parameters and for the K-corona parameters.
Those offset corrections made on the Stokes parameters referred to the north-south axis of the Sun, the axis of reference for the measurements.

Influence of Those Corrections on the Accuracy of Observations

It is not possible to completely correct for the observations from sky and instrumental contamination; it is only possible to correct a part of the polarization of skylight (the part due to multiple scattering). The drift and offset corrections are based on rough hypotheses (e.g., to set a minimum value to 0). Thus, even after correction, there are still some limitations on the use of the data.

The uncertainty due to skylight polarization is less at 10747 Å than in the visible part of the spectrum. According to Leroy and Ratier (1974), it can be assumed that the remaining uncertainty, after the second harmonic correction, is about $3 \times 10^{-8} B_0$ in the low corona and decreases below $1 \times 10^{-8} B_0$ for the highest scans. Therefore, skylight polarization does not compromise the accuracy of K-corona measurements, except perhaps where it is very small, such as in polar coronal holes.

Detilt correction is based on the assumption that the observed parameters do not change between two contiguous points over the north pole of the Sun. Equilibrate correction approximates to 0 the minimum value of the parameter being considered, over the scan. It is well known, from synoptic observations, that the K-corona is weak over the poles (see for example, Fisher and Seagraves, 1984). As the coronal temperature is lower over the poles than in low-latitude regions, it is likely that emission line signals are very small in the polar regions. So the approximations used to apply the detilt and equilibrate corrections are, except in the polar regions themselves, small in comparison with the values of the measured parameters. For high-latitude regions (above 60°) it is
necessary to consider the values of both the parameters and the corrections to decide what part of the data is suitable for quantitative analysis.

In summary, the corrections discussed above are believed to improve the quality of the measurements for latitudes below 60° without unreasonable assumptions. The corrections can also be used with observations for higher latitudes when the data have been carefully examined.
III. KELPA5 and KELPA4 Programs

KELPA5 Program

This program generates a four-panel image of each KELP scan.

Main program: kelpa5

Subroutines: scalita3, etc.

Linker: kelpa5.cmd

Files: The required KELP files must be placed in "list.dat" and "list.das"--identical files in each.

Outputs: The program generates a file designated "map.meta," which can be displayed by the standard instructions:

mctrtek -s1 < map.meta.

The images generated are:

Upper left: \( I_K \) and \((pI)_K\) equilibrated

Upper right: \( I_{10747} \) and \((pI)_{10747}\) equilibrated

Lower left: \( I_K \) and \((pI)_K\) unequilibrated

Lower right: \( I_{10747} \) and \((pI)_{10747}\) unequilibrated.

The detilt correction is applied for the four images, and the second harmonic correction is applied to the two \((pI)_K\) images.
Figure 1 gives one example of a four panel image.

Numerical Outputs:

a) Top of the figure

File: file designation

rad: radial distance of scan from center of solar disk in \( R_\odot \)

sky: sky radiance in \( 10^{-6} \, B_\odot \) and its standard deviation ( )

H: time of beginning of scan

fov: diameter of field of view in minutes of arc

int: integration times for each point in seconds

detilt: list the values in \( I_{lk}, q_{lk}, u_{lk}, q_k, \) and \( u_k \) required to yield closure of the complete scan around the Sun

b) Upper left image

\( q_k \): mean and standard deviations ( ) for the entire scan

\( u_k \): mean and standard deviations ( ) for the entire scan

S/N: mean value of signal to noise in \( q_k \)

S/N > 2xx: number of points x where S/N > 2

equil: \( q \) and \( u \) = the values of \( q_k \) and \( u_k \) used to accomplish the equilibration
FILE: OT2677.012 rad: 1.46 sky: 6.6 (0.3) H 17 31 fov 2.00 int 5.0

detilt: sky 0.17 line 0.01 qk 0.005 ulk-0.023 qs-0.003 uk-0.001

$q$: 0.032 (0.021)
$ul$: 0.003 (0.002)
S/N: 9.8 S/N>2 115
equil: $q$-0.009 u 0.003 dir 159 qm 0.009

$I$: 0.71 (0.55)
$pI$: 0.036 (0.074)
To: 26.6 (24.4)
S/N: 3.0 S/N>1.6 77
equil: $q$ 0.070 u 0.003 dir 159 Im 0.121

$q$: 0.01 (0.021)
$ul$: 0.002 (0.001)
S/N: 12.4 S/N>2 125
harm: cos 0.006 sin-0.002

$I$: 1.34 (0.65)
$pI$: 0.142 (0.074)
To: 37.1 (27.5)
S/N: 5.1 S/N>2 123
$I(M)$: 2.90 Im 0.63
dir = heliocentric direction where abs(qK) is minimum (within 25° of each pole)

qm = minimum value of qn

c) Upper right image

$I$: mean and standard deviations (\(\sigma\)) of \(I_{lk}\) for entire scan

\(pI\): mean and standard deviations of \((pI)_{lk}\) for entire scan

Te: mean and standard deviations of the absolute value of the deviation of the polarization from the radial direction

S/N: mean signal to noise in \((pI)_{lk}\)

S/N > 1.6xx: number of points x where S/N > 1.6

equil: \(q\) and \(u\) = the values of \(q_{lk}\) and \(u_{lk}\) required to bring about equilibration

dir = heliocentric direction around which the values of \(q_{lk}\) and \(u_{lk}\) are used to apply the equilibrate correction (\(\bar{q}_{lk} = \bar{u}_{lk} = 0\)).

\(pI_{lm}\) = minimum value of \((pI)_{lk} = (q_{lk}^2 + u_{lk}^2)^{1/2}\).

d) Lower left image (when different from the upper left one)

harm: the sine and cosine coefficients used to remove the second harmonic signal (the sky polarization-brightness) from the continuum signal

\(P_K\) (M) and \(P_Km\) : maximum and minimum values, respectively, of abs \((P_k)\) around the scan
e) Lower right image (when different from the upper right one)

$I(M)$ and $I_m$: maximum and minimum values of $I_{lk}$, respectively, around the scan.

Such four-panel images have been generated for each KELP scan. They display the measurements of the scan with and without the equilibrate correction as well as the mean values of the different parameters and the values of the equilibrate and second harmonic corrections. By examining those images, one can determine the quality of the scan and decide whether it is necessary to use the equilibrate correction.

Sometimes it may be impossible to recover some data, even using corrections, because of very poor observing conditions or sporadic instrumental problems. Nonetheless, such data can still be used for their qualitative value; for example, the values of the parameters are obviously incorrect because of an erroneous calibration, but the shape of the scan remains consistent with good scans obtained for other heights. It may also be that only parts of a scan are suitable for use.

After examination, a value of a parameter called $neq$ is assigned to each scan, depending on its quality and on the corrections it needs:

$neq = 0$: unusable (or unreadable) scan

$neq = 1$: equilibrate correction for $q_{lk}$ and $w_{lk}$ (and eventually $I_{lk}$)

$neq = 2$: equilibrate correction like $neq = 1$ plus for $q_k$ and $w_k$.

$neq = 3$: quantitatively unusable scan (the difference from $neq = 0$ is that a qualitative use—for example, to see the existence of certain structures—remains possible)

$neq = 4$: scan usable without correction

$neq = 5$: a best scan exists at the same height, for the same day
neq = 6: scan partly usable
neq = 7: equilibrate correction for $I_k$
neq = 8: equilibrate correction for $q_k$ and $u_k$
neq = 9: equilibrate correction for $I_k$ and $q_k$ and $u_k$
neq = 10 + (1 to 9): detilt not used.

To use a data set (for instance, all the scans for a whole day), the values of neq for the corresponding scans must be put in a file (generally called kelp*.ne). For scans in which neq = 6, another file contains the limits (in heliocentric coordinates) of the parts of the scan used; this file is generally called kelp*.ne6.

KELPA4 Program

The study of those data begins by examination of the polarization maps obtained for each day. Those maps display the large-scale organization of emission-line polarization. The KELPA4 program generates a polarization map for each KELP date (see Figure 2 for an example).

Main program: kelpa4
Linker: kelpa4.cmd

Files: The required KELP files must be placed in “list.dat”, which must correspond to the files contained in one working tape (V 39163 to V 39168). The corresponding “kelp*.neq” and “kelp*.ne6” files must be copied in two files, kelpu.neq and kelpu.ne6, respectively.

Outputs: The program generates a file designated “map.meta,” which can be displayed by the standard instruction:
The images generated represent the polarization maps for the days contained in the working tape, together with the solution (and the corrections) indicated in the kelp*.neq and kelp*.ne6 files. Note that the disk diameter is not drawn to the same scale as the scan heights. The \((pI)_k\) values are represented by directed line segments whose length gives the magnitude and whose direction maps the orientation.

In the upper part of the plot are given the following indications (each line corresponds to a scan):

- name of the file containing the scan
- \(R\): radial distance of scan from the center of the solar disk in \(R_O\).
- eq: value of neq
- \(pI_e\) and \(pI_k\): mean value of \((pI)_k\) for latitudes below and above 60°, respectively.
- \(I_e\) and \(I_p\): mean value of \(I_k\) for latitudes below and above 60°, respectively.
- \(N_e\) and \(N_p\): number of measurements used for latitudes below and above 60°, respectively. If neq is not 6, \(N_e\) and \(N_p\) are generally 86 and 30.
REFERENCES


FIGURE CAPTIONS

Figure 1. Four panel images for the scan at 1.46 \( R_O \) on 26 October 1977, generated with the program KELPA5. In this example, large offsets, on the same order of magnitude of the mean value of the signals, must be removed from the line "Stokes parameters."

Figure 2. Polarization map for 26 October 1977, generated with the program KELPA4, after corrections.