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Agriculture and
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Surveys Through
Aerospace
Remote Sensing

Supporting Research

June 1980

TECHNICAL REPORT

AN ALGORITHM FOR ESTIMATING CROP CALENDAR SHIFTS OF SPRING SMALL GRAINS USING LANDSAT SPECTRAL DATA

Eric P. Crist and William A. Malila

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16. Abstract

This report documents a computer algorithm for estimating crop calendar shifts of fields (or pixels) observed several times during a growing season by the Landsat multispectral scanner. It is based on the use of mathematical representations, termed profiles, to describe the overall continuous pattern of crop spectral development from temporally discrete sets of Landsat observations. The agrophysical and remote-sensing bases of the profile approach are described, along with documentation of the crop-calendar-shift subroutine which is written in FORTRAN. While extensions to other crops and regions would be possible, the specific profile built into this subroutine was designed for first-order shift estimation and analysis of Landsat observations of spring small grains (e.g., wheat and barley) in the Northern U.S. Great Plains.

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TECHNICAL REPORT

AN ALGORITHM FOR ESTIMATING CROP CALENDAR SHIFTS OF SPRING

SMALL GRAINS USING LANDSAT SPECTRAL DATA

BY

Eric P. Crist and William A. Malila

This report describes results of research carried out in
support of the Area Estimation Design Element of the Supporting
Research Project.

Environmental Research Institute of Michigan
P.O. Box 8618
Ann Arbor, Michigan 48107

June 1980

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FOREWORD

The work reported herein was conducted by the Environmental
Research Institute of Michigan for Supporting Research, one of eight
projects of AgRISTARS, the program for Agriculture and Resources
Inventory Surveys through Aerospace Remote Sensing. AgRISTARS is a
six-year program of research, development, evaluation, and application
of aerospace remote sensing for agricultural resources which was
initiated in Fiscal Year 1980. AgRISTARS is a cooperative effort of
five federal agencies of the United States -- Department of Agriculture,
USDA; National Aeronautics and Space Administration, NASA; Department
of Commerce, USDC; Department of Interior, USDI; and the Agency for
International Development, USAID.

The goal of the program is to determine the usefulness, cost, and
extent to which aerospace remote sensing data can be integrated into
existing or future USDA systems to improve the objectivity, reliability,
timeliness, and adequacy of information required to carry out USDA
missions. The overall approach is comprised of a balanced program of
remote sensing research, development, and testing which addresses
domestic resource management as well as commodity production infor-
mation needs in both domestic and foreign regions.

The Supporting Research Project's objective is to develop improved
technology through research to assess crop area and condition, in
support of other projects which address improved commodity production
forecasts in foreign and domestic areas, early warning of changes in
production conditions and expectations, improved yield estimation, and
other applications. Dr. Jon D. Erickson, NASA Johnson Space Center,
Code SF3, is the NASA manager of the Supporting Research Project and
Thomas Pendleton, Code SF3, the Technical Coordinator for the reported
effort.

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INTRODUCTION

The cyclic coverage of satellite-borne remote sensing systems, such as Landsat, and the availability of spatially registered data have allowed the utilization of temporal information in analysis and discrimination of crop types. While the temporal-spectral pattern of development has proven to be an important piece of information, particularly in analyst identification of the crop type of data samples [1], its use has been somewhat hindered by the intermittent nature of the Landsat observations and confusion caused by differences in the planting dates and development patterns of neighboring fields of the same crop. This shortcoming may be overcome by estimating the overall pattern of spectral development for each field or pixel from the set of samples provided by Landsat. Based on this more complete description of sample characteristics, important information can be extracted for use in analysis and classification. This report presents an algorithm designed to estimate one important piece of information--the relative crop calendar shift--from observations of spring small grains [2,3].

2
BASIS OF CROP CALENDAR SHIFT ESTIMATION
FROM LANDSAT SPECTRAL DATA

Temporal-spectral profile characterization plays a key role in the utilization of multitemporal Landsat data for crop calendar shift estimation. This section reviews the agrophysical basis of such characterization, describes the crop calendar shift estimation concept, and discusses profile modeling of spring small grains.

2.1 TEMPORAL-SPECTRAL PROFILE CHARACTERIZATION

The sequence of development stages through which plants of a given crop type progress in the course of a growing season is accompanied by a related sequence of spectral reflectance stages. While not every stage of physiological development will necessarily result in a differentiable set of reflectance properties, those stages corresponding to observable differences in plant morphology or canopy structure will influence reflectance. Since most of the morphological changes occur gradually rather than abruptly, particularly when viewed at the population (field or pixel, i.e., picture element) level, it is reasonable to assume that the spectral development of a field could be represented by a continuous function.

The intermittent observations from a remote sensing platform such as Landsat can be viewed as discrete samples from such continuous functions, and can provide important information for crop identification and condition assessment. However, if the continuous function represented by the Landsat samples could be reconstructed, considerably more complete information could be available. Profile characterization is the process of fitting mathematical functions (profiles) to a set of observations of a given scene element.

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While the temporal pattern of any spectral band or variable could be fit with a mathematical function, those spectral features most closely correlated to describable plant or field phenomena are probably of greatest use. In particular, indicators of "greenness" (spectral variables which are sensitive to the green vegetation component of agricultural signatures) such as the Greenness variable produced by the Tasseled-Cap transformation [4,5] often exhibit temporal patterns which are relatively easy to characterize mathematically and contain substantial information.

Most crops follow a general pattern consisting of a period of increasing greenness to a maximum value, followed by a period of declining greenness. The rate of greenness increase or decline is closely tied to the rates of change in leaf area and canopy closure, and the rates of plant maturation. Specifically, we would expect a low rate of greenness increase as the plants emerge and begin to affect the spectral reflectance properties of the field, followed by a more rapid rate of increase corresponding to the period of most rapid bio-mass production. Then, as the maximum greenness is approached, increases in greenness will occur at a declining rate, since they involve lessening changes in leaf area or canopy closure. A similar sequence of rate changes will occur as the plants turn from green to yellow/brown.

The sequence of rate changes described suggests that sigmoidal curve shapes could be used to characterize both the greenness-increase and greenness-decline phases of crop spectral development. Such curve shapes are commonly used to describe growth and development phenomena in biological populations. A curve of Greenness vs. day of year for spring small grains is illustrated in Figure 1.

Within the group of crops that follow this general spectral development pattern, significant variations in the overall temporal pattern can occur. The particular sequence of development stages through which a crop passes affects the spectral character and the
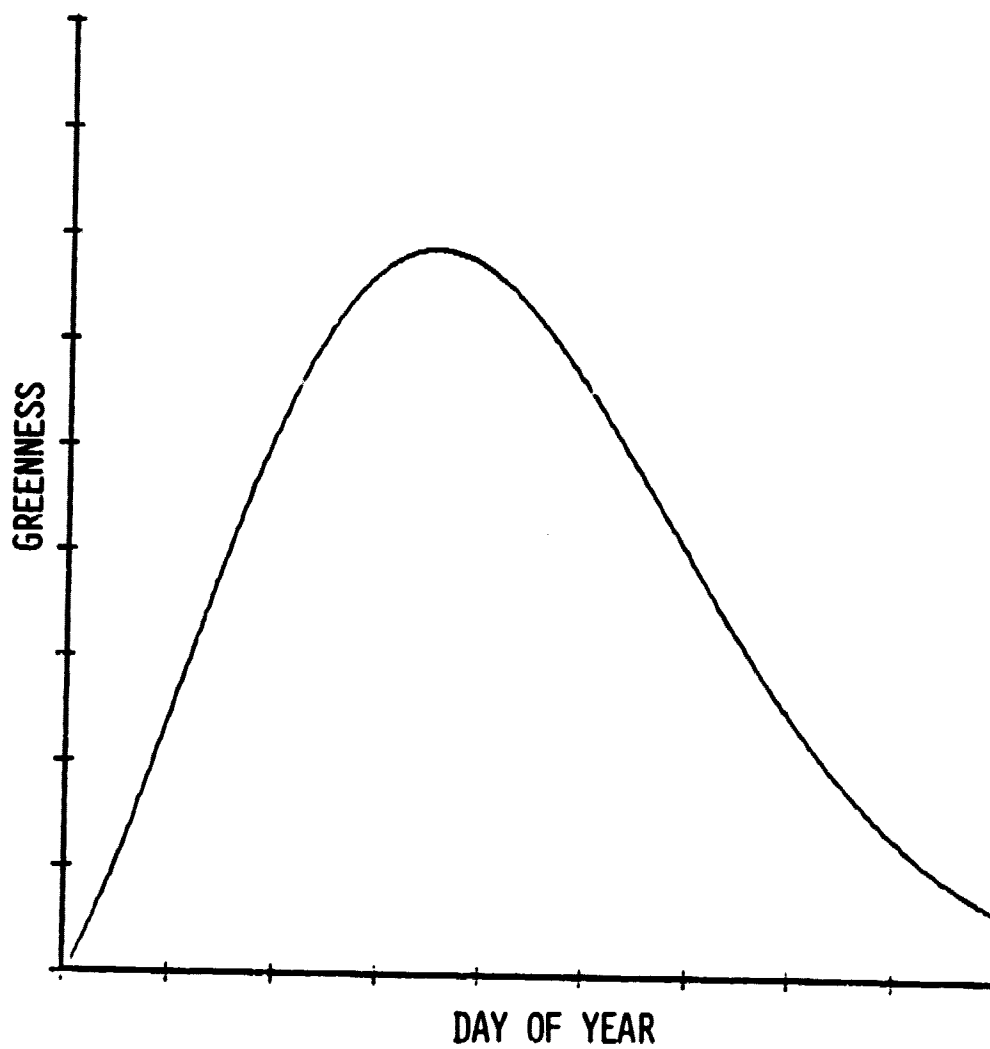
3

GREENNESS

DAY OF YEAR

FIGURE 1.   SPRING SMALL GRAIN GREENNESS PROFILE

temporal-spectral pattern of the crop. Variations in growing conditions can also alter the character of the individual plants and the canopy structure in the field, and thus again change its spectral qualities and temporal-spectral pattern. Some such differences can be adapted to by a well-chosen profile model form and can be detected by evaluation of model parameters. Other differences, however, may be of such a nature that they cannot be accurately represented by the same model. Different greenness measures can also behave differently in this regard [6].

2.2 CROP CALENDAR SHIFT ESTIMATION CONCEPT

Healthy fields of a given crop type might be expected to follow a common pattern of spectral development in the course of a growing season with the result that, on any given day, spectral signals from nearby fields wouldn't vary to any great degree. It is more common, however, to encounter wide dispersion of signal values, as depicted in Figure 2a. Crop calendar shift techniques are intended to account for that portion of signal variability which is due to differences in stage of development on the day of observation. As illustrated in Figure 2b, the highly variable data points of Figure 2a can all be fit with the same profile shifted along the time axis. By shifting all the data points to a common profile, as in Figure 2c, the spectral impact of development stage differences is adjusted for and better comparison of fields is made possible.

The idea of using temporal-spectral patterns to adjust for development stage differences was first suggested by Dr. Gautam D. Badhwar [7]. Starting from this initial work by Badhwar, we at ERIM developed refinements of the crop calendar shift technique and alternative approaches [8,3]. First, in order to represent the actual pattern of spectral development of the crop of interest, we developed and began to use the model form (Equation 2) which is discussed in

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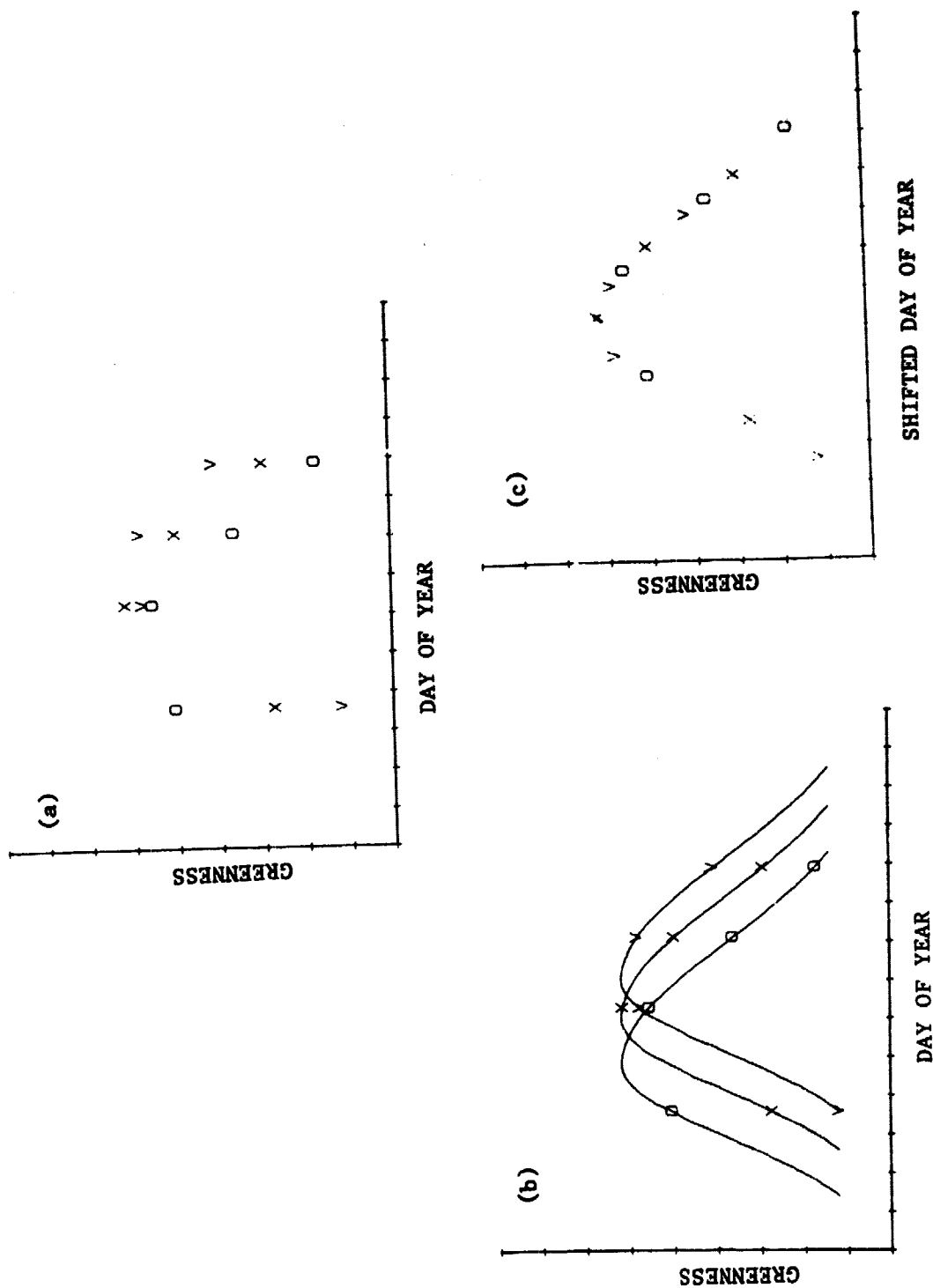
FIGURE 2. CROP CALENDAR SHIFT ESTIMATION -- BASIC CONCEPT

Section 2.3. (Badhwar, in turn, continued development of his approach, adding a model form related to Equation 2 [9].) Second, we used a cross-correlation computation in determining the goodness-of-fi. of a set of data values to the shifted reference profile. The cross-correlation measure is of the form:

$$R = \frac{2}{1 + \frac{\Sigma F_{i+\tau}^2 * G_i^2}{(\Sigma F_{i+\tau} G_i)^2}} \tag{1}$$

where

F_i = reference profile function value

G_i = data value

τ = shift value

This measure has the advantage of being essentially independent of scale and so places emphasis on the overall shape of the data profile rather than its amplitude which can be influenced by factors not related to stage of development.

Figure 3 illustrates results obtained when the ERIM crop calendar shift technique was applied to actual Landsat data from spring wheat pixels [10].

2.3 PROFILE MODELING FOR SPRING SMALL GRAINS

Any of a variety of mathematical model forms might be used to represent the temporal-spectral characteristics of crops. The initial model form developed at ERIM for characterizing green development profiles of spring small grains is of the following form [2,3,8,10]:

$$F(t) = at^b e^{ct^2} \tag{2}$$

Not Adjusted

Adjusted
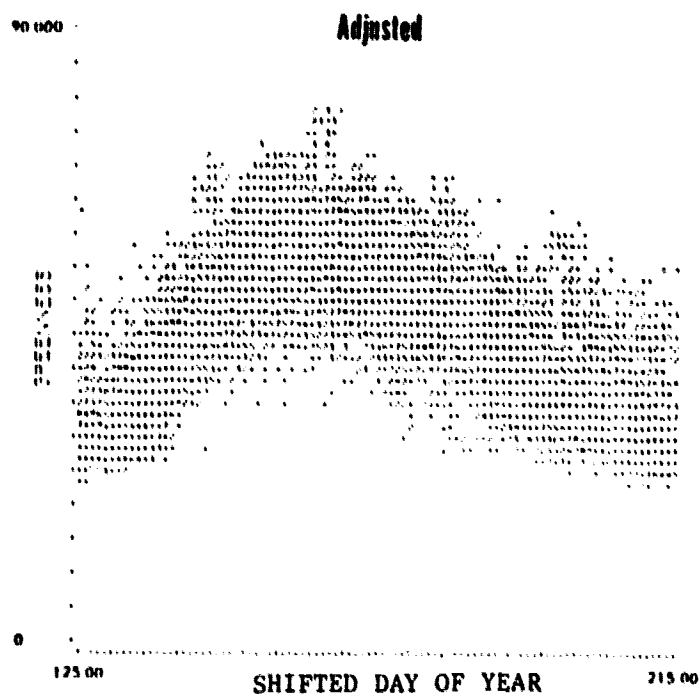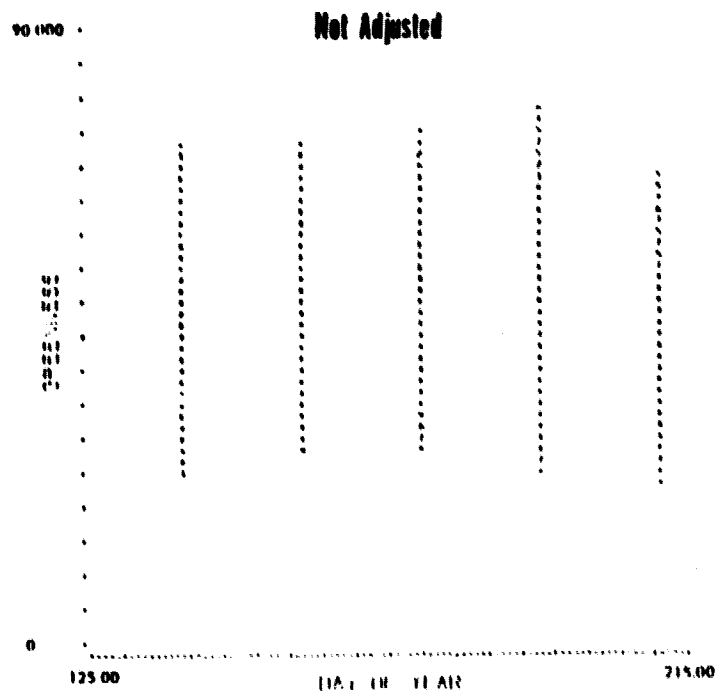
SHIFTED DAY OF YEAR

FIGURE 3. RESULTS OF CROP CALENDAR SHIFT ESTIMATION APPLIED TO ACTUAL
LANDSAT DATA (Spring Wheat Pixels)

where

$F(t)$ = profile value at time t

t = (day of year) - (day of first detectable
green development)

and

a,b,c = model parameters, with b and c determining
the shape of the profile.

This model form best exhibits the desired double-sigmoid shape for representing green development, as illustrated in Figure 1, when the spectral variable being used has values near zero at t=0. This implies, in general, a need for both a spectral and a temporal offset, the first being the value of the green measure for t < 0 (i.e., the value for bare soil) and the second being the day of first detectable green development.

Specification of the bare soil value, i.e., the spectral offset, is simplified by use of data normalization to reduce variability caused by external (non-crop) effects (as discussed in Section 3.3) and use of Tasseled-Cap Greenness as the green measure because it tends to keep constant values in the presence of soil reflectance variations. The CCSHFT subroutine described in this report expects to receive, as inputs, Tasseled-Cap Greenness values computed from Landsat multispectral scanner (MSS) band values according to the following relationship* [5]:

$$G = -0.2837 \text{ MSS4} - 0.66006 \text{ MSS5} + 0.57735 \text{ MSS6} \qquad (3)$$
$$+ 0.38833 \text{ MSS7} + 32.$$

where the Landsat MSS band values preferably have been normalized against externally caused variations (Section 3.3). Values for the profile variable in CCSHFT are computed as follows:

$$F_i = G_i - 25. \qquad (4)$$

---

*LACIE Landsat-2 calibration of the data is assumed.

This spectral offset has been found satisfactory for use in analyzing
and processing spring small grains data from the Northern U.S. Great
Plains [2,10].

Determination of the temporal offset, which can vary from sample
to sample, can be accomplished with a crop calendar shift estimation
procedure, as previously discussed.

The reference profile of Greenness that is built into the code of
CCSHFT was determined through regression analysis and least squares
fitting of data values from several 5x6-mile segments to the model form
of Equation 2.

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CONSIDERATIONS AND LIMITATIONS

Three general categories for consideration in the application of
temporal-spectral characterization techniques are level of accuracy,
model form attributes, and data normalization.

3.1 LEVEL OF ACCURACY

Temporal-spectral profiles may be used for a wide variety of pur-
poses. Corresponding to this variety is a range of accuracies required
from the model form. For some purposes it may suffice to roughly
approximate the general shape of the profile, even to the point of
simply connecting the observations with a sequence of straight line
segments. At the other extreme, a highly accurate fit of physically-
based mathematical form may be required, drawing on growth and develop-
ment models, weather data, and other types of data in addition to the
spectral samples. Between these extremes is a range of profile appli-
cations with a range of accuracy demands. Each new application must
take into account its required level of accuracy, and any model should
be used only at the level of accuracy for which it was developed, or
at higher levels only after careful testing.

For crop calendar shift estimation of spring small grains, we have
found that the day on which the maximum profile value occurs is the
most dominant and consistent profile feature. This peak occurs just
prior to or at the start of heading when green leaf area is at a maxi-
mum. A good overall characterization of the profile shape is sufficient
for estimating the peak date, and we have found the model form of
Equation 2 to be satisfactory.

Other crop calendar dates, such as date of planting or specific
growth stages, might be inferred through use of this approach but only

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insofar as their relationship to the date of peak is constant or nearly
so. For example, a preliminary evaluation of crop calendar shift tech-
nology applied to field reflectance measurements from soybean fields
found a correlation between the shift estimate and row spacing; row
spacing influenced when maximum cover occurred and, consequently,
affected the day of maximum Greenness. Fields planted on the same
day were shifted different amounts, and thus planting date estimates
based on crop calendar shift would have been in error.

3.2 MODEL FORM ATTRIBUTES

For a model form to be of practical use in characterizing crop
temporal-spectral profiles, the number of parameters which must be
estimated should be kept small. In addition, the overall characteris-
tics of the profile shape should be easily derived from the estimated
parameters. The model must produce stable results, and be able to
adapt to the range of shape variations likely to be encountered. Nor-
mal variations shouldn't adversely affect the profile estimation process.
At the same time, however, and particularly in applications for which
the accuracy requirement is high, the model must respond to those dif-
ferences which carry the information of interest and maintain a close
fit to the data samples.

Some characteristics of green development profiles of spring small
grains and Equation 2 were noted in the preceding section. During our
prior development [2,10] of a spring wheat labeling procedure, we com-
puted separate profiles for wheat and barley for several segments. We
found that crop calendar shifts computed using these different profiles
for reference usually differed by less than two days and so were able
to use a single reference profile for shift calculations in the pro-
cedure. For other purposes, we have computed segment-specific profiles
based on shifts estimated with the general reference profile [2,3].

3.3 DATA NORMALIZATION

In order to insure that profile shapes fit to Landsat observations
are influenced only by agrophysical phenomena, and to allow comparison
of profiles over wide geographical regions, data normalization is
highly desirable, if not essential. Corrections for sun angle, sensor
calibration, and atmospheric haze effects, and detection of clouds,
defective data, etc., should be carried out prior to profile charac-
terization, particularly when profile features are to be used for crop
identification or condition assessment. We recommend and use ERIM's
spatially-varying XSTAR haze correction algorithm [10,11] for correc-
tion of atmospheric effects and associated preprocessing algorithms
[5,10].

4
DETAILS OF CROP-CALENDAR-SHIFT SUBROUTINE CCSHFT

This section describes our crop-calendar-shift subroutine called CCSHFT. User documentation is presented in Appendix A, a FORTRAN listing in Appendix B, and test cases and results in Appendix C.

It is important to indicate here what this subroutine does, what it requires, what environment it will best operate in, and some things it does not do.

The subroutine program does:

(1) Operate on multidate values of the Tasseled-Cap Greenness variable (see requirements and preferences below),

(2) Determine if sufficient appropriate acquisitions are present, and

(3) Compute an estimated day of peak Greenness and a goodness of fit, assuming the observations to be from a spring small grain.

The subroutine requires or assumes:

(1) A minimum of three acquisitions that are separated by 17 or more days and occur during the growing stages of wheat -- after emergence and before harvest.

(2) Tasseled-Cap Greenness values with a 32-count offset having been added to eliminate negative values. (See Equation 3, Sec. 2.3)

The preferred operating environment provides:

Data that have been preprocessed to reduce non-crop-related variations due to satellite calibration, sun angle, and atmospheric haze. We use and recommend use of the ERIM spatially varying XSTAR algorithm and associated correction factors. (See Sec. 3.3)

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The subroutine does not:

(1) Make a detailed estimate of any crop stage other than day of peak Greenness (which apparently occurs just prior to heading at the time of peak leaf area and/or flag leaf development).

(2) Estimate the value of peak Greenness or other specific profile characteristics, since they are not required for the intended application, crop calendar shift estimation for spring small grains.

The steps followed by the subroutine are as follows:

(1) Read in data values and corresponding days of year.

(2) Compute rough estimate of day of peak Greenness.

(3) Accept acquisitions within a prescribed window around the estimated peak.

(4) Compute a cross-correlation function between the observed values and corresponding values of a standard small-grains reference profile, as they are shifted in time past each other.

(5) Choose that shift value which maximizes the cross-correlation function and compute the corresponding day of peak Greenness.

(6) Output the shift value and a goodness of fit.

The goodness-of-fit value returned by the subroutine is derived from the maximum cross-correlation coefficient, and typically ranges from 0 to 1, where 1 represents a perfect fit. However, negative values are possible and indicate a very poor fit.

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APPENDIX A

USER DOCUMENTATION OF SUBROUTINE CCSHFT

ROUTINE: CCSHFT

VERSION: 1.0

DATE: February 1980

PROGRAMMER: E. Crist $\mathcal{E}.\mathcal{C}.$

LANGUAGE: FORTRAN

INTERFACE: A Standard FORTRAN Integer Function

PURPOSE: To compute an estimate of the day of maximum Greenness for
           small grains targets.

CALLING SEQUENCE:

          IRC=CCSHFT(DATA,ACQDAY,NACQ,PKDAY,GFIT)

                       or

       CALL CCSHFT(DATA,ACQDAY,NACQ,PKDAY,GFIT)

ARGUMENTS:

NAME	TYPE	DESCRIPTION
DATA(15)	R	Tasseled-cap Greenness values (with 32-count offset), or -99.0 if flagged by SCREEN.
ACQDAY(15)	I	Acquisition days (1-366) corresponding to values in DATA().
NACQ	I	Number of acquisitions.
PKDAY	I	Output estimate of day of peak Greenness, or '0' if no peak estimate can be made.
GFIT	R	Output measure of data fit to profile based on cross-correlation factor.

RETURN CODES:

    CCSHFT = 0   Successful return

           1   Too few acquisitions

           2   Too few or inadequately spaced acquisitions
               (after first rough shift)

DESCRIPTION:

    CCSHFT carries out the following sequence of steps in estimating
the day of maximum Greenness:

1.   Check acquisition availability -- there must be a minimum of
     three non-SCREENed acquisitions. If there are less than three,
     CCSHFT = 1, and return to calling program.

2.   Fit a quadratic to three acquisitions, including the one with the
     largest Greenness value. The maximum value of the quadratic is
     the first estimate of the day of peak Greenness. If the quadratic
     cannot be fit, the acquisition day corresponding to the highest
     Greenness value in DATA() is used as the first peak estimate.

3.   Line up the data to a reference Greenness profile by matching
     the peak day estimate to the peak day of the profile. The
     reference profile is illustrated in Figure A-1.

4.   Re-check acquisition availability -- now there must be at least
     three acquisitions in the range marked 'A' in Figure 1. In
     addition, a spacing constraint is applied, such that consecutive
     acquisitions by different satellites (i.e., approximately 9-day
     spacing) are only treated as one acquisition in meeting the three
     acquisition requirement. If there are less than three adequately
     spaced acquisitions, CCSHFT = 2, and return to calling program.

5.   Shift the data values in time relative to the reference profile
     (±30 days) and select that shift which maximizes the cross
     correlation term,

REFERENCE PROFILE
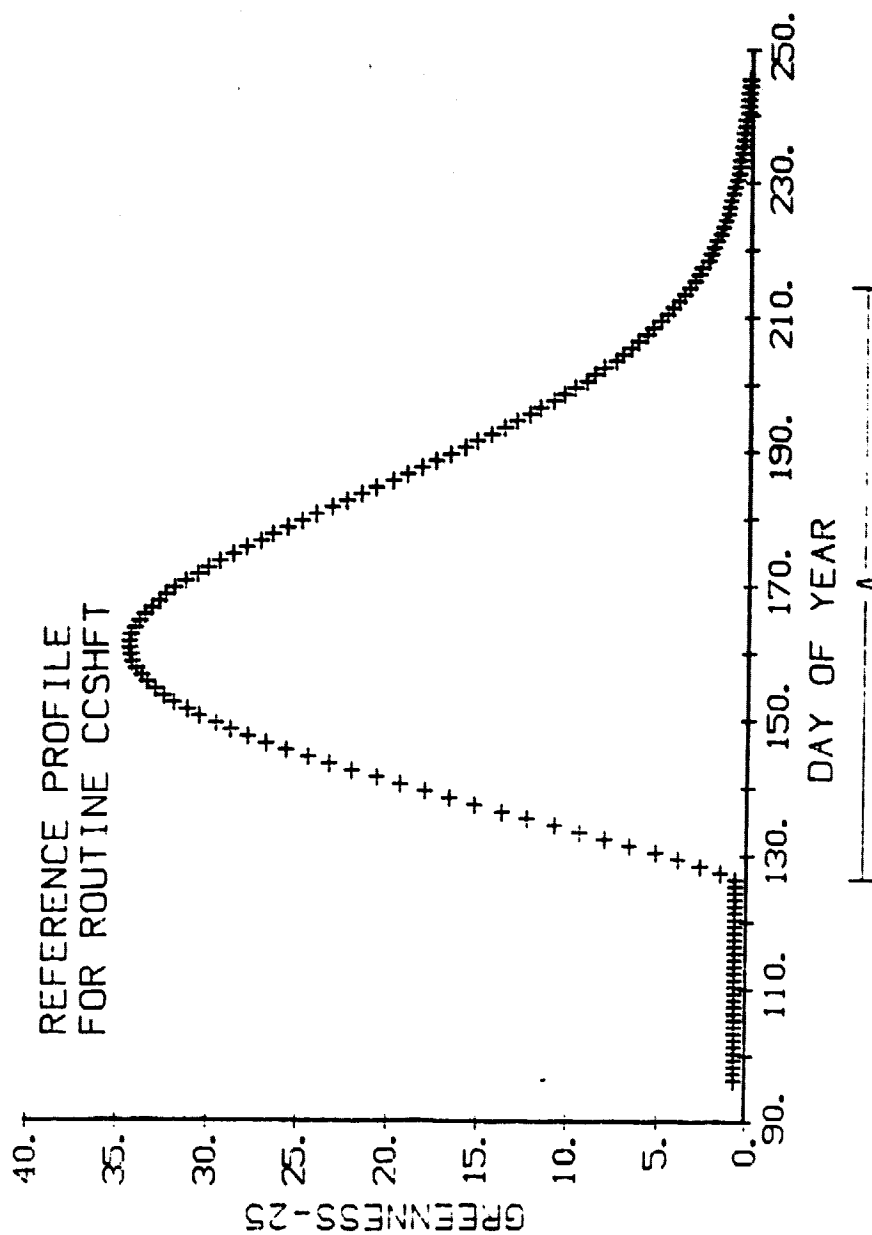FOR ROUTINE CCSHFT

FIGURE A-1.

$$R = \cfrac{2}{1 + \cfrac{\sum F_{i+\tau}^2 \ast G_i^2}{\left[\sum F_{i+\tau} \ G_i\right]^2}}$$

where F_i is the reference profile value,

G_i is the data value,

τ is the shift value.

6. Compute the final peak day estimate by using the selected shift value to adjust the first peak day estimate.

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APPENDIX B

FORTRAN LISTING OF SUBROUTINE CCSHFT

```
      INTEGER FUNCTION CCSHFT(DATA,ACQDAY,NACQ,PKDAY,GFIT)
C************************************************************************
C*
C*      ROUTINE TO ESTIMATE DAY OF PEAK GREENNESS FOR GRAIN TARGETS.
C*
C*......................................................................
C*
C*          ARGUMENT      TYPE      DESCRIPTION
C*
C*          DATA(15)       R        TASSELED-CAP GREENNESS VALUES, OR
C*                                  -99.0 IF FLAGGED BY SCREEN.
C*
C*          ACQDAY(15)     I        ACQUISITION DAYS (1-366) CORRESPONDING
C*                                  TO DATA VALUES.
C*
C*          NACQ           I        NUMBER OF ACQUISITIONS INPUT.
C*
C*          PKDAY          I        OUTPUT ESTIMATED DAY OF PEAK GREENNESS
C*                                  (1-366).
C*
C*          GFIT           R        MEASURE OF FIT AT MAXIMUM
C*                                  CROSS-CORRELATION.
C*
C*......................................................................
C*
C*      WRITTEN BY E. P. CRIST
C*                 ENVIRONMENTAL RESEARCH INSTITUTE OF MICHIGAN
C*                 P.O. BOX 8618
C*                 ANN ARBOR, MICHIGAN  48107
C*
C************************************************************************
C*
C*      DECLARATIONS AND DIMENSIONS
C*
        INTEGER PKDAY,SDAY,SHIFT,TDIFF,TOPDAY
C*
        INTEGER ACQDAY(15),DAY(15),T(3)
C*
        REAL INT,MAX,MAXR
C*
        REAL DATA(15),G(3),GR(15),PROFIL(150)
C*
        DATA PROFIL/0.651,0.651,0.651,0.651,0.651,
       &0.651,0.651,0.651,0.651,0.651,0.651,0.651,0.651,
       &0.651,0.651,0.651,0.651,0.651,0.651,0.651,0.651,
       &0.651,0.651,0.651,0.651,0.651,0.651,0.651,0.651,
       &0.651,0.651,1.596,2.693,3.894,5.176,6.517,7.904,
       &9.323,10.764,12.216,13.671,15.119,16.553,17.965,19.348,
       &20.697,22.004,23.265,24.474,25.627,26.719,27.746,28.706,
       &29.595,30.412,31.153,31.818,32.405,32.915,33.345,33.698,
       &33.972,34.170,34.292,34.340,34.315,34.221,34.058,33.831,
       &33.541,33.192,32.787,32.379,31.821,31.268,30.673,30.039,
       &29.371,28.671,27.943,27.191,26.418,25.628,24.824,24.010,
       &23.188,22.362,21.533,20.706,19.882,19.064,18.255,17.455,
       &16.668,15.894,15.136,14.394,13.671,12.967,12.282,11.619,
```

```
     &10.977,10.357,9.760,9.185,8.633,8.104,7.597,7.114,
     &6.652,6.213,5.796,5.400,5.025,4.670,4.334,4.018,
     &3.721,3.441,3.179,2.933,2.703,2.487,2.287,2.100,
     &1.925,1.764,1.614,1.475,1.346,1.227,1.117,1.016,
     &0.923,0.838,0.759,0.688,0.622,0.562,0.507,0.456,
     &0.411,0.369,0.332,0.298,0.267,0.239,0.213,0.190,
     &0.170/
C*
      CCSHFT=0
C*
C*********************************************************************
C*
C* STEP 1:
C*
C*   FIT A QUADRATIC TO THE THREE HIGHEST GREENNESS VALUES IN ORDER TO
C* GET A FIRST ROUGH ESTIMATE OF THE DAY OF PEAK GREENNESS.
C*
      NUSED=0
      MAX=0
      DO 10 IA=1,NACQ
        IF (DATA(IA).EQ.-99.) GO TO 10
          NUSED=NUSED+1
C*
C* GR()  CONTAINS NON-SCREENED DATA VALUES, OFFSET BY 25 COUNTS.
C* DAY() CONTAINS THE CORRESPONDING ACQUISITION DAYS OF YEAR.
C*
          GR(NUSED)=DATA(IA)-25.
          DAY(NUSED)=ACQDAY(IA)
C*
C* LOCATE HIGHEST GREENNESS VALUE.
C*
          IF (DATA(IA).LE.MAX) GO TO 10
            MAX=DATA(IA)
            IMAX=NUSED
   10 CONTINUE
C*
C*   THREE NON-SCREENED ACQUISITIONS ARE REQUIRED - LESS WILL
C* NOT PRODUCE A RELIABLE ESTIMATE OF THE SHIFT. IF THREE
C* ACQUISITIONS ARE NOT AVAILABLE, SET CCSHFT=1 AND RETURN.
C*
      IF (NUSED.GE.3) GO TO 15
        CCSHFT=1
        PKDAY=0
        GFIT=0.
        RETURN
C*
   15 CONTINUE
C*
C*   TWO ACQUISITIONS IN ADDITION TO THE MAXIMUM ARE TO BE USED.  THE
C* CHOICE OF ACQUISITIONS DEPENDS ON THE LOCATION OF THE MAXIMUM.
C* IDEALLY, ONE ACQUISITION ON EITHER SIDE OF THE MAXIMUM IS CHOSEN. IF
C* THE MAXIMUM IS THE FIRST OR LAST ACQUISITION, HOWEVER, THE TWO
C* NEAREST ACQUISITIONS ARE USED.
C*
      IF (NUSED-IMAX)20,20,25
```

30

```
      20   IUSE=IMAX-2
           GO TO 40
      25 IF (IMAX-1)30,30,35
      30   IUSE=IMAX
           GO TO 40
      35 IUSE=IMAX-1
      40 CONTINUE
C*
C* DATA ARRAYS ARE FURTHER SUBSET FOR EASE OF QUADRATIC COMPUTATION.
C*
           IUSE=IUSE-1
           DO 50 IA=1,3
             IUSE=IUSE+1
             G(IA)=GR(IUSE)
             T(IA)=DAY(IUSE)
      50 CONTINUE
C*
C*    COMPUTE A STRAIGHT LINE THROUGH THE FIRST AND THIRD POINTS.  IF THE
C* MIDDLE VALUE FALLS BELOW THIS LINE, THE QUADRATIC COMPUTATION WILL
C* FIND A MINIMUM INSTEAD OF A MAXIMUM.  IN THIS CASE, USE THE DAY OF
C* THE MAXIMUM GREENNESS OBSERVATION AS THE FIRST PEAK DAY ESTIMATE.
C*
           SLOPE=(G(1)-G(3))/(T(1)-T(3))
           INT=G(1)-T(1)*SLOPE
           CHKVAL=SLOPE*T(2)+INT
C*
           IF (G(2).GE.CHKVAL)GO TO 55
             TOPDAY=DAY(IMAX)
             GO TO 70
      55 CONTINUE
C*
C* COMPUTE TERMS OF THE QUADRATIC EQUATION.
C*
           DIF1=T(1)-T(2)
           DIF2=T(2)-T(3)
           SUM1=T(1)+T(2)
           SUM2=T(2)+T(3)
           DIFSQ1=DIF1*SUM1
           DIFSQ2=DIF2*SUM2
           DIFG1=G(1)-G(2)
           DIFG2=G(2)-G(3)
C*
           A=(DIF2*DIFG1-DIF1*DIFG2)/(DIF2*DIFSQ1-DIF1*DIFSQ2)
C*
C*    COMPUTATION OF DAY OF PEAK REQUIRES DIVISION BY 'A' TERM, SO
C* IF A=0, THE COMPUTATION CANNOT BE MADE.  IN THIS CASE, AGAIN,
C* THE DAY OF THE MAXIMUM GREENNESS OBSERVATION IS USED AS THE
C* FIRST PEAK DAY ESTIMATE.
C*
           IF (A.NE.0.) GO TO 60
             TOPDAY=DAY(IMAX)
             GO TO 70
      60   CONTINUE
C*
           B=(DIFG2-DIFSQ2*A)/DIF2
```

31

```
        TOPDAY=-1.*B/(2.*A)+.5
C*
C*    THE MAXIMUM VALUE OF THE QUADRATIC MUST FALL IN THE RANGE
C* OF THE THREE DATA VALUES USED IN ITS DETERMINATION.  OTHERWISE,
C* USE THE NEAREST OF THE THREE AS THE PEAK DAY ESTIMATE.
C*
        IF (TOPDAY-T(1))61,65,65
   61      TOPDAY=T(1)
           GO TO 70
   65   IF (TOPDAY-T(3))70,70,66
   66      TOPDAY=T(3)
   70 CONTINUE
C*
C*    COMPUTE THE DIFFERENCE BETWEEN THE REFERENCE PROFILE PEAK
C* DAY AND THE ESTIMATED PEAK DAY OF THE GIVEN TARGET.
C*
        SHIFT=160-TOPDAY
C*
C*******************************************************************
C*
C* STEP 2:
C*
C*    THE FINAL ESTIMATE OF THE DAY OF PEAK GREENNESS IS COMPUTED
C* BY DETERMINING THE SHIFT ALONG THE DAY OF YEAR AXIS WHICH
C* MAXIMIZES THE CROSS-CORRELATION BETWEEN THE DATA VALUES AND
C* A REFERENCE PROFILE.
C*    THE REFERENCE PROFILE CONSISTS OF VALUES CORRESPONDING TO
C* A 90-DAY INTERVAL WHICH ENCOMPASSES ESSENTIALLY THE ENTIRE
C* GROWING SEASON FOR SPRING SMALL GRAINS, AND A 30-DAY 'TAIL'
C* ON EITHER SIDE.  FOR ANY GIVEN SET OF OBSERVATIONS, ONLY THOSE
C* WHICH FALL IN THE 90-DAY INTERVAL (USING THE DAY OF PEAK
C* GREENNESS ESTIMATE JUST COMPUTED) ARE CONSIDERED IN THE
C* CROSS-CORRELATION CALCULATION.
C*
        NSPRD=0
        NUSED=0
        DO 90 IA=1,NACQ
          IF (DATA(IA).EQ.-99.) GO TO 90
            SDAY=ACQDAY(IA)+SHIFT-94
            IF (SDAY.LE.30 .OR. SDAY.GT.120) GO TO 90
C*
C*           OBSERVATIONS MUST BE MORE THAN 9 DAYS APART (SEE BELOW).
C*
             IF (NUSED.GT.0) GO TO 75
               TDIFF=18
               GO TO 80
   75          CONTINUE
               TDIFF=SDAY-DAY(IPREV)
   80          CONTINUE
             IF (TDIFF.LT.15) GO TO 85
               IPREV=NUSED+1
               NSPRD=NSPRD+1
   85          CONTINUE
               NUSED=NUSED+1
               GR(NUSED)=DATA(IA)-25.
```

```
              DAY(NUSED)=SDAY
  90 CONTINUE
C*
C*    SECOND CHECK OF ACQUISITION AVAILABILITY.  REQUIREMENTS ARE:
C*       1) THREE ACQUISITIONS IN THE 90-DAY PROFILE INTERVAL
C*       2) MORE THAN 9 DAY SPACING BETWEEN SUCCESSIVE ACQUISITIONS.
C* THE SECOND CONSTRAINT IS THE RESULT OF OBSERVATIONS THAT
C* IN TERMS OF THE SHIFT CALCULATION, DATA WHICH ARE TOO CLOSELY
C* SPACED DO NOT BEHAVE AS INDEPENDENT OBSERVATIONS.  THE CUT-OFF
C* OF 15 DAYS USED IN THE PROGRAM IS NOT ABSOLUTE, BUT WAS
C* CHOSEN TO ELIMINATE CONSECUTIVE ACQUISITIONS FROM DIFFERENT
C* SATELLITES WHILE ALLOWING CONSECUTIVE ACQUISITIONS FROM THE
C* SAME SATELLITE.
C*    ACQUISITIONS NOT MEETING THE SPACING CRITERION ARE STILL USED
C* IN THE SHIFT CALCULATION, IF THERE ARE ENOUGH WELL -SPACED
C* ACQUISITIONS.
C*
      IF (NSPRD.GE.3) GO TO 100
        CCSHFT=2
        PKDAY=0
        GFIT=0.
        RETURN
 100 CONTINUE
C*
C* ALL SHIFTS OF + OR - 30 DAYS FROM THAT COMPUTED WITH THE
C* QUADRATIC ARE CONSIDERED.  THE MAXIMUM CROSS-CORRELATION,
C* AND THE CORRESPONDING SHIFT, ARE UPDATED AS APPROPRIATE.
C*
      MAXR=0.
      ISTEP=-11
      DO 120 IST=1,61
        ISTEP=ISTEP+1
        SUMPRD=0.
        SSQPRD=0.
        SSQDAT=0.
        DO 110 ID=1,NUSED
          SDAY=DAY(ID)+ISTEP
          SUMPRD=SUMPRD+GR(ID)*PROFIL(SDAY)
          SSQPRD=SSQPRD+PROFIL(SDAY)*PROFIL(SDAY)
          SSQDAT=SSQDAT+GR(ID)*GR(ID)
 110    CONTINUE
C*
      R=2./(1.+SSQDAT/SUMPRD*(SSQPRD/SUMPRD))
C*
      IF (R.LT.MAXR) GO TO 120
        MAXR=R
        NSHIFT=ISTEP
 120 CONTINUE
C*
C* THE FINAL SHIFT IS THE COMBINATION OF THE FIRST (BASED ON THE
C* QUADRATIC), AND THE SECOND (BASED ON THE CROSS-CORRELATION TO
C* THE REFERENCE PROFILE).  THE ESTIMATED DAY OF PEAK GREENNESS
C* IS THE REFERENCE DAY OF PEAK GREENNESS (DAY 160) ADJUSTED BY
C* THE ESTIMATED SHIFT.
C*
      PKDAY=160-(SHIFT+NSHIFT)
C*
      GFIT=10.*MAXR-9.
      RETURN
      END
```

APPENDIX C

TEST CASES AND TEST RESULTS FOR SUBROUTINE CCSHFT

ΣERIM

TEST CASES FOR ROUTINE CCSHFT

A series of test cases was run to verify the proper functioning
of CCSHFT. Attached are listings of the testing program 'TESTCC.F',
test data 'TESTDATA', and output results 'TEST.RESULT'. The cases
and their purposes are as follows:

Case 1   - test normal flow of program

Case 2   - test first check of acquisition availability
(lines 74-101)

Case 3   - test mechanism for assuring that the quadratic
estimates a maximum rather than a minimum
(lines 134-141)

Case 4,5   - test selection of acquisitions for quadratic,
and mechanism for adjusting peak estimate
to fall in data range (lines 111-118,173-178)

Case 6   - test second acquisition check - less than 3 acqs

Case 7   - test second acquisition check - minimum spacing
requirements (lines 204-244)

Case 8,9   - illustrate GFIT values from non-typical data

```
********************************************************
**                                                  **
**          TESTCC.F                                 **
**                                                  **
**      14:54:40    02-28-80                         **
**                                                  **
********************************************************

1          INTEGER ACQDAY(5),PKDAY,CCSHFT
2          REAL GREEN(5),GFIT
3          NACQ=5
4     C
5          DO 100 I=1,3
6          READ(0,10)ACQDAY
7   10     FORMAT(5I9)
8          READ(0,15)GREEN
9   15     FORMAT(5F5.1)
10    C
11         IRC=CCSHFT(GREEN,ACQDAY,NACQ,PKDAY,GFIT)
12    C
13    C      WRITE(6,20)I,IRC,PKDAY,GFIT
14  20     FORMAT('0CASE ',I1,/,5X,'RETURN CODE= ',I1,3X,'PKDAY= ',I3,
14.5     &   5X,'GFIT= ',F10.8)
15    C
16  100    CONTINUE
17         STOP
18         END
```

```
*************************************************************
**                                                       **
**                    TESTDATA                           **
**                                                       **
**            14:54:40      02-28-80                      **
**                                                       **
*************************************************************
```

```
 1        139 157 175 193 211
 2         45.0  60.0  55.0  40.0  30.0
 3        139 157 175 193 211
 4         45.0 -99.0  55.0 -99.0 -99.0
 5        139 157 175 193 211
 6         60.0  45.0  55.0  40.0  30.0
 7        139 157 175 193 211
 8         30.0  30.0  40.0  55.0  65.0
 9        139 157 175 193 211
10         65.0  55.0  40.0  30.0  30.0
11        139 157 175 193 211
12         60.0 -99.0  40.0 -99.0  30.0
13        139 157 165 193 211
14         45.0  60.0  55.0 -99.0 -99.0
15        139 157 175 193 211
16         45.0  45.0  45.0  45.0  45.0
17        139 157 175 193 211
18         55.0  50.0  45.0  50.0  55.0
```

∑ERIM

```
*************************************************************
**                                                       **
**              TEST.RESULT                              **
**                                                       **
**          14:54:40      07-28-80                       **
**                                                       **
*************************************************************
```

CASE 1
     RETURN CODE= 0   PKDAY= 161   GFIT= 0.99549484

CASE 2
     RETURN CODE= 1   PKDAY=   0   GFIT= 0.0

CASE 3
     RETURN CODE= 0   PKDAY= 152   GFIT= 0.32548237

CASE 4
     RETURN CODE= 2   PKDAY=   0   GFIT= 0.0

CASE 5
     RETURN CODE= 0   PKDAY= 141   GFIT= 0.99728203

CASE 6
     RETURN CODE= 2   PKDAY=   0   GFIT= 0.0

CASE 7
     RETURN CODE= 2   PKDAY=   0   GFIT= 0.0

CASE 8
     RETURN CODE= 0   PKDAY= 160   GFIT= 0.44945621

CASE 9
     RETURN CODE= 0   PKDAY= 155   GFIT= 0.29122353