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*A Manual for Analysis of
Hemispherical Canopy Photography*

Los Alamos

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Hemispherical Canopy Photography*

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Los Alamos

SOFTWARE COPYRIGHT

TRADEMARKS

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PREFACE

CANOPY[(c)] is a public domain program that I developed for digital image analysis of hemispherical (fisheye) canopy photography. My interest in canopy photography began in 1982, while I was a graduate student in the Department of Organismic and Evolutionary Biology at Harvard University. My dissertation research focused on the morphology, biomechanics, ecology, and evolution of arborescent (tree) palms in tropical rainforests. I became fascinated with the prospect of characterizing the light environment of young palms and canopy trees as they grow in the light-limited environment of the forest understory. Thomas Givnish, then a Harvard professor, first suggested that I use hemispherical canopy photography to characterize the light environment above individual plants. Delving into the literature, I found that the theoretical basis of the technique had been well worked out by Margaret Anderson at Cambridge University. The fundamental strength of the technique was that it used the geometry of canopy openings to estimate light penetration, rather than more difficult and expensive direct measures of light integrated over time and space. Various researchers had successfully used canopy photography in field studies of understory light environment, though the technique was limited by the tedious and subjective analysis of photographs using grid overlays. Various attempts had been initiated to allowed automated digital analysis of canopy photographs; however, no suitable system had yet been developed. I decided to take on the challenge of developing an image analysis system for rapid and accurate analysis of canopy photographs.

I began developing the hemispherical canopy photography technique as a side project while I completed my dissertation research on the mechanical architecture of arborescent palms. At Harvard University, Peter Ashton, William Bossert, Thomas Givnish, and P. B. Tomlinson encouraged me in my early work on canopy photography. I received a grant from the Atkins Garden Fund at Harvard to purchase a Nikkor hemispherical lens and set about refining the field methods to characterize the light environment of individual palms and of the forest in general at La Selva Biological Field Station in Costa Rica. I designed a self-leveling mount that allowed me to take photographs at different levels in the forest understory. I took large numbers of canopy photographs, both above marked plants and at vertical and horizontal intervals in sample grids. Simultaneously, I began working on the image analysis system: first learning about video cameras, microcomputers, and image processing techniques, and gradually acquiring the components necessary for an analysis system, most purchased using personal funds.

While I was at Harvard, John George, in the Life Sciences Division at Los Alamos National Laboratory, hired me as a graduate research assistant to develop microcomputer image analysis techniques during the summers. Though this did not allow me to work directly on canopy photograph analysis, it did allow me to learn programming and image processing techniques. I taught myself the "C" programming language, which has been invaluable. I received a Smithsonian Tropical Research Institute Short-Term Fellowship in 1985 to work with Alan P. Smith and to take canopy photographs in the forest of Barro Colorado Island in Panama. In 1985, I also received a contract from NASA/NSTL to take a series of canopy photographs in sample grids in various forest conditions at La Selva Biological Field Station.

In 1986 I took a position as a Director Funded Postdoctoral Fellow in the Environmental Science Group at Los Alamos National Laboratory. There I developed various microcomputer image analysis capabilities, including the public domain program IMAGE(c), which I wrote in collaboration with Douglas M. Ranken. Thomas Hakonson and Fairley Barnes, in the Environmental Science Group, were especially supportive of my efforts to complete *CANOPY*. Support for the project came from the Environmental Science Group, the Department of Energy National Environmental Research Park program, and National Science Foundation Grant #BSR85-16371. Under the NSF grant I served as a consultant to set up a canopy photography analysis system at La Selva Biological Field Station in Costa Rica, work conducted in collaboration with David Clark, Deborah Clark, and Steven Oberbauer. While at Los Alamos, I completed *CANOPY*. Subsequently, while a postdoctoral fellow with Harold Mooney at Stanford University, and with additional support from Susan Ustin at the University of California at Davis, I added refinements to *CANOPY*, adapted the program to various sets of hardware, and wrote this manual.

Other researchers have been developing hemispherical canopy photography analysis systems in parallel to my own, a situation that has allowed for fertile exchange of ideas. In particular, among the various researchers, Alan Smith and Robin Chazdon offered considerable encouragement and assistance throughout my own effort.

This manual represents the culmination of seven years of research--as a side project that has taught me a great deal and that has resulted in development of a useful field tool. I trust that this manual will make *CANOPY* accessible to other researchers and encourage further development and refinement of techniques to measure plant canopy geometry. A companion publication, A Manual for Microcomputer Image Analysis (Rich et al. 1989), provides additional background on microcomputer image analysis using video input.

Paul M. Rich, 26 June 1989,
Department of Biological Sciences,
Stanford University

A MANUAL FOR ANALYSIS OF HEMISPHERICAL CANOPY PHOTOGRAPHY

by

Paul M. Rich

ABSTRACT

Hemispherical canopy photography involves taking photographs through a hemispherical (fisheye) lens pointed upward from beneath a plant canopy. The resulting photographs can be analyzed to determine the geometry of canopy openings and to calculate potential light penetration. This manual serves as a comprehensive guide to the program *CANOPY*©, a public domain microcomputer program for image analysis of hemispherical canopy photography. Included are discussions of theory, research applications, field methodology, hardware setup and operation, and software setup and operation. *CANOPY* enables video digitization of negatives, real-time display of positive images, interactive determination of a threshold to distinguish foliage from canopy openings, editing of photographs with poor exposure, rapid calculation of various measures of canopy geometry and indices of potential light penetration, and convenient output of results. A series of utility programs allow user specification of theoretical or empirical distributions of direct sunlight and diffuse skylight for a given site.

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CHAPTER I. INTRODUCTION

OVERVIEW

The Nature of Hemispherical Canopy Photography

Hemispherical canopy photography is a technique for studying plant canopies using photographs taken through a hemispherical (fisheye) lens from beneath a canopy looking upward. Such hemispherical photographs provide an extreme wide angle view, often with up to a 180º field of view. The photographs can be analyzed to determine the geometry of canopy openings, and, in turn, to estimate light levels beneath the canopy. Thus, canopy photographs can be used to assess local light environment beneath plant canopies and to infer properties of plant canopies. Hemispherical canopy photography is a technique that directly measures canopy geometry and that indirectly estimates light levels.

Purpose and Organization of the Manual

This manual is intended as a comprehensive guide to the technique of hemispherical canopy photography, in particular using the program *CANOPY* for microcomputer image analysis of canopy photographs, and using the programs *SUN* and *SKY* for calculating distributions of direct sunlight and diffuse skylight, respectively. The manual is divided into two parts: Part One consists of four chapters that provide an introduction and general treatise of hemispherical canopy photography; and Part Two consists of six chapters that provide operation and reference guides to the programs *CANOPY*, *SUN*, and *SKY*. This chapter provides a general introduction and overview of hemispherical canopy photography, including a description of the nature of the technique, background concerning use of the technique by various researchers, and a discussion of research applications for the technique. Chapter II describes the general theory of hemispherical canopy photography, hardware design for video image analysis, and software design of the program *CANOPY*. Chapter III gives details of field methods for obtaining hemispherical canopy photographs. Chapter IV explores future prospects for the technique, including technique refinement and enhancement, other approaches to studying canopy geometry, and an overall conclusion. Chapter V describes hardware and software setup. Chapter VI provides a guide to the operation of *CANOPY*, including a detailed description of analysis methods. Chapter VII provides a reference guide to CANOPY, with a comprehensive alphabetical listing of all commands. Chapter VIII provides a guide to the operation of the utility program *SUN*; Chapter IX provides a comprehensive reference guide to *SUN*; Chapter X provides a guide to the operation of *SKY*;

and Chapter XI provides a comprehensive reference guide to *SKY*. Appendices A through D include a listing of menu screens, hardware specification, detailed file formats, a listing of program files, and a description of the negative holder design. Background on the fundamentals of microcomputer image analysis using video input is provided in the companion publication "A Manual for Microcomputer Image Analysis" (Rich et al. 1989).

The Program CANOPY

CANOPY is a public domain program for microcomputer image analysis of hemispherical canopy photography. The program is entirely written in the "C" programming language. CANOPY runs on a video image analysis system based on IBM PC compatible microcomputers (Fig. 1). The basic steps of analysis using CANOPY involve 1) digitization and display of canopy photographs, 2) distinguishing foliage from canopy openings, 3) initiation of calculations, and 4) output of results (Fig. 2). A user-friendly menu structure allows for convenient and efficient program control. Hardware control of image digitization and display is fully integrated with analytical capabilities. CANOPY calculates various measures of canopy geometry and indices of light penetration, including indirect and direct site factors (ISF and DSF). Analysis results can be read directly from the computer display monitor and output to data files. The utility programs SUN and SKY are used to create site-specific files that allow customization of analyses for a particular study site.

CANOPY offers many advantages over other systems that have been developed for analysis of hemispherical canopy photographs. A two-display-monitor system is used, with separate computer and image display monitors. Images can be input directly through a video camera, as either negatives or positive transparencies. Digitization of video input with a framegrabber allows real-time display of digitized images, with video images digitized at the rate of 30 frames per second. *CANOPY* uses RS-170 or CCIR video for input, the most common black and white video standards in the United States and Europe, respectively. The use of hardware lookup tables (LUTs) allows display of negatives as positives in real-time. Graphics-overlay positioning grids are used for precise positioning of photographs. An interactive classification routine allows the user to adjust a threshold intensity value that distinguishes foliage from canopy openings, producing a classified image. The user can toggle instantaneously between a continuous tone display of the canopy photograph and a threshold display of the classified image.

Fig. 1.

A microcomputer image analysis system. The basic components are A) a microcomputer (IBM compatible) equipped with a digitizer/display adapter, B) a computer display monitor, C) an image display monitor, D) a video camera fitted with a macro lens, and E) a backlit film holder.

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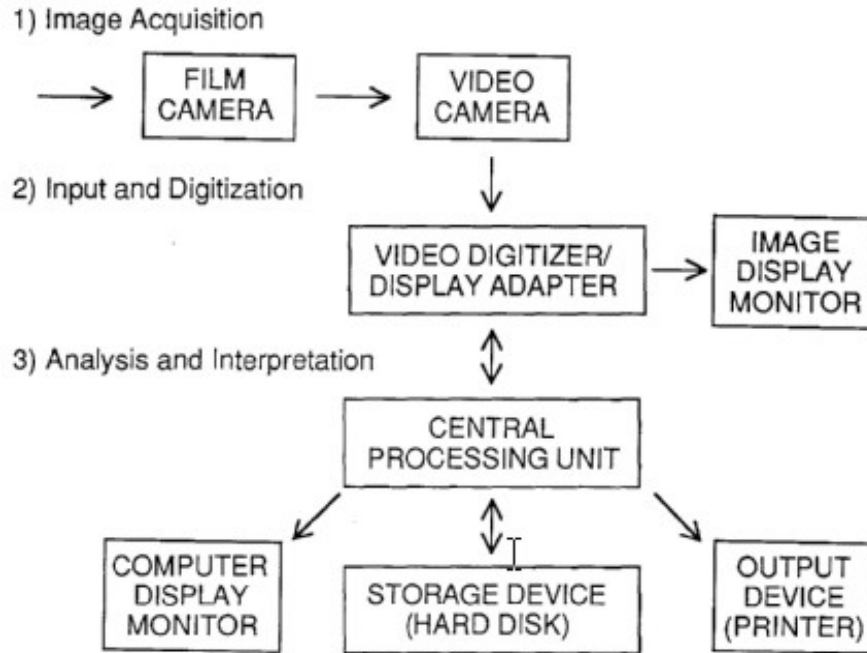
Fig 2.

Conceptual representation of the technique of hemispherical canopy photography. The basic steps are 1) photograph acquisition in the field, 2) video image input and digitization, and 3) image analysis and interpretation. Black and white hemispherical photographs are acquired in the field, taken beneath plant canopies looking upward. Images are input directly from backlit negatives or transparencies with a video camera. The analog video signal goes to a digitizer/display adapter that is controlled by a microcomputer and has capabilities for digitization, storage of digital images in an image buffer, and conversion of digital data back to analog for display on an image monitor. The central processing unit controls the digitizer/display adapter, transfers information to and from the digitizer/display adapter, allows interactive user input, displays information on a computer monitor, stores results, and outputs results to printers. Image analysis includes steps to 1) classify images (to distinguish foliage from canopy openings), 2) determine how diffuse skylight and direct sunlight are expected to penetrate through the canopy openings, and 3) display and output the results.

Calculations are very rapid because *CANOPY* uses an efficient image combination algorithm that merges the classified image with images that describe the distribution of direct sunlight and diffuse skylight. Results can be automatically output to data files for archiving and further analysis. Actual computation and results output generally require less than one minute (less than 10 seconds on fast 80386-based microcomputers). Typically, each photograph can be analyzed in two to five minutes, including all steps of film positioning, digitization, selection of a threshold, calculation, and output of results. *CANOPY* is fully configurable, such that a user can specify detailed site-specific characteristics to be used in calculations. Access to intermediate calculations of the distribution of canopy openings as a function of zenith and azimuth angles allows users to design their own detailed analyses of canopy geometry.

Hardware Requirements

    CANOPY runs on IBM compatible computers equipped with 640K RAM, a hard disk, a mathematics coprocessor, and a video digitizer/display adapter. Various digitizer/display adapters are supported, including the Imaging Technology *PCVISION* and *PCVISIONplus* adapters and the Data Translation *DT2853* adapter. In addition, the image analysis system must include a video display monitor, video camera fitted with a macro lens, backlighting source, film holder, and copy stand. Table I lists the image analysis system hardware requirements, along with some of the specific products that work with *CANOPY*. Appendix B gives further details concerning hardware. As an add-on to an existing microcomputer, a full image analysis for use with *CANOPY* will cost less than $7000. Rich (1989) explains the functioning of the microcomputer image analysis system.

Table I. CANOPY image analysis system hardwaren (costs are approximate).

MICROCOMPUTER
    IBM compatible with 640K RAM, hard disk, and mathematics coprocessor; printer and mouse optional ($2000-$6000).
VIDEO DIGITIZER/DISPLAY ADAPTER
    video framegrabber with hardware lookup tables (Imaging Technology *PCVISIONplus* with external synchronization cable, $2100).
VIDEO DISPLAY MONITOR
    standard RGB video with underscan and external synchronization (Sony *PVM-1271Q*, $1000).
VIDEO CAMERA AND MACRO LENS
    solid-state video camera with F to C mount adapter and quality macro lens (Cohu *4815-2100*, $1800; Nikkor *55-mm micro* $300)
FILM HOLDER
    quality film positioner with X,Y and rotation adjustment (Marron Carrell *positioner compound* with 35mm negative carrier, $780; custom stand, $200)
LAMP
    even backlighting source (Aristo *V-56* with *7452* standard color lamp,$200)
COPY STAND AND TABLE ($200-$500)
CABLES AND CONNECTORS ($50)

BACKGROUND

Hill (1924) first designed a hemispherical (fisheye) lens for view of the whole sky to study cloud formation. Evans and Coombe (1959) superimposed sun path diagrams on hemispherical photographs to study the light environment under forest canopies. Anderson (1964) provided the theoretical basis for using hemispherical photographs to estimate direct sunlight and diffuse skylight components of light penetration through plant canopies. Analysis of hemispherical photographs has been used in a diverse range of studies to characterize plant canopy structure and light penetration, as has been reviewed by several recent researchers (Chazdon and Field 1987, Rich 1988, Becker et al. 1989). General treatments on the technique have been supplied by Anderson (1964, 1970, 1971) and Pearcy (1989). Until recently, interpretation of hemispherical photographs has required tedious manual analysis using sampling grids. Jupp et al. (1980) developed a computer program, *PISCES*, for analysis of hemispherical photographs, which still required manual photograph analysis and data entry. Automated image digitization has been attempted by various researchers (Bonhomme and Chartier 1972, Olsson et al. 1982, Chan et al. 1986). Chazdon and Field (1987) developed a microcomputer analysis system, *SOLARCALC*, based on the Apple Macintosh personal computer, with digital scanning of photographic prints. More recently, integrated microcomputer image analysis systems based on IBM compatible personal computers have been developed that use video for direct input of negatives, the systems *CANOPY* (Rich 1988) and *SYLVA* (Becker et al. 1989). *CANOPY* and *SYLVA* have various advantages over *SOLARCALC*, including more rapid and convenient video digitization and better integrated analysis and hardware control capabilities. *CANOPY* has many advantages over *SYLVA*, including use of a higher quality digitization and display adapter, direct display of negatives as positives, an explicit interactive means for choosing thresholds, and greater flexibility for incorporating site-specific information.

RESEARCH APPLICATIONS

Hemispherical photography can be used in a variety of ways to study canopy geometry and light penetration. With hemispherical photography, any plant canopy can be studied, ranging from crop systems to natural forests, as long as it is feasible to take photographs from beneath the canopy. Hemispherical photographs can be taken above individual plants growing in the understory, to study relations between understory light, ecophysiology, and demography. Light maps can be constructed, by acquiring hemispherical photographs at series of horizontal and vertical positions, to examine spatial and temporal variability of light under plant canopies. By studying gap frequency and zenith angle relations in hemispherical photographs, it is possible to estimate various structural

properties of plant canopies, such as leaf area index, leaf angle, and the size and spacing of plants. For study of community dynamics, canopy photography can be used as a means to document and quantify canopy gap formation and closure, and to measure seasonal changes in foliage densities. Canopy photography can also be used as a ground-truth technique for studies of plant canopies using remote sensing from aircraft and satellites.

CHAPTER II. THEORY AND PROGRAM DESIGN

GENERAL PRINCIPLES

The Nature of Hemispherical Photographs

In essence, hemispherical photographs produce a projection of a hemisphere of directions on a plane (fig. 3). The exact nature of the projection varies according to the lens that is used. Hemispherical canopy photographs are taken pointed directly upward, and with the top of the camera oriented to north. In a perfect equiangular projection of a 180o field of view, the resulting circular image shows a complete view of all sky directions, with the zenith in the center of the image and the horizons at the edges. North is toward the top of the image, south toward the bottom, east toward the left, and west toward the right. East and west are reversed from usual convention in maps because the view is upward rather than downward. In such an equiangular projection, the zenith angle (the angle between the zenith and a given sky location) is directly proportional to the distance along a radial line. More generally, any hemispherical lens produces an image in which the zenith is in the center of the image, the maximum view angle is at the edges of the image, and intermediate locations represent intermediate zenith angles. Within the field of view of any particular lens, it is possible to precisely locate any intervening sky direction. If a photograph is taken beneath a canopy pointed directly upward and oriented relative to north, it is possible to determine the locations of any canopy openings by their positions, provided that the projection produced by the lens is understood.
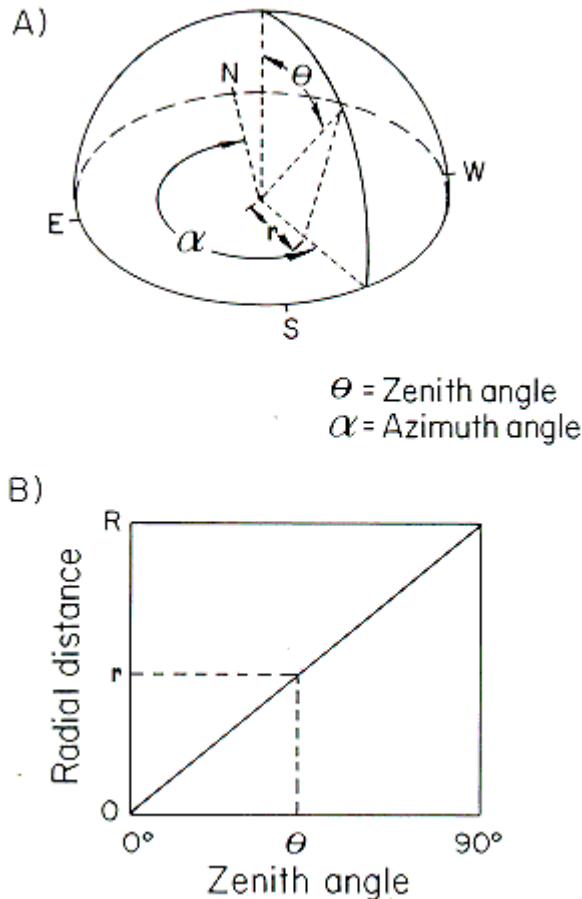
Fig 3.

An equiangular hemispherical (fisheye) projection. A) For an equiangular hemispherical projection, a hemisphere of directions are projected on a plane. In the resulting circular image, the zenith is in the center and the horizons are toward the edges. B) Zenith angle is proportional to distance along a radius, and R is the total radius of the resulting projection.

Measurement of the Geometry of Canopy Openings

A hemispherical canopy photograph is essentially a map of the locations of canopy openings relative to the location from which the photograph is taken (Fig. 4). The major tasks for analysis of hemispherical canopy photographs are first to distinguish foliage from canopy openings and second to determine the directional location of canopy openings. Manual techniques for analysis of hemispherical photographs involve overlaying sampling grids upon a photograph and then tallying the proportion of canopy openings within each grid region. Digital analysis is basically the same process, in which first each image location is classified as foliage or canopy opening; next the sky location for the image location is evaluated; and then the classification and sky location are used for further calculations. Thus, the initial basis for analysis of hemispherical canopy photographs is determining what is called a canopy opening and the geometry of where openings are located. The next stage in analysis is to determine the implications or consequences of having canopy openings at particular locations.

Estimation of Light Penetration Through Canopy Openings

One consequence of having a canopy opening at a particular sky location is that light can pass unimpeded through the opening. Two types of light can potentially pass through a canopy opening: diffuse skylight (indirect radiation that is scattered off the atmosphere) and direct sunlight (direct radiation penetrating when a canopy opening coincides with the position of the sun). If we assume that most solar radiation penetrating through a plant canopy comes through canopy openings, then levels of solar radiation can be estimated as the sum of direct sunlight and diffuse skylight coming through openings. Thus, a reasonable estimate of radiation from direct sunlight can be obtained by looking at the intersection between canopy openings and the amount of direct sunlight that can be expected from that sky direction. Similarly, a reasonable estimate of radiation from diffuse skylight can be obtained by looking at the intersection between canopy openings and the amount of diffuse skylight that can be expected from that sky direction.
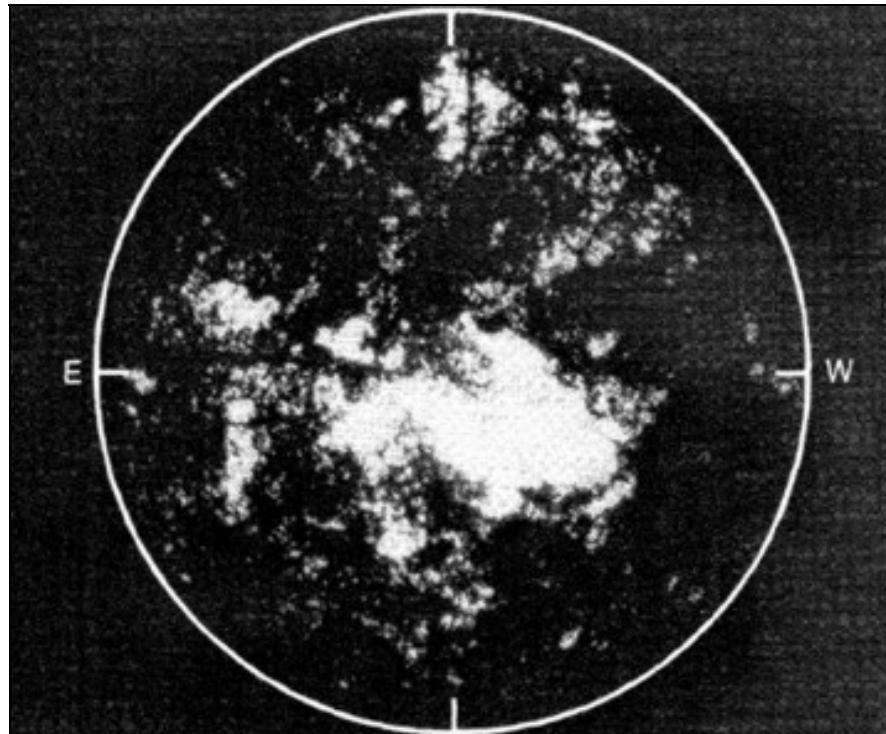
Fig 4.

A hemispherical photograph showing a treefall gap in the rain forest of La Selva Biological Field Station, Costa Rica.

In this simple model, as viewed from beneath a canopy, foliage absolutely blocks incoming radiation and canopy openings allow radiation to pass unimpeded. Radiation transmitted or scattered through foliage is ignored. Analysis of light penetration through canopy openings considers first the amount of direct sunlight and second the amount of diffuse skylight that can be expected from that sky direction. Direct sunlight for a particular location depends upon the relative position of the sun as it changes through the day and through the year. Diffuse skylight for a particular location depends upon the amount of incident radiation that scatters from each sky direction. Thus, For any given period of time, the total global radiation reaching a location under a plant canopy is the sum of direct sunlight and the diffuse skylight penetrating through canopy openings.

Indirect and Direct Global Site Factors

Indirect site factor (ISF) is defined as the proportion of diffuse skylight and direct site factor (DSF) is the proportion of direct sunlight under a plant canopy relative to that in the open. Total global radiation is the sum of the diffuse skylight (indirect radiation) and direct sunlight (direct radiation) for a location in the open at the earth's surface. Let us define global site factor (GSF) as the total proportion of global radiation under a plant canopy relative to that in the open (total site factor of Anderson, 1964). GSF is a weighted sum of ISF and DSF:

$$[GSF] = p_i[ISF] + p_d[DSF] \quad , \tag{1}$$

where p_i is the proportion of diffuse skylight and p_d is the proportion of direct sunlight that comprise the total radiation under the canopy. ISF, DSF, and GSF can be translated to absolute levels of radiation flux for a particular period of time by multiplying by the appropriate radiation values measured in the open for the site.

ISF and DSF can readily be estimated from canopy photographs, given assumptions about the contribution of diffuse skylight and direct sunlight from each sky direction. GSF can be estimated if we have an estimate of the relative proportions of diffuse skylight and direct sunlight in the open, either determined empirically or theoretically. Becker (1987) presents a means for estimating the relative contribution of direct and indirect radiation by measuring the atmospheric clearness at a particular site. In general, there is a direct relationship between atmospheric clearness (global radiation/extraterrestrial radiation) and the proportion of direct sunlight, and a complementary inverse relationship between atmospheric clearness and the proportion of diffuse skylight (Becker 1987). For example, based on empirical models for a series of different study sites, an atmospheric clearness of 0.3 implies that roughly 0.2-0.4 of radiation flux can be expected from direct sunlight and 0.6-0.8 from diffuse skylight; whereas an atmospheric clearness of 0.65 implies that roughly 0.7-0.9 of radiation flux can be expected from direct sunlight and about 0.1-0.3 from diffuse skylight.

Estimation of Radiation Flux

Radiation flux can be variously expressed, in terms of energy flux or in terms of photon flux density (PFD). For study of plant ecophysiology, especially when studying processes of light interception for photosynthesis, it is useful to measure photosynthetically active radiation (PAR), those wavelengths that are active in photosynthesis (400-700 nm). PAR flux is referred to as photosynthetic photon flux density (PPFD). ISF, DSF, and GSF can be considered to be proportional estimates of energy flux, PPFD, or PFD for total radiation. Insofar as energy flux, PPFD, and PFD for total radiation differ, distributions of diffuse skylight and direct sunlight used to calculate ISF and DSF should be formulated accordingly for a particular site. Long-term monitoring of direct sunlight and diffuse skylight for a given site can be accomplished using pyranometers (for total radiation) or quantum sensors (for PAR) attached to data loggers. Two sensors are required, one to monitor global radiation flux and a second to monitor diffuse skylight. The diffuse skylight sensor must be fitted with a shadowband to block radiation along the sun path. Direct sunlight is calculated as the difference between observed global radiation flux and diffuse skylight flux.

BASIC METHODS OF HEMISPHERICAL CANOPY PHOTOGRAPHY

Basic Methods

The three basic stages of hemispherical canopy photography are image acquisition, digitization, and analysis (Fig. 2). Image acquisition involves taking hemispherical photographs in the field beneath plant canopies. Image digitization involves input of the image in an analog format and conversion into digital format, in the case of CANOPY using video input of negatives to a video framegrabber. Image analysis involves classification of images to distinguish foliage from canopy openings, combining classified information with information about distributions

of direct sunlight and diffuse skylight, calculation of measures of canopy geometry and indices of light penetration, and output of results. Table II lists the basic steps of the technique.

Compounding of Errors

Hemispherical canopy photography is a close-range remote sensing technique. As with any remote sensing technique, errors can occur at any stage of image acquisition, digitization, or analysis. Table II lists the steps at which errors can occur. Because many steps are involved, accumulated error can become great unless strict quality control is exercised. A severe error at any stage can invalidate the final results, even if other steps are without error. Strict protocols should be developed and followed to prevent problems from compounded errors.

SOFTWARE DESIGN

General Design

At the core of the program *CANOPY* is a threshold algorithm and an image combination algorithm. The threshold algorithm allows the user to classify a hemispherical photograph into foliage and canopy openings. The image combination algorithm rapidly calculates the location and potential light penetration through canopy opening by merging information from a classified image with distributions of direct sunlight and diffuse skylight. Site-specific distributions of direct sunlight and diffuse skylight are precalculated and stored in files. Corrections for

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Table II. Levels at which errors can be introduced in hemispherical canopy photography (Rich 1988).

IMAGE ACQUISITION
- Camera positioning
    horizontal/vertical position
    film plane horizontality
    azimuth rotation
- Exposure
- Sky lighting evenness
- Foliage lighting evenness (reflections)
- Optical distortion

IMAGE DIGITIZATION
- Registration/alignment
    size
    x,y translation
    rotation
- Focus
- Aperture adjustment
- Optical distortion
- Video noise
- Digitizer noise
- Resolution limitations

IMAGE ANALYSIS
- Distinguishing foliage from canopy openings
- Assumed direct sunlight distribution
- Assumed diffuse skylight distribution
- Assumed surface of interception
- Image editing/enhancement

a given lens projection are included in the calculations. The distribution files, along with weighting files and correction files, allow great flexibility in specifying site-specific characteristics. Depending upon a particular user's needs, specification of site-specific characteristics can incorporate either refined theoretical models or empirical data obtained from long-term monitoring of solar radiation. Specification of site-specific characteristics can refine the ability to calculate expected light penetration over any given period of time, for instance, integrated over a particular month of the year, or integrated over an entire year.

Control Structure

*CANOP*Y is designed to be operated efficiently by novice users. Commands are generally entered as single keystroke mnemonics and are fully listed in menus. The flow of the program (from digitization, to image classification, to calculation) follows a natural and convenient progression. Results can automatically be output to data files. Image editing capabilities are provided to allow modification of images that are poorly exposed. System configuration can be modified from within the program, and configuration changes remain in effect when the program is run in the future.

Hardware Control

The program is fully integrated to control hardware and take advantage of advanced hardware capabilities. Video digitization and hardware LUT display allow real-time digitization and display of negatives as positives. Typically, images are digitized at 512 (h) by 480 (v) resolution with 8 bits of intensity data per pixel (640 by 480 pixel resolution for the 12.5 MHz Imaging Technology adapters). Seven-bit intensity values are retained, which allows for representation of 128 levels of gray (2^7), with the additional bit per pixel used for graphics overlay. Positioning grids, displayed in graphics overlay, include a circular grid that allows adjustment of image size and X,Y translation, a label grid that allows alignment relative to internal labels imprinted by a camera databack, and a compass alignment grid that allows rotation relative to magnetic and true north. Hardware lookup capabilities are used to allow instantaneous toggling between continuous tone and threshold display, and to display changes in the threshold value used for the threshold display.

Threshold Algorithm for Distinguishing Foliage and Canopy Openings

A threshold algorithm is used to distinguish foliage from canopy openings. Use of a threshold algorithm is one of the simplest and most effective means for classifying an image. Classification is achieved by determining a threshold intensity value that distinguishes foliage from canopy openings. In the case of a positive image, any intensity value above the threshold is classified as canopy opening and any value below the threshold is classified as foliage. Similarly, for a negative image, any intensity value below the threshold is classified as canopy opening and any value above the threshold is classified as foliage.

To determine thresholds, *CANOPY* uses an interactive technique, in which the user can view and change the threshold value for the classified image while in a threshold display mode (Fig. 5). The user can instantaneously toggle back and forth between the threshold display and a continuous tone display, while increasing or decreasing the threshold value until edges of the classified image best match foliage/canopy opening edges of the continuous tone image. Subjectivity in the choice of thresholds is minimized by adopting strict protocols for deciding thresholds, by practice, and by use of high contrast images taken under even lighting conditions. Successful classification depends upon having high contrast photographs in which foliage is consistently darker than canopy openings. Problems arise if parts of the sky are darker than foliage (for example, dark clouds) or if parts of the foliage are brighter than the sky (for example, reflections on leaves). In addition, larger canopy openings tend to be brighter than smaller openings, leading to an overrepresentation of the size of larger openings and an underrepresentation of smaller openings. Within reason, images can be edited to compensate for dark sky regions or bright foliage regions.

Image Combination Algorithm for Rapid Calculation

An efficient image combination algorithm is used to calculate openness, ISF, and DSF. The image combination algorithm merges the classified image with distribution files for direct sunlight and diffuse skylight (Fig. 6). The image combination algorithm is very rapid because it involves merging images in which important calculations have been made ahead of time. Calculations that categorize each pixel location are made when producing distribution files for diffuse skylight and direct sunlight. Diffuse skylight distribution files specify 160 sky regions that correspond to 20 ranges of zenith angle and 8 ranges of azimuth angle. Direct sunlight distribution files specify 168 sky regions that correspond to half-hour intervals through the day and month intervals through the year. On a pixel-

A)
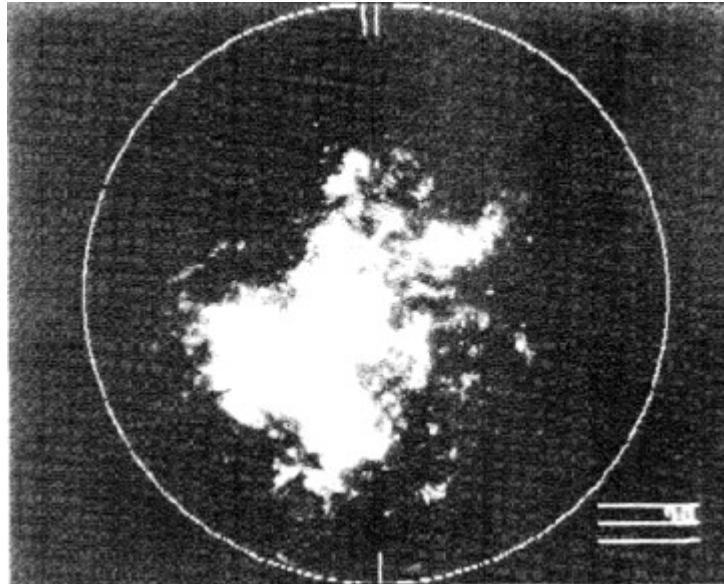
B)
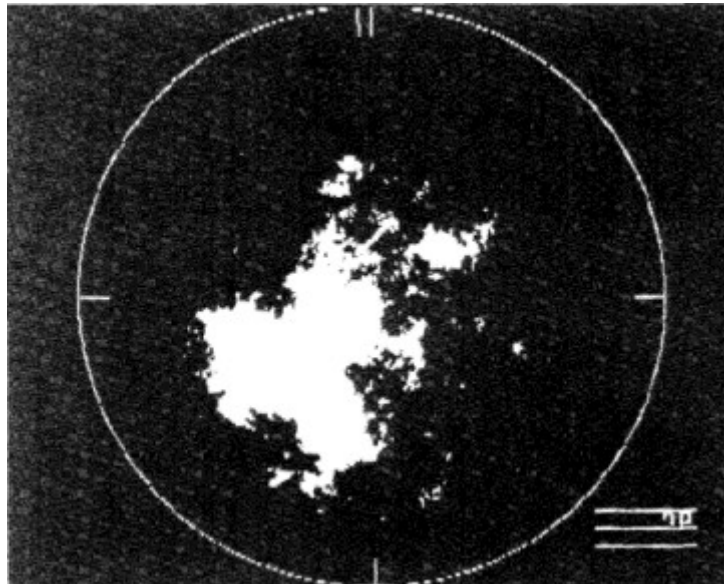
Fig 5.

Image classification using a threshold algorithm. Images are classified by setting a threshold that distinguishes foliage from canopy openings. An interactive technique allow the user to compare an unclassified continuous tone image (A) with a classified threshold image (B).
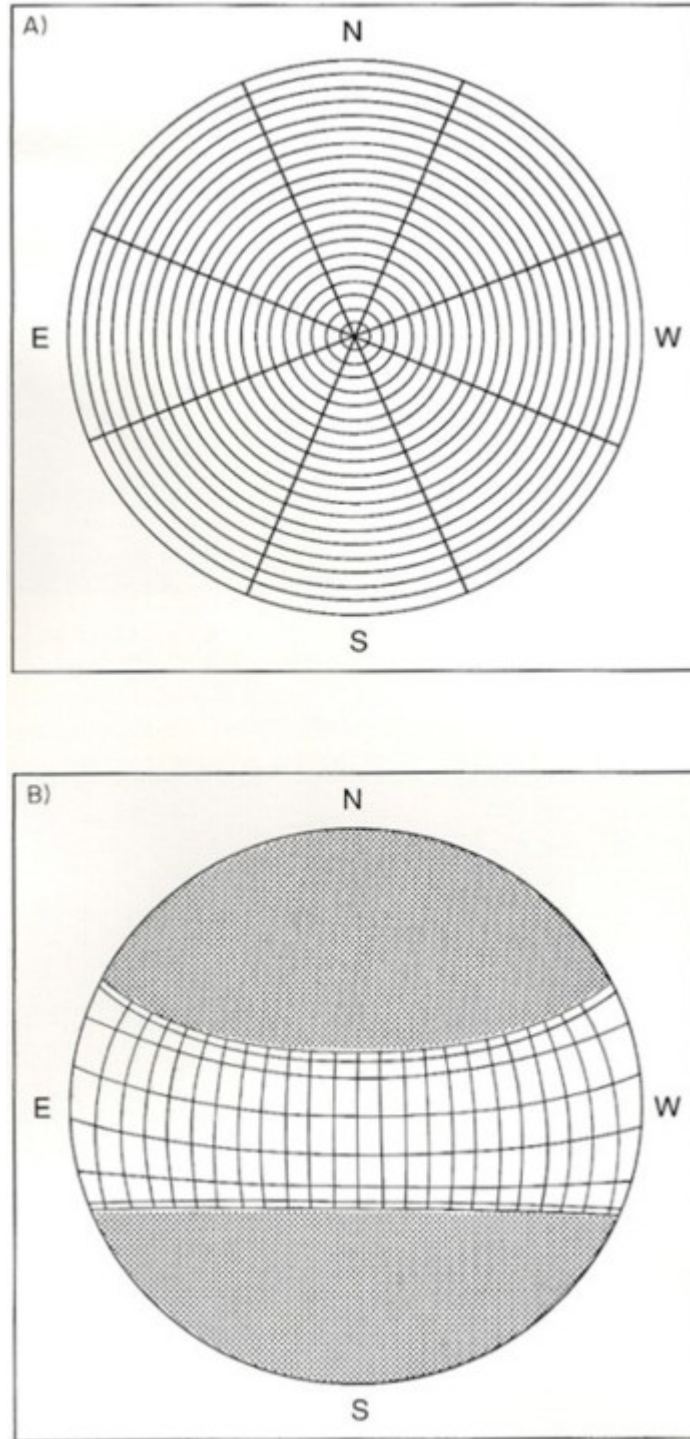
Fig 6.

Diffuse skylight and direct sunlight distributions. A) An example of a diffuse skylight distribution specifies 160 sky regions for 20 equal ranges of zenith angles and 8 azimuth directions. In this case, particular skylight distributions can be specified by using appropriate weighting factors for each sky region. B) An example of a direct sunlight distribution specifies sky ranges along the solar track that correspond to 24 intervals of time through the day and to month-long periods through the year. Seven regions specify the month periods, because the sun sweeps across each region twice throughout the year. In this case, the direct sunlight distribution is for 10.43° north latitude (for use at La Selva Biological Station, Costa Rica).

by-pixel basis the hemispherical image is scanned; pixels to be counted as canopy openings are tallied according to the sky region to which the pixel corresponds; and the total number of pixels in each sky region are counted. The unweighted openness of each sky region is calculated as the number of pixels counted as canopy openings divided by the total number of pixels in all sky regions. ISF is calculated as the number of pixels counted as canopy openings within a region of a diffuse skylight distribution divided by the number of pixels in the region, and summed over all regions. DSF is calculated as the number of pixels counted as canopy openings within a region of a direct sunlight distribution divided by the number of pixels in the region, and summed over all regions. Each sky region is multiplied by appropriate normalized weighting factors and cosine correction factors, as specified in weighting and correction files. The weightings are applied in calculation of all results, whereas final results are presented both with and without corrections (such as cosine corrections).

CALCULATIONS AND ANALYTICAL RESULTS

Unweighted Openness

Unweighted openness is calculated for each of 160 sky regions across the entire sky. Unweighted openness results are summarized in a table that lists values for each of 20 zenith angle ranges and 8 azimuth angle ranges. Unweighted openness for a given sky region is expressed as the proportion of openness relative to all sky regions. Totals for a range of elevation angles are listed down the right side, totals for a range of zenith angles are listed along the bottom row, and the overall total is in the lower-right corner. These values include weightings specified by the sky weighting file, but do not include cosine corrections. Unweighted openness values in this table can be used for calculations of structural properties of canopies, for example, allowing mathematical inversion of estimated azimuthally average gap fractions to calculate leaf area index and mean foliage angle distribution (Norman and Campbell 1989). It should be noted that because the unweighted openness values are expressed as proportions relative to all regions, for calculation of gap fractions unweighted openness for each region must be divided by the maximum possible unweighted openness of the region. This maximum unweighted openness of each region can be calculated by setting a threshold that classifies the image as 100% open, performing calculations, and then reading maximum unweighted openness from the table of unweighted openness.

Indirect Site Factor (ISF)

ISF is calculated for each of 160 sky regions across the whole sky. ISF results are summarized in a table that lists values for each of 20 zenith angle ranges and 8 azimuth angle ranges. Totals for a range of elevation angles are listed down the right side, totals for a range of zenith angles are listed along the bottom row, and the overall total is in the lower-right corner. ISF values include weighting specified by the sun weighting file, but the detailed table does not include cosine corrections. ISF for a given sky region is expressed as the openness within the region times the relative contribution of the region to ISF. Thus, in a case where all regions are weighted equally, the ISF of a region is simply the openness within the region divided by the number of regions. Note that this is different from the unweighted openness, which expresses openness as a proportion of the sum of all regions. A summary table includes the overall ISF and an overall corrected ISF that includes a cosine correction.

Unweighted Openness Along the Sun Path

Unweighted openness along the sun path is calculated for each of 168 sky regions along the sun path. Unweighted openness along the sun path results are summarized in two tables that list values for each of 24 half-hour intervals through the day and for each month through the year. Unweighted openness for a given sky region is expressed as the proportion of openness relative to all sky regions along the sun path. Totals for a given month are listed down the right side of the second table, totals for a given half-hour interval are listed along the bottom row of both tables, and the overall total is in the lower-right corner of the second table. These values include weightings specified by the sun weighting file, but do not include cosine corrections. It should be noted that because the unweighted openness values are expressed relative to all regions, openness within the region must be calculated by dividing by the maximum possible unweighted openness of the region. This maximum unweighted openness of each region can be calculated by setting a threshold that classifies the image as 100% open, performing calculations, and then reading maximum unweighted openness from the table of unweighted openness along the sun path.

Direct Site Factor (DSF)

DSF is calculated for each of 168 sky regions along the sun path. DSF results are summarized in two tables that list values for each of 24 half-hour intervals through the day and for each month through the year. Totals for a given month are listed down the right side of the second table, totals for a given half-hour interval are listed along the bottom row of both tables, and the overall total is in the lower-right corner of the second table. These values include weightings specified by the sun weighting file, but the detailed tables do not include cosine corrections. DSF for a given sky region is expressed as the openness within the region times the relative contribution of the region to DSF. Thus, in a case where all regions are weighted equally, the DSF of a region is simply the openness within the region divided by the number of regions. Note that this is different from the unweighted openness along the sun path, which expresses openness as a proportion of the sum of all direct sunlight regions. A summary table includes the overall DSF and an overall corrected DSF that includes a cosine correction. In addition, the summary table includes the corrected and uncorrected DSF listed by month, in which the DSF is normalized only relative to the sun path regions corresponding to that month.

Canopy Openings as a Function of Time of Day

Optionally, one can calculate the intersection of the sun with canopy openings for a particular day of the year. Results are output as a list of times through the day at which the sun path intersects with canopy openings. Time intervals are limited by image resolution (pixel size). From these results one can calculate the expected duration of sunflecks throughout the day for a given geometry of canopy openings.

SITE-SPECIFIC CONFIGURATION

Diffuse Skylight Distribution Files

Diffuse skylight distribution files specify 161 regions: one region that defines the portion of an image that is outside the hemispherical photograph and 160 regions that divide up the sky (Fig. 7). The 160 sky regions include 20 ranges of zenith angle and 8 ranges of azimuth angle. Sky regions are each assigned a unique one-byte integer label, in which 0 represents the region outside the hemispherical photograph, 1-8 represent the outermost annulus, 9-16 represent the next outermost, and so on to 153-160, which represent the innermost annulus. Within an annulus octants are labeled in counter-clockwise order starting at the octant centered at north. Thus regions that are multiples of 1-8 respectively, follow the following order: 1x is north (N), 2x is northeast (NE), 3x east (E), 4x southeast (SE), 5x south (S), 6x southwest (SW), 7x west (W), and 8x northwest (NW), where x is an integer in the range 1-20. Note that east and west are reversed from the usual convention because sky projections are viewed from beneath looking upward. For example, the region labeled 2 is in the outermost annulus in the NE azimuth direction; the region labeled 155 in the innermost annulus in the E azimuth direction. Certain sky regions corresponding to the outer annuli may not be represented, depending upon the maximum field of view of the hemispherical lens being used.

The utility program SKY can be used to generate diffuse skylight distribution files for a particular site and hemispherical lens. For calculations, SKY requires specification of 20 ranges of zenith angle that correspond to regions of equal illuminance from diffuse skylight, and specification of a seventh-order polynomial that corrects for radially symmetric lens distortion.

Direct Sunlight Distribution Files

Direct sunlight distribution files specify 169 sky regions: one region that defines the portion of an image that is outside the sun path and 168 regions along the sun path (Fig. 8). The regions along the sun path include 24 half-hour intervals through the day and seven one-month intervals through the year. Note that five of the one-month intervals use have sky regions that represent two different months (for example, May and July) because the sun path shifts first from south to north and then from north to south through the seasons; whereas December and June are represented by unique sky regions. Sky regions are each assigned a unique one-byte integer label, in which zero represents the region outside the sun path, 1-24 represent December, 25-48 represent January and November, 49-72 represent February and October, 73-96 represent March and September, 97-120 represent April and August, 121-144 represent May and July, and 145-168 represent June. Within each sequence (1-24, 25-48, ...), each region corresponds to a half-hour interval. For example, the region labeled 2 corresponds to the 6:30-7:00 half-hour interval in the month of December; and the region labeled 45 corresponds to the 16:00-16:30 half-hour interval in the month of January or November. In the program CANOPY, times are labeled by the half-hour at the end of the interval

Fig 7.

Schematic of how diffuse skylight distributions are labeled. Each of 160 sky regions for the entire sky is assigned a unique integer label. Sky regions are labeled in a counterclockwise inward spiral, starting with the outer annulus in a north azimuth direction (greatest zenith angle). Note that the regions of the innermost annulus are assigned values 153 through 160.

Fig 8.

Schematic of how direct sunlight distributions are labeled. Each of the 168 sky regions along the sun track is assigned a unique integer label. Sky regions are labeled sequentially through time of day (east to west), starting at the most southern month-interval (December) and proceeding northward through each month-interval.

(for example 16:00-16:30 is labeled 16:30). The first time interval for a day (6:30) corresponds to all times before 6:30; and the last time interval for a day (18:00) corresponds to all times after 17:30. Certain sky regions may not be represented, depending upon the latitude and maximum field of view of the hemispherical lens being used.

The utility program SUN can be used to generate direct sunlight distribution files for a particular site and hemispherical lens. For calculations, SUN requires specification of latitude, 8 solar declinations that define the boundaries between months, a seventh-order polynomial that corrects for radially symmetric lens distortion, and the maximum view angle of the hemispherical lens.

Weighting Files
Each of the sky regions of the direct sunlight and diffuse skylight distributions can be weighted by specifying appropriate coefficients in the sun and sky weighting files, respectively. Sun weighting coefficients can account for differences in expected direct radiation levels due to zenith angle and to changes in atmospheric conditions that relate to time of day and time of year, both due to weather and to path-length through the atmosphere. Similarly, sky weighting coefficients can account for asymmetrical distributions of diffuse skylight.

Sun and sky weighting files can be created and modified using a text editor (see Appendix C for Weighting File Formats). For a given direct sunlight distribution, SUN provides capabilities to output weighting coefficients that correct for path-length of the atmosphere as a function of zenith angle at sea level. *SUN* also allows output of the zenith angles at the centroid of each region of a sunlight distribution (see Appendix C for Zenith Angle File Format). Zenith angle files can be used to calculate weighting coefficients when using any user-defined weighting function that is zenith angle dependent.

Correction Files
Each of the sky regions of the direct sunlight and diffuse skylight distributions can be cosine corrected by specifying correction coefficients in the sun and sky cosine correction files, respectively. A standard cosine correction describes expected light interception by a flat, horizontal surface. Cosine corrections for surfaces that are not horizontal can also be specified in correction files. For example, an non-horizontal cosine correction can be used to calculate expected light interception by a leaf in any particular orientation. In addition, other types of corrections can be specified in correction files. For example, a correction that follows the leaf angle distribution in the crown of a particular plant can be used to estimate light interception by the crown surface. Such corrections can be used to test models of optimal surfaces of interception given a particular distribution of canopy openings. Sun and sky cosine correction files (for a flat, horizontal surface) can be created using the utility programs *SUN* and *SKY*, respectively. Correction files can also be created and modified using a text editor (see Appendix C for Correction File Formats).

Calculation of Diffuse Skylight Distributions and Weighting Coefficients
Two distributions of diffuse skylight have come into common usage: a uniform overcast sky distribution (UOC) and a standard overcast sky distribution (SOC). In a UOC, diffuse radiation flux is the same from all sky directions. In an SOC, diffuse radiation flux varies with zenith angle according to the following relation from Moon and Spencer (1942):

$$L_\theta = (L_Z/3) \cdot (1 + 2\cos\theta) \quad , \tag{2}$$

where θ is the zenith angle, L_θ is the luminance (radiation flux) from a given sky direction, and L_Z is the luminance at the zenith. In general, diffuse skylight flux from a set of sky directions can be calculated as follows:

$$I = \frac{\displaystyle\int_{\theta_1}^{\theta_2}\int_{\alpha_1}^{\alpha_2} L(\theta, \alpha) \sin\theta \, d\theta \, d\alpha}{\displaystyle\int_{0}^{\pi/2}\int_{0}^{2\pi} L(\theta, \alpha) \sin\theta \, d\theta \, d\alpha} \quad , \tag{3}$$

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where I is the total diffuse skylight radiation flux over the region defined by the zenith angle (θ) and the azimuth angle (α), $L(\theta, \alpha)$ is a function that describes the radiation flux (L) as a function of θ and α, θ_1 and θ_2 are two specific zenith angles and α_1 and α_2 are two specific zenith angles. The term $\sin\theta$ appears in the equation because the radius of each circular slice of a hemisphere at zenith angle θ varies with the $\sin\theta$. For a UOC, substituting a constant value for $L(\theta, \alpha)$ in equation (3) gives the following solution:

$$I = \cos\theta_1 - \cos\theta_2 \quad , \tag{4}$$

For an SOC, substituting L_Z of equation (2) for $L(\theta, \alpha)$ in equation (3) gives the following solution:

$$I = [1/4 \, (1 + 2\cos\theta_2 + \cos2\theta_2)] - [\, 1/4 \, (1 + 2\cos\theta_1 + \cos2\theta_1)] \quad , \tag{5}$$

Table III gives zenith angles and corresponding weighting factors for a UOC and an SOC, calculated using equations (4) and (5). Solutions are shown for elevation angles that correspond to equally weighted regions and weightings that correspond to fixed elevation angle ranges. The two solutions for each sky distribution give essentially equivalent solutions when ISF is calculated. However, a solution using weightings that correspond to fixed elevation angle ranges may be more useful for making calculations of structural properties of canopies. The solutions do not include a cosine correction, as does the solution used by Anderson (1964). Though a cosine correction could be included in the skylight distribution files or weighting files, more flexibility is provided by including a cosine correction separately. A cosine correction is included separately after other calculations by multiplying each region by the cosine at the mean zenith angle of the sky region. Such cosine corrections can be generated by *SKY* and are specified in a correction file. It should be noted that UOC and SOC are essentially arbitrary skylight distributions

Table III. Zenith angles (θ) and sky weighting coefficients (W) for a uniform overcast sky (UOC) and a standard overcast sky (SOC). Equivalent calculation of indirect site factor (ISF) can be obtained using either appropriate zenith angles that define regions that are weighted equally or a fixed set of zenith angle regions that define regions that are appropriately weighted. Twenty concentric annuli are specified from the inside to the outside, with a zenith angle of zero assumed as the starting point.

Annulus	UOC Equal θ	UOC Weighting W	UOC Fixed θ	UOC Angle W	SOC Equal θ	SOC Weighting W	SOC Fixed θ	SOC Angle W
1	18.1948°	1.0	4.5°	0.00308	14.9197°	1.0	4.5°	0.00462
2	25.8519°	1.0	9.0°	0.00923	21.2857°	1.0	9.0°	0.01377
3	31.7883°	1.0	13.5°	0.01532	26.3080°	1.0	13.5°	0.02267
4	36.8698°	1.0	18.0°	0.02131	30.6669°	1.0	18.0°	0.03115
5	41.4096°	1.0	22.5°	0.02718	34.6263°	1.0	22.5°	0.03907
6	45.5729°	1.0	27.0°	0.03287	38.3234°	1.0	27.0°	0.04627
7	49.4583°	1.0	31.5°	0.03837	41.8418°	1.0	31.5 °	0.05263
8	53.13.1°	1.0	36.0°	0.04362	45.2383°	1.0	36.0°	0.05805
9	56.6330°	1.0	40.5°	0.04861	48.5554°	1.0	40.5°	0.06245
10	60.0000°	1.0	45.0°	0.05330	51.8273°	1.0	45.0°	0.06576
11	63.2563°	1.0	49.5°	0.05766	55.0836°	1.0	49.5°	0.06794
12	66.4218°	1.0	54.0°	0.06166	58.3523°	1.0	54.0°	0.06898
13	69.5127°	1.0	58.5°	0.06529	61.6617°	1.0	58.5°	0.06889
14	72.5424°	1.0	63.0°	0.06851	65.0422°	1.0	63.0°	0.06770
15	75.5225°	1.0	67.5°	0.07131	68.5292°	1.0	67.5°	0.06548
16	78.4630°	1.0	72.0°	0.07367	72.1681°	1.0	72.0°	0.06231
17	81.3731°	1.0	76.5°	0.07557	76.0178°	1.0	76.5°	0.05828
18	84.2608°	1.0	81.0°	0.07701	80.1643°	1.0	81.0°	0.05352
19	87.1340°	1.0	85.5°	0.07798	84.7439°	1.0	85.5°	0.04815
20	90.0000°	1.0	90.0°	0.07846	90.0000°	1.0	90.0°	0.04231

that are useful primarily for comparison with other researchers' results. Meaningful empirical and theoretical distributions are complex to determine, but much needed for refinement of the technique. *CANOPY* can accommodate any such refinement.

Users can also design their own programs for creating specialized diffuse skylight distribution files (see Appendix C for Diffuse Skylight Distribution File Format). For example a non-symmetrical sky distribution could be specified. However, in general it is best to account for non-symmetrical distributions by using appropriate weighting values in the sky weighting file. Also, for non-symmetrical specification of regions, the calculations would be correct, but the labels for zenith and azimuth angle ranges in results tables would not be correct.

Calculation of Direct Sunlight Distributions and Weighting Coefficients

Sun azimuth and zenith angles are calculated according to the following standard relations (Gates 1980, Anonymous 1984):

$$\beta = \arcsin(\sin\!\varnothing\sin\delta + \cos\!\varnothing\cos\delta\cos h) \tag{6}$$

$$\alpha = 2\arctan((\cos\delta\sin h)/(\cos\!\varnothing\sin\delta - \sin\!\varnothing\cos\delta\cos h - \cos\beta)), \tag{7}$$

where β is the elevation angle, $\varnothing$ is the latitude, δ is the solar declination for a given date, h is the hour angle, and α is the azimuth angle. Elevation angle is the complement of the zenith angle θ (i.e., $\beta = 90^o - \theta$). Solar declinations for any given date are listed in <u>The</u> <u>Astronomical</u> <u>Almanac</u> (Anonymous 1990, see also List 1971, Table 169). Hour angle is calculated as $h = 180^o - (T^. 15^o)$, where T is the solar time in hours. Solar time must be corrected for longitude (see Boes 1981). Table IV lists the default solar declinations and the corresponding dates used to determine the solar declinations to define month intervals in the program *SUN*.

The relative proportion of direct sunlight from a given sky direction is influenced by the atmosphere, both due to weather conditions and due to differences in path-length through the atmosphere as a function of zenith angle. The optical air mass is the path-length of atmosphere that the sun's rays must traverse to reach the surface of the earth. Generally, optical air mass is defined as a proportion of the path-length when the sun is at the zenith. For zenith angles less than 80°, path-length varies with the secant of the zenith angle (Gates 1980):

$$m(\theta) = \sec\theta = 1/\cos\theta \quad, \tag{8}$$

where θ is the zenith angle and $m(\theta)$ is the optical air mass as a function of zenith angle. For zenith angles greater than 80°, refraction is important. The <u>Smithsonian</u> <u>Meteorological</u> <u>Tables</u> (List 1971) provides a table of calculated values of optical air mass as a function of zenith angle (Table 137), including corrections for refraction at zenith angles greater than 80°. Without weather effects, direct radiation flux varies with zenith angle according to the following relation (Gates 1980):

$$S\theta = S_0\,\tau^{m(\theta)} \quad, \tag{9}$$

Table IV. Default solar declinations and corresponding dates used to define month intervals through the year in direct sunlight distribution files.

SOLAR DECLINATION	JULIAN DAY	DATE
-23.45^o	355	December 21 (winter solstice)
-22.58^o	6, 341	January 6, December 7
-16.21^o	36, 312	February 5, November 8
-5.73^o	66, 281	March 7, October 8
$+5.73^o$	95, 252	April 5, September 9
$+16.21^o$	126, 220	May 6, August 8
$+22.58^o$	157, 188	June 6, July 7
$+23.45^o$	172	June 21 (summer solstice)

where S_θ is the radiation flux from direct sunlight when the sun is at a given zenith angle θ, S_0 is the radiation flux outside the atmosphere, τ is the atmospheric transmittance, and m is the optical air mass. Atmospheric transmittance is the proportion of radiation that would be transmitted from outside the atmosphere to the earth's surface along the vertical (zenith) path, and has been observed to vary from 0.4 to 0.8, with a typical value of 0.6 (Gates 1980). *SUN* uses equations (8) and (9) and Table 137 of the Smithsonian Meteorological Tables (List 1971) to calculate weighting coefficients of direct radiation flux for each region along the sun path.

As for diffuse skylight distribution files, users can also design their own programs for creating specialized sunlight distribution files (see Appendix C for Direct Sunlight Distribution File Format). It is even possible to divide the sky into regions that correspond to shorter or longer time intervals through the day or year. In such a case, the calculations would be correct, but the labels for columns (time of day interval) and rows (month interval) in tables of results would not be correct.

Lens Corrections

A lens correction function for a given lens can be calculated empirically or, in some cases, determined from specifications provided by the lens manufacturer (Herbert 1986, 1987). For calculations using the programs *SUN* and *SKY* a seventh-order polynomial can be used to correct for lens deviation from an equiangular projection. A seventh-order polynomial can then be fitted to the lens correction function, forcing the polynomial to pass through zero and the maximum angle of the lens. Lens correction coefficients correspond to a polynomial that describes the expected angle position in an equal angle projection as a function of the actual observed angle. Table V lists an example of lens correction coefficients used for a lens with no distortion and for the Nikkor 8mm hemispherical lens.

Table V. Lens correction coefficients for a seventh-order polynomial that describes radially symmetrical distortion for a perfect lens (no correction) and for the Nikkor 8-mm hemispherical lens.

COEFFICIENT	PERFECT LENS	NIKKOR LENS
0	0	1.256138E-03
1	1	1.090603E+00
2	0	3.432221E-04
3	0	-4.067174E-05
4	0	9.732894E-07
5	0	-1.745721E-08
6	0	1.666496E-10
7	0	-6.403817E-13

CHAPTER III. FIELD METHODS

GOAL OF PHOTOGRAPH ACQUISITION

When acquiring hemispherical canopy photographs in the field, the basic goal is to obtain high quality photographs. Photograph quality is critical. Poor quality photographs are difficult to analyze and can produce ambiguous results. Good quality photographs result when sufficient care is taken to position, level, and orient the camera correctly, when the exposure is correct, when the sky lighting is very even, and when there are no bright reflections. High contrast images with even sky lighting are best obtained on days with evenly overcast skies, or, if this is not possible, early in the morning or late in the afternoon.

HARDWARE AND SUPPLIES

Camera System

A high quality hemispherical lens should be used if available, though for many purposes satisfactory results can be obtained using an inexpensive hemispherical lens that fits in front of the standard lens of a 35mm camera. High quality hemispherical lenses and rugged cameras are manufactured by many companies, including Canon, Minolta, and Nikon. In the field, I use a camera system consisting of a Nikkor 8mm hemispherical lens and a Nikon FM2 camera body. The camera body is equipped with a databack that automatically imprints a unique number in the corner of each photograph. The Nikkor lens produces high quality photographs and is fitted with an internal filter ring. The camera has an internal meter that is used to determine exposure.

Film

For quality hemispherical canopy photographs, it is desirable to use a high speed black and white film. I use Kodak Tri-X black and white film (ASA 400). I have also successfully used Ilford HP5 black and white film (ASA 400). Film is developed in Microdol-X developer to produce high contrast negatives.

Additional Supplies

A good shoulder satchel is useful for carrying supplies necessary for hemispherical canopy photography, including film, data notebooks, pens or pencils, a compass, lens cleaning supplies, spare batteries, and plastic bags. A good compass is necessary for orienting the camera assembly relative to north. For cleaning the lens and camera, it is wise to carry cleaning brushes, lens cleaning fluid, and lens tissue. Spare batteries should be carried for the camera light meter and databack. In case of rain, sufficient plastic bags should be carried to enclose all equipment. A folding umbrella can also be useful to protect the equipment.

Self-Leveling Camera Mount

A self-leveling camera mount that causes the lens to point directly upward can facilitate positioning of the camera, particularly in situations where hemispherical canopy photographs are taken at great heights above the ground or in awkward positions. In my field assembly, the camera and hemispherical lens is fitted in a custom self-leveling mount (Fig. 9). The milled aluminum mount clamps securely around the hemispherical lens. The mount is suspended in a set of gimbals, wherein there are two axes of free rotation, each axis at right angles to the other and parallel to the ground. The weight of the camera and lens suspended below the mount causes the mount to level itself. A set of weights are secured to the bottom of the mount to make the film plane exactly horizontal. The mount assembly is supported on a tripod or monopod.

Camera Positioning Equipment

Placement of the camera assembly on a tripod allows precise positioning, but only up to the maximum height of the tripod. Support of the camera assembly on a monopod allows one to work up to greater heights and allows simpler transport between sites. When using a monopod, it is best to also use a self-leveling camera mount. A monopod can be held at maximum extension of the arms, to obtain photographs up to 2.5 or 3.0 m above the ground (Fig. 10A). In addition, a monopod setup can be used from ladders to take photographs at greater heights. I have taken canopy photographs successfully to heights of 7.5 m using tall folding aluminum step ladders (see Fig. 10B), and to heights up to 12 m using Swedish climbing ladders and a climbing harness (Fig. 10C).
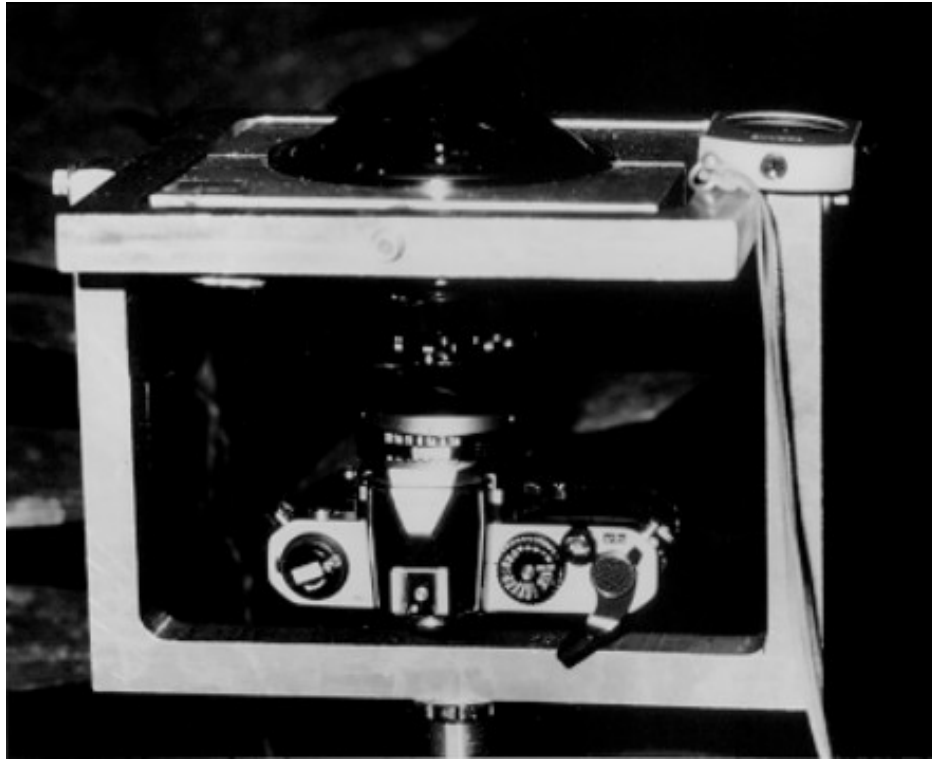
Fig 9.

Camera setup used for hemispherical canopy photography. The camera and hemispherical lens are suspended on a self-leveling mount. The camera must be properly positioned beneath a plant canopy, leveled (which occurs automatically with this design), and oriented relative to north

Optional Equipment for Camera Orientation and Location of Photograph Edges

Various researchers have found it useful to use lights in the field of view to facilitate camera orientation or to assist in identifying the edges of photographs. A bright lamp mounted on a pole can be held in the direction of magnetic north to serve as a reference when positioning the film in rotation during digitization. A set of lights attached to the camera mount at the edge of the field of view can assist with locating the edge of the field of view during digitization.

IMAGE ACQUISITION

General Protocol

A standardized field protocol should be adopted for acquisition of hemispherical canopy photographs, thus ensuring uniform quality of photographs for analysis. Table VI provides a general field protocol for acquiring canopy photographs.

Fig. 10A.

Photographs can be taken at different heights under forest canopies using a monopod to suspend the camera setup at arm's length while standing on the ground. Figures 10B and 10C show two additional camera positioning methods.

Fig. 10B.

Use of a tall folding step ladder to suspend the camera setup allows camera positioning at greater heights than shown in Fig. 10A.

Fig. 10C.

Use of Swedish climbing ladders attached to a tree and a climbing harness allows photographs to be taken at much greater heights than shown in Figs. 10A and B.

Preparations Before Going into the Field

Before going into the field, all equipment and supplies should be assembled and tested. A checklist of equipment and supplies should be reviewed. Sufficient film should be placed in a sealed plastic bag. For efficiency, film canisters can be labeled ahead of time. Similarly, data notebooks can be partially filled out ahead of time. The camera light meter and databack should both have good sets of batteries.

Camera Positioning and Orientation

The camera must be properly positioned, leveled, and oriented before the exposure is determined and the photograph is taken. Proper positioning includes correct location horizontally and vertically, whereas orientation refers to rotation of the camera relative to north. First the camera should be positioned above the correct horizontal location. Then the camera should be raised or lowered to the proper height. In cases where the camera is very close to the ground, it may be necessary to crouch or even lie down to get out of the lens field of view. Then the camera should be leveled, if a self-leveling mount is not used. After the camera is positioned and leveled correctly, the orientation should be adjusted so that magnetic north is located directly toward the top of the image. This can be accomplished in various ways. For example, one can affix a compass to the monopod or camera mount and rotate the assembly until the compass lines up correctly. Alternatively, one can first locate a reference object toward magnetic north and then sight along an edge of the camera mount to achieve proper orientation.

Photograph Exposure

The internal camera light meter can be used to obtain consistent exposures. First the ASA should be properly set on the camera. In my experience, I have found that the best exposure tends to be one stop below the metered exposure. Often it is a good idea to bracket exposures, taking a photograph one stop below and one stop above the metered exposure. Photographs should be taken using a red filter. Red filters tend to increase contrast between foliage and canopy openings. Metering must be done with the filter in place. When metering the exposure, it is necessary to temporarily move the camera from its correct position and make adjustments of the shutter speed and aperture. After making adjustments, the camera should be returned to its correct position, and orientation relative to north should be verified. In general, it is a good idea to shoot at a shutter speed of 125 (1/125 second) and adjust the exposure with the aperture ring. For this reason "shutter speed preferred" or non-automatic cameras are preferred.

Taking Photographs

After the camera assembly is properly positioned and the exposure settings are correct, photographs can be taken. In general, photographs should be taken using the camera self-timer. After the self-timer is set, the camera assembly should be stabilized until the shutter releases. Before the shutter releases, fine adjustments to the camera position can be made; but such adjustments should be completed well before the shutter releases, to ensure that the camera is stable while the photograph is taken.

Table VI. General field protocol for photograph acquisition.

1) Assemble camera and lens in mount; set ASA; load film; place assembly on tripod or monopod; remove lens cap.

2) Position and level camera assembly at proper height above ground.

3) Orient top of camera assembly to magnetic north.

4) Set exposure time and aperture.

5) Take photograph using the camera self-timer.

6) Repeat steps 2-5.

Use of Camera Databacks

A camera databack can be used to imprint labels in the corner of each photograph. In general, it is best to use a mode that prints a unique number on each photograph. Most databacks have an autoincrementing number label option. Rather than resetting the number label to zero at the start of each roll of film, it is better to continue to use greater numbers. Thus each photograph has a unique number, and labeling confusion can be avoided. In addition, because labels are always imprinted in the same relative position of each photograph, the position of the labels can be used as an internal reference for positioning the photographs during digitization.

Field Records

Field records should be kept to keep track of pertinent hemispherical canopy photograph data. At minimum, field records should include the film roll number, unique photograph number (as imprinted by the databack), and location. The location may be a location in a sample grid or transect line or the plant above which a photograph is taken. In addition, the date, time of day, exposure settings, height above the ground, weather/sky conditions, and additional notes can be recorded. Weather/sky conditions can include such categories as sunny, partly cloudy, overcast, sprinkling, and raining. Some researchers prefer to write with indelible pens; however, I prefer mechanical pencils that will not fail in the rain. Waterproof notebooks are especially useful for humid or rainy study locations. Preprinted data sheets can minimize the amount of writing that must be done in the field.

Weather and Lighting Considerations

The ideal condition for taking hemispherical canopy photographs is an evenly overcast sky. In the absence of an overcast sky, photographs are best taken early or late in the day, when view of the sun is likely to be blocked by the canopy. Canopy photographs taken with direct sunlight in the field of view tend to be unevenly exposed, with a bright region around the sun and with reflections on leaves. Uneven sky lighting makes it difficult to precisely distinguish foliage from canopy openings using a threshold technique. Bright reflections on leaves can be mistaken for openings. Whenever possible photographs should only be taken when the sky is overcast, because sky lighting conditions play such a significant role in determining photograph quality.

Permanent Photograph Sites

Establishment of permanent photograph sites enables one to take repeated photographs of the same canopy through time. Such time records enable documentation of seasonal changes in canopy openness and light penetration, and also enable monitoring of directional changes in canopies, for instance formation or closure of treefall gaps. For such work, it is important to position and orient the camera in exactly the same way each time a photograph is taken. One means for exact positioning involves setting up permanent posts with a pin-registered platform that directly supports the camera mount.

Special Methodology for the Humid Tropics

The humid tropics can be a difficult environment for hemispherical canopy photography, primarily because the high humidity is very rough on field equipment. High humidity can cause camera electronics and mechanical components to malfunction, and cause fungus to grow between lens elements. For this reason, the camera and lens should be stored in a "dry box" or air-conditioned environment when not in use. If a camera and lens are stored in an air-conditioned environment, they should be heated above outside temperature before use in the field. Otherwise, water will condense on the cold surfaces. When working in the hot, humid tropics of Costa Rica, I used a "dry box", which consisted of a cabinet that was heated by a series of incandescent light bulbs and placed within an air-conditioned laboratory. This "dry box" was kept at a temperature above the outside temperature while in equilibrium with the lower-humidity air of the laboratory, thus providing a good environment for camera and lens storage.

FILM PROCESSING AND ARCHIVING

Film Processing

Film should be processed promptly after taking hemispherical canopy photographs. Prompt processing allows one to assess the quality of the photographs and to go back and retake any photographs that are not of suitable quality. In some cases it may be desirable to develop the film in the field, especially when working in isolated field sites where it may not be possible to retake photographs in the future. Processing for black and white film can be done inexpensively with the following equipment and supplies: developing tank, film loading bag, Microdol-X

developer, stop bath, fixer, photo flow, and negative hangers. Use of fresh chemicals is important, so one should pay attention to expiration dates. Developer can be reused, and generally it is good to have separate bottles labeled "new" for fresh developer and "used" for once-used developer. Then developer can be rotated from the "new" to the "used" bottle when it is used the first time, and discarded after a second use from the "used" bottle. Similarly, care should be taken to assess the freshness of stop bath; and fixer should also be rotated. While the negative strip are drying, weights should be hung from the bottom of the strips to prevent curling. For further information, general black and white development techniques are described in any photography manual and specific instructions are supplied with the developing chemicals. Table VII provides a listing of a protocol for processing of Kodak Tri-X film.

Table VII. Film processing protocol.

1) Load film into developing tank (in dark room or film loading bag).

2) Fill tank with Microdol-X developer; develop for 8 minutes in small tank or 9 minutes for large tank; agitate (4 turns per agitation)--2X per minute for small tank or 1X per minute for large tank.

3) Pour off developer ("new" to "used" bottle or "used" to discard).

4) Rinse in running water for 1 minute and then drain.

5) Fill tank with stop bath; leave for 1 minute; agitate 2X.

6) Pour stop bath back into bottle (discard if purplish).

7) Rinse in running water for 1 minute.

8) Fill tank with fixer; agitate 15 seconds per minute for 10 minutes.

9) Pour off fixer into appropriate bottle.

10) Open tank, rinse in water for 20 minutes.

11) Rinse in photo-flo and hang negatives to dry.

Photograph Archiving
  Once negatives are dry, they should be properly stored and labeled. I prefer to use archive-quality negative storage sheets that hold six strips of six photographs each. These negative storage sheets can be stored in standard three-ring binders. Negatives can be easily surveyed without removal from the storage sheets, and even viewed as positives by holding whole sheets under the video camera while digitizing with the negative continuous tone display. Negatives that are to be analyzed can be temporarily removed. As with any photographic materials, negatives should be stored in a cool, dark location.

CHAPTER IV. FUTURE PROSPECTS

TECHNIQUE REFINEMENT

More work is needed to refine and improve hemispherical canopy photography as a technique. For a given site, long-term monitoring of solar radiation is needed to determine site-specific distributions of diffuse skylight and direct sunlight used by *CANOPY*. This requires on-going monitoring of both diffuse skylight and direct sunlight in the opening. Hemispherical photography and direct measurement techniques need to be further calibrated and compared. The importance of penumbral effects, reflections on leaves, and transmission through foliage needs to be assessed for particular sites. The importance of each source of error in the hemispherical photography technique must be evaluated, including problems arising during photograph acquisition, digitization, and analysis. The two greatest difficulties appear to be first, obtaining photographs with even sky lighting and no leaf reflections, and second, consistently choosing the same threshold to distinguish foliage from canopy openings. Tests are needed to establish the level of consistency that can be obtained in different analyses of the same photograph. Similarly, consistency tests are needed for series of hemispherical photographs taken at the same microsite under different sky conditions.

Now that various systems are available for analysis of hemispherical photographs, consistency across the systems needs to be evaluated. Results from analysis of the same sets of photographs need to be compared across systems. The goal is to obtain a level of standardization, whereby results of different studies are comparable. In cases where measurements are sufficiently refined, it should be possible to compare results in either proportional indices (such as ISF and DSF) and in absolute measures of energy or photon flux. Such refinement requires that comparable records of solar radiation flux exist for different sites, to allow calibration and cross-checking of light penetration estimates from hemispherical photographs.

FUTURE ENHANCEMENTS

The general availability of miniature solid-state video cameras and portable microcomputers present the possibility to design a dedicated field-portable system for hemispherical canopy photograph analysis. Such a field-portable system could directly input hemispherical images with a high resolution solid-state video camera. The video camera could be integrated with a flash digitizer to allow direct digitization. The digital images can either be stored for later analysis or analyzed immediately in near real-time using a portable microprocessor. The results could be viewed on a computer console and saved in digital formats. The basic analysis approach of the program *CANOPY* could be readily incorporated in such a field-portable system.

The utility of hemispherical photography would be greatly expanded if better means could be devised to acquire images under short canopies and at greater heights in tall canopies. The most promising approaches would use either a miniature video camera equipped with a miniature hemispherical lens or fiber optics. Under tall canopies, a portable telescoping tower could support such a camera at different heights. A gyroscopically-stabilized self-leveling platform could facilitate proper leveling of the image plane. A compass orientation system could automatically correct for image rotation relative to true north.

LASER TECHNIQUES

Though hemispherical canopy photography is fundamentally a technique that measures the geometry of canopy openings, difficulties arise because of light variability. Ambient light is used to distinguish canopy openings from foliage, making hemispherical photography a "passive" sensing system. "Active" sensing systems, which provide their own energy to examine features of interest, offer many advantages for study of the geometry of plant canopies. Among such active techniques, one promising approach is development of a scanning laser technique. This technique involves firing a laser in a known direction from beneath the canopy and sensing reflections back from foliage. If no reflections are observed, a canopy opening is present. Such a system could even resolve the distance to the nearest obstruction, if an appropriate ranging laser is used. By mounting the laser on a scanning mount, it would be possible to simulate the sun path for any particular day of the year and calculate exactly when direct sunlight would penetrate. It would also be possible to subsample the distribution of openings through which diffuse skylight would penetrate.

CONCLUSION

Recent advances in video and microcomputer technology have provided us with new hardware tools for the study of plant ecology. *CANOPY* is a software tool that takes full advantage of these new capabilities for low-cost microcomputer image analysis of hemispherical canopy photography. Though the technique of hemispherical canopy photography has been available since the 1950s, its widespread use has been limited by the difficulty of analysis. Using *CANOPY*, it is now possible to analyze large numbers of hemispherical photographs rapidly and accurately. *CANOPY* allows for great flexibility in specifying site-specific characteristics. Full advantage of this flexibility requires detailed characterization of solar radiation for particular sites. However, reasonable analyses can be performed for canopy photographs from sites where only limited site-specific information is available. Hemispherical canopy photography offers distinct advantages over other techniques for measuring light. In particular, large sample sizes can be gathered rapidly. With an understanding of limitations of the technique, hemispherical photography can be applied to a broad range of problems that require characterization of canopy structure and expected light penetration through canopies.

CHAPTER V. SETUP

HARDWARE SETUP
The basic steps of hardware setup include 1) setup and configuration of the microcomputer, 2) configuration and installation of the digitizer/display adapter, 3) setup and connection of the image display monitor, 4) setup and connection of the video camera and lens, and 5) setup of the film holder and backlighting source.

Setup and Configuration of Microcomputer
The microcomputer should be set up so that the *DOS* operating system is installed on the hard disk. The *AUTOEXEC.BAT* file should contain an appropriate *PATH* command to make utilities such as custom batch files available. Approximately one megabyte of hard disk space must be available for installation of the program *CANOPY*. The programs *SUN* and *SKY* require approximately one additional megabyte of hard disk space. A mathematics coprocessor should be installed and a mouse or other compatible locator device should be connected to the proper serial or bus port.

Configuration and Installation of Digitizer/Display Adapter
The digitizer/display adapter jumpers should be set to the appropriate configuration and the adapter should be installed in an available expansion slot. The user should follow configuration and installation procedures supplied by the manufacturer of the digitizer/display adapter. In general, the default I/O and image buffer addresses should be used unless there is a conflict with other hardware installed in the microcomputer. (See Appendix B for additional hardware information.)

Setup and Connection of Image Display Monitor
The image display monitor should be positioned so that the user can readily look back and forth between it and the computer display monitor. The image display monitor should be set on an RGB mode with underscan and external synchronization on. The red, green, and blue outputs from the digitizer/display adapter should be connected to the corresponding red, green, and blue RGB inputs of the image display monitor. The optional external synchronization output from the digitizer/display adapter should be connected to the external synchronization input of the image display monitor. Alternatively, a short cable can be run from the image display monitor green output to the external synchronization input. All connections should be properly terminated. Typically, this means that the 75 Ohm termination switch should be in the on position unless an output connector or cable is attached. Thus, the green channel should not be terminated if the green output channel is looped through to the external synchronization input.

Setup and Connection of Video Camera and Lens
The lens should be properly attached to the video camera. Typically, a high quality macro lens is attached to the video camera, using an F to C mount adapter, which screws into the C mount of the video camera and clamps on the "bayonet" F mount of the lens. The video camera should be mounted on a copystand pointed downward. The video camera video output should be connected to the input of the digitizer/display adapter. The power supply cable should be attached to the power supply input of the video camera, and the power supply should be plugged in. Care should be taken to turn off or disconnect the video camera power supply when it is not in use. Before connecting the video output to the digitizer/display adapter, it is a good idea to test that the video camera is functioning correctly by connecting the video output to a black and white (RS-170) channel of a video display monitor.

Setup of Film Holder and Backlighting Source
The film holder (film holder with custom stand) should be positioned directly beneath the video camera on the copy stand. The backlighting source should be positioned beneath the film holder such that it is centered under the film holder stage opening. The power cable of the backlighting source should be attached to the appropriate power supply and the power supply should be plugged in. The plane of the film holder should be made parallel to the image plane of the video camera using the adjustable feet of the film holder stand. One way to achieve this is to ascertain that 1) the copy stand is level, by using a level attached to the copy stand, 2) the camera is held vertical, by using a level attached to the camera, and 3) the film holder is level, by using a level attached to the film holder. It may be necessary to adjust the copystand to be certain that the copy platform is square with the camera support bar.

The relative positioning of the video camera image plane and the film plane should be checked periodically. Oftentimes it is desirable to draw or tape marks on the video camera mount and platform of the copy stand to assure that positioning will be correct.

SOFTWARE SETUP

Software setup requires a basic knowledge of DOS operating system commands and pathnames--in particular the commands *DIR*, *COPY*, *MD* (*MKDIR*), *CD* (*CHDIR*), *DEL*, *PATH,* and *APPEND*. *APPEND* is only available in *DOS* version 3.3 and above. Also, knowledge of the use of batch files is very useful. For details refer to the *DOS* operating manual for your computer. The steps of software setup are 1) creation of a program directory on the hard disk for the program *CANOPY*, 2) copying necessary files to the program directory, 3) creation of a custom startup batch file, 4) creation of a custom initialization batch file, and 5) making appropriate changes to the *CANOPY.CNF* configuration file. In addition, if necessary, a custom direct sunlight distribution file, diffuse skylight distribution file, sun weighting file, sky weighting file, sun correction file, sky correction file, sun grid file, and sky grid file should be created and added to the program directory. In general, the system should first be tested using supplied files before customization.

Creation of a Program Directory and Copying Files

As with most software, backup copies of the distribution disks should be made before installing the program. Create a directory on the hard drive for *CANOPY* (e.g., c:\ip\canopy). Copy the following files from the *CANOPY* distribution disks into the *CANOPY* program directory: *CANOPY.EXE*, *CANOPY.CNF*, *SUN.EXE*, *SUN.CNF*, *SKY.EXE*, *SKY.CNF*, *PSEUDO.LUT*, a direct sunlight distribution file (e.g., *1043.SUN*), a diffuse skylight distribution file (e.g., *ISON.SKY*), a sun weighting file (e.g., *NOSUN.WGT*), a sky weighting file (e.g., *NOSKY.WGT*), a sun correction file (e.g., *1043C.COR*), a sky correction file (e.g., *ISOC.COR*), sun grid file (e.g. *1043*.GRD), and a sky grid file (e.g., *ISO.GRD*). See Appendix D for a listing of files.

Creation of a Startup Batch File

A custom startup batch file (e.g., *RUNCAN.BAT*) can be used for such tasks as to run *PATH* and *APPEND* commands to allow access to the *CANOPY* from within other directories), to change to the appropriate directory when starting, and to start the program. Generally such a batch file should be included with other batch files in a separate directory which is made available via a PATH command specified within the AUTOEXEC.BAT file (e.g., c:\bat or c:\utility). The following is an example of a custom startup batch file:

```
PATH C:\;C:\DOS\;C:\BAT;C:\IP\CANOPY
APPEND C:\IP\CANOPY
D:
CD \DATA
CANOPY
```

This startup batch file sets the path and append commands to include the program directory for *CANOPY*, changes to drive D:, then changes to a data directory where result files are to be stored, and finally starts the program *CANOPY*.

Creation of an Initialization Batch File

A customized initialization batch file can be created to automatically run a series of commands each time the program *CANOPY* is started. For example resident drivers for a mouse or other locator device can be loaded this way. The configuration file *CANOPY.CNF* includes the filename of the initialization batch file. The initialization batch file should be included in the program directory for *CANOPY*. The following is an example of an initialization batch file:

```
MOUSE
CPANEL
```

This initialization batch file loads the mouse driver (*MOUSE.COM*) and mouse resident control panel program (*CPANEL.COM*).

Changing the Configuration Files

The configuration file *CANOPY.CNF* can be changed from within the program *CANOPY* or (for experienced users) using a text editor. Similarly the configuration files *SUN.CNF* and *SKY.CNF* can be changed from within the corresponding programs *SUN* and *SKY* or using a text editor. See Appendix C for configuration file formats. To change the configuration file *CANOPY.CNF* from within *CANOPY*, change to the program directory and start *CANOPY* using the -r option, for example:

> C:\>**CD \IP\CANOPY<ENTER>**
> C:\IP\CANOPY>**CANOPY -r<ENTER>**

After *CANOPY* displays the credit screen, press any key to continue. If working with negatives, toggle continuous tone display (**CON LUT**) to **NEG** using the key combination <**Alt-1**>, toggle threshold display (**THR LUT**) to **NEG** using the key combination <**Alt-2**>, and toggle the calculation mode (**CALC MODE**) to **NEG** using the key combination <**Alt-M**>. If working with positive photographs or transparencies, toggle **CON LUT**, **THR LUT**, and **CALC MODE** to **POS. POS** or **NEG** appears next to the appropriate menu choices on the computer display screen. Next go to the configuration menu by entering <**Alt-C**>. The configuration menu should appear, with commands **0** through **E** shown along with the current settings for each of the corresponding configuration settings. Change any of the configuration settings to the appropriate settings for your system (see Chapter VII, <**Alt-C**>, **CONFIGURATION**). After completing changes in configuration, exit from the configuration menu by entering <**ESC**> and then exit from *CANOPY* by entering <**ESC**> again followed by entering **Y** to verify that you really want to quit.

To change the configuration file *SUN.CNF* from within *SUN*, change to the program directory and start canopy using the **-r** option, for example:

> C:\IP\CANOPY>**SUN -r<ENTER>**

After *SUN* displays the credit screen, press any key to continue. Press **<Alt-C>** to enter the configuration menus. Enter any appropriate changes in the digitizer/display I/O and image buffer addresses and other configuration settings (see Chapter IX, **<Alt-C>**, **CONFIGURATION**). After completing changes in configuration, exit from the configuration menu by entering **<ESC>** and then exit from *SUN* by entering <**ESC**> again followed by entering **Y** to verify that you really want to quit.

To change the configuration file *SKY.CNF* from within *SKY*, change to the program directory and start canopy using the (**-r** option), for example:

> C:\IP\CANOPY>**SKY -r<ENTER>**

After *SKY* displays the credit screen, press any key to continue. Press <**Alt-C**> to enter the configuration menus. Enter any appropriate changes in the digitizer/display I/O and image buffer addresses and other configuration settings (see Chapter XI, **<Alt-C>**, **CONFIGURATION**). After completing changes in configuration, exit from the configuration menu by entering **<ESC>** and then exit from SKY by entering <**ESC>** again followed by entering **Y** to verify that you really want to quit.

Testing *CANOPY*, *SUN*, and *SKY*

Before proceeding to customize *CANOPY* for your system, it is a good idea to test that it runs correctly with your hardware and software setup. First make sure that all cables are correctly connected and that the image display monitor is on. Then start the program *CANOPY* by typing **CANOPY** followed by <**ENTER**> on the *DOS* command line (or optionally enter the name of the startup batch file if it includes the command **CANOPY**). If a "floating point error" message appears on the screen, a mathematics coprocessor is probably not present in the microcomputer. After *CANOPY* begins to run, first any initialization batch file commands should run, then the image display should clear and a graphics circle should appear on the image display, and then the credit screen should appear on the computer display. If the system freezes, the digitizer I/O address is probably incorrect in the configuration file or jumpered incorrectly on the digitizer/display adapter. If no graphics overlay appears on the image display, the image buffer is probably incorrect in the configuration file or jumpered incorrectly on the digitizer/display adapter.

Such problems can also occur if two devices are trying to use the same memory address. To proceed from the credit screen to the main menu, press any key.

A series of simple tests will serve to make sure that the system is functioning correctly and at the same time begin to familiarize the user with operation of the program. If the program does not function as described, go back and check both hardware and software setup. Be sure that the video camera is on and properly connected before continuing. Test digitization by entering **D**. An image should appear on the image display. Adjust the aperture and focus to make the image distinct (any image will do). Make sure that continuous digitization is on by waving your hand in front of the camera. Next press **F** to stop digitization and turn on the threshold display. Press **F** once more to toggle back to continuous tone display, and then once more to toggle to threshold display. While in threshold display, press **+** and then **-**, while watching the threshold value at the bottom of the computer display. The threshold value should increase or decrease accordingly, while simultaneously changing the appearance of the thresholded image on the image display. Press **G** several times and make certain that a compass grid turns on and off on the image display. Then reset the system by pressing **<Ctrl-R>**. Press **C** to initialize calculations. The program will stop running if correct files are not present or if they are incorrectly specified in the configuration file. A series of results screens should appear. Press any key to proceed from one screen to the next. After getting back to the main menu, exit the program by pressing **<ESC>** followed by **Y** to verify that you really want to quit.

Finally test the utility programs *SUN* and *SKY*. *SUN* is started by typing **SUN** followed by **<ENTER**>, and *SKY* is started by typing **SKY** followed by **<ENTER>**. After each of these programs starts, the image display monitor should flash and then clear. Press any key to pass from the credit screen to the main menu. Press **D** to begin drawing a distribution file. A graphics representation of the distribution file should appear in pseudocolor display on the image display. Stop drawing by pressing **<ESC>**. There may be a delay before drawing stops, as a set of calculations is completed. Exit the program by pressing <**ESC**> followed by **Y** to verify that you really want to quit.

Customizing Files Used by *CANOPY*

Generally, a custom direct sunlight distribution file and sun cosine correction file, sun cosine correction file, and sun grid file should be created for a given latitude and hemispherical lens correction using the utility program *SUN* (see Chapter VIII). Similarly, a custom diffuse skylight distribution file, sky cosine correction file, and sky grid file should be created for a given set of azimuth angles and hemispherical lens correction using the utility program *SKY* (see Chapter X). This allows the user to specify parameters for particular study sites. If various sites are being studied or different equipment is being used for different sets of photographs, a series of files can be created for each site and set of equipment. In general, the weighting files that specify no weighting (*NOSUN.WGT* and *NOSKY.WGT*) should be used, unless the user wishes to fit his or her own theoretical or empirical weighting. Weighting files can be modified and created using text editors or with software written by the user. All customized files that are to be used with *CANOPY* should be copied into the program directory and unnecessary files should be deleted from the program directory. After placing new files in the program directory, the configuration file should be changed accordingly using the **<Alt-C>** command within *CANOPY* or using a text editor.

CHAPTER VI. GUIDE TO OPERATION OF CANOPY

GOAL OF ANALYSIS

When one analyzes hemispherical canopy photographs, the basic goal is to obtain meaningful and consistent analytical results. Consistent results depend upon consistent high quality of the photographs being analyzed and conscientious adherence to a strict analysis protocol. Meaningful analytical results derive from proper configuration and operation of the program *CANOPY*.

PROGRAM CONTROL

To Start *CANOPY*

First run a startup batch file (e.g., *RUNCAN.BAT*), if one has been set up to run the *PATH* command and switch to the appropriate working directory. The startup batch file can include the command **CANOPY** to start *CANOPY*. Otherwise enter the appropriate startup commands and then enter **CANOPY** to start *CANOPY*. The initialization batch file (e.g., *INITCAN.BAT*) will automatically run, for example, loading the mouse driver. A credit/copyright screen will appear on the computer display and the user will be prompted to press any key to continue. After any key is pressed, the main menu screen will appear. When starting *CANOPY*, including the option **-r** on the command line prevents resetting and clearing of the digitizer, which is especially useful if one wishes to continue working on an image that is already loaded into the digitizer/display adapter image buffer:

d:\pathname>**CANOPY -r<Enter>**

When the computer is started with a cold boot, *CANOPY* should be run without the **-r** option, to initialize the digitizer/display adapter registers.

Command Selection

Commands are selected from the keyboard with single keystrokes, as indicated in the menus. A simple mnemonic corresponds to each keyboard choice (see Chapter VII). In general, escape **<ESC>** will end or abort a process at any stage. Various prompts, submenu lists of choices, messages, and control information will appear at appropriate times after entering a command. In addition to the main menu, there are separate menus for configuration and editing (see Appendix A).

Control Information

Useful control information appears on the computer display at appropriate times. The menu name is always displayed at the top of the computer display monitor; the current active set of display LUTs (**CONTINUOUS**, **THRESHOLD**, or **PSEUDOCOLOR**) and the current threshold value are displayed on the bottom line; the second line from the bottom displays the name of the current image, if the image has been saved or loaded.

Additional control information shown in the main menu includes whether positive (**POS**) or negative (**NEG**) display LUTs are currently in use for the continuous tone display (**<Alt-1>, CON LUT**) or the threshold display (**<Alt-2>**, **THR LUT**), whether the calculation mode (**<Alt-M>, CALC MODE**) is positive (**POS**) or negative (**NEG**), whether the pause placed between each result screen (**W, WAIT**) is toggled **ON** or **OFF**, whether the output of a data file (**O, OUTFILE**) is **ON** or **OFF**, and whether a label attached to each set of analyses (**P, PHOTO LABEL**) is toggled **ON** or **OFF**.

Similarly, appropriate control information is displayed in edit and configuration modes. When the user is editing, a display appears that shows the coordinates and data values of the pixels at the two diagonal corners of the rectangle cursor. In edit mode, the active edit value is also displayed. In the configuration mode, the current default values are displayed beside the menu choice for each parameter.

ANALYSIS METHODS

General Protocol

Analysis of hemispherical canopy photography involves a cycle of photograph positioning, digitization, determination of a threshold to distinguish foliage from canopy opening, calculation, and output of results. Before starting analysis, the hardware and software must be properly set up and the program *CANOPY* must be running, with the main menu visible. Table VIII is a summary listing of the general protocol for analysis of hemispherical canopy photographs.

Hardware Startup and Adjustment

Before starting, the hardware must be properly set up (as described in Chapter V). The image plane of the video camera should be made parallel to the plane of the film holder; the backlighting lamp should be turned on; and the video camera should be turned on. Exact vertical positioning of the video camera must be adjusted while digitizing an image, as described below.

Configuring the Image Display

The continuous tone and threshold display modes should be set before beginning to analyze photographs. Continuous tone display produces black and white images composed of 128 different levels of gray and is used for examination of photographs. Threshold display produces images in which all pixels are either black or white, with no intermediate levels of gray. Threshold display shows what portions of an image are classified as foliage and what portions are classified as canopy openings. In general, when working with positives, the continuous tone display (**CON LUT**, **<Alt-1>**) and threshold display (**THR LUT, <Alt-2>**) should both be set to positive (**POS**); and when working with negatives, both continuous tone and threshold display should both be set to negative (**NEG**). For the continuous tone display, the positive mode uses a positive linear ramp LUT, which displays all image data in direct

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Table VIII. General protocol for analysis of hemispherical canopy photographs.
1) Turn on and adjust hardware (video camera, lamp, copy stand, film holder).
2) Set configuration parameters: **CON LUT (<Alt-1>), THR LUT (<Alt-2>),** and **CALCMODE (<Alt-M>).**
3) Adjust image size, focus, translation, rotation, and lens aperture while digitizing (**D**) an image with clear borders.
4) Set output parameters: **OUTFILE (O)**, **WAIT (W)**, **PHOTO LABEL (P)**, photograph counter.
5) **DIGITIZE (D)**.
6) Position negative or slide.
7) **FREEZE (F)**.
8) Toggle back and forth between threshold and continuous tone display (**F**) while adjusting the threshold up and down (**+/-**).
9) **CALCULATE (C)**.
10) Repeat steps 5-9 for next photograph.

proportion to their intensity values. The negative mode uses a negative linear ramp LUT, which displays all image data in inverse proportion to their intensity values. The setting for the threshold display determines whether threshold display will appear as black below the threshold value and white above the threshold value (**POS**), or as white below and black above the threshold value (**NEG**). The threshold display is set separately from the continuous tone display in case a user has a preference for viewing white canopy openings on a black foliage background or dark canopy openings on a white foliage background.

Setting the Calculation Mode

Care should be taken to set the calculation mode appropriately at the start of an analysis session, before initiating calculations. The calculation mode determines whether all intensity values above the threshold or all intensity values below the threshold will be counted as canopy openings. In general, when working with positives, the calculation mode (**CALC MODE, <Alt-M>**) should be set to positive (**POS**); and when working with negatives, the calculation mode should be set to negative (**NEG**). Note, that if the calculation mode is incorrectly set, all proportional indices (for example, ISF and DSF) will be calculated as one minus the correct value (for example, an ISF of 0.43 should actually be 0.57).

Digitization

Video images are digitized continuously at the rate of one image (one frame) each 1/30 second. Digitization is started by pressing **D (DIGITIZE)**, and digitization is stopped by pressing **F (FREEZE)**. To specify when digitization is occurring, a message (**"DIGITIZING..."**) appears. When the user first starts a session of photograph analysis, adjustment of the size, position, and focus of images should be accomplished while digitization is on. In the usual cycle of photograph analysis, digitization is toggled on, the photograph is properly positioned, and then digitization is toggled off.

Positioning of Photographs

Proper positioning of photographs is critical, so that sky positions within a photograph register with the direct sunlight and diffuse skylight distributions used for analysis. The hemispherical photograph should be positioned so that the photograph edges line up with the edges of the circular positioning graphics overlay, and so that true north is directly toward the top of the image display monitor. In practice, first the size and X,Y position of the image should be adjusted, then the aperture and focus should be adjusted, and finally the rotation should be adjusted.

To start, a negative or transparency should be placed in the film holder (Fig. 11). The photograph must sit flat in the holder. The photograph should have distinct edges, visible for all sides of the circular field of view. Often, an overexposed photograph can best provide such distinct edges. A good practice is to select a calibration photograph that is used whenever adjustments are made. Image size is determined by the distance of the focal plane from the subject, so it is primarily changed by moving the video camera up or down on the copy stand. Coarse adjustment of image X,Y position is accomplished by moving the entire film holder and fine adjustment by using the X,Y translation knobs of the film holder. Aperture and focus are set using the adjustment rings of the lens. Because a change in focus will also change the size of the image, it is necessary to go through several cycles of fine adjustment in which distance of the video camera from the photograph and focus are alternately changed. The final minor changes in size adjustment can be made with the focus ring. The final minor changes in X,Y position of the image can be made using film holder X,Y translation knobs.

In cases where a databack is used to imprint labels on photographs, the imprinted labels can be used as an internal reference for fine adjustment of photograph position. This is especially useful for photographs where the edges of the field of view are not visible. The imprinted labels can be lined up with the label alignment grid shown in graphics overlay. The position of the label grid can be adjusted in the system configuration (**<Alt-C> CONFIGURATION**).

Image rotation should be adjusted after image size, focus, X,Y position, and aperture are correct. This is accomplished by loosening the rotation set screws of the film holder and rotating the stage that holds the film. Once the rotation is correct, the set screws can be resecured. A north/south east/west graphics overlay compass grid can be toggled on to facilitate adjustment of rotation. Separate tic marks are shown for true north, south, east, west, and magnetic north. The location of magnetic north is, for use in the usual case, wherein photographs are taken with the camera top oriented toward magnetic north. If internal references for north (for example a flashlight on a pole) were used when taking photographs, this reference can be lined up with the magnetic north tic mark. Otherwise, a good means for adjusting rotation involves 1) temporarily shifting the X,Y position so the edge of the film shows on the

Fig. 11.

The blacklit film holder. This commercially available film holder has a movable stage that can be translated in the X, Y dimensions and rotated about a central axis. A custom stand with adjustable level feet allows alignment of the stage with the video image plane. A backlighting source beneath the stage produce very even illumination.

image display monitor; 2) rotating the film stage so that the film edge is made square with the display monitor edge; 3) shifting the X,Y position back so the photograph is centered again; and 4) once the photograph is made square with the video camera in this manner, making an additional rotation to compensate for magnetic north, by sighting on the photograph location that lines up with the true north tic mark and then rotating the photograph so that location lines up with the magnetic north tic mark.

It is a good idea to adopt a protocol wherein image alignment, focus, and aperture are recalibrated periodically in the normal course of photograph analysis. In some cases minor adjustment of alignment may be desirable for each photograph. There is essentially no variation in vertical (Y) position of photographs relative to the edges of the film, but there can be minor variation in horizontal (X) position of photographs due to "play" in the tension of the film as it is advanced.

Setting Data File Output

Results of analyses can be automatically saved in a data file. Output of data files is toggled on and off by pressing **O** (**OUTFILE**). If data file output is on, tables of results will be saved in a data file after each set of calculations. When toggling data file output on, the user is first prompted for whether to save all results (**A**) or only summary results (**S**); and then the user is prompted for the name of a file to which results are saved. The "all results" option includes 1) tables of unweighted openness and indirect site factor (ISF) as a function of azimuth and zenith angle, 2) unweighted openness along the sun path and direct site factor (DSF) as a function of time of day and month, and 3) summary tables of ISF and DSF (weighted and unweighted, with DSF by month). The "summary" option includes only the summary tables of ISF and DSF. Data file output will continue until toggled off. The main menu shows the current data file output configuration (**OUTFILE ON** or **OFF**).

Setting Wait

An optional wait prompt allows the user to examine tables of results as they are calculated. After each screen of results is displayed on the computer display monitor, the user is prompted to press any key to continue. The wait prompt is always on when the system starts. The wait prompt can be toggled on and off by pressing **W (WAIT)**. When the wait prompt is toggled off, pauses between result screens will not appear. This option is useful to speed processing when all results output is being directed to a data file, and it is not necessary to examine results as they are calculated. The main menu shows the current wait prompt configuration (**WAIT ON** or **OFF**).

Setting the Photograph Counter

An autoincrementing photograph counter automatically assigns a unique numeric label to each set of photograph analyses. The numeric label appears with each table of results, both displayed on the computer display monitor and in data files. When the system starts the counter is set to zero. The counter can be set to any integer value by pressing **<Ctrl-U>** to increase the counter, <**Ctrl-D**> to decrease the counter, and <**Ctrl-Z**> to reset the counter to zero. The value of the photograph counter is shown on the right side of the main menu screen. The photograph counter autoincrements by one after each set of analyses is complete. The current value of the counter always applies to the next set of analyses to be performed. Thus each set of analysis results can always be identified by a unique numeric label, and the user can choose any integer value to assign to a given analysis.

Entering Photograph Labels

In addition to the standard numeric labels, a unique alphanumeric label, up to 29 characters long, can also be assigned to each set of analysis results. The photograph label option can be toggled on and off by pressing **P** (**PHOTO LABEL**). When the photograph label option is toggled on, the user is prompted to enter a label for each set of analysis results. The main menu shows the current photograph label configuration (**PHOTO LABEL ON** or **OFF**).

Selection of a Threshold

A threshold intensity value defines the way in which an image is classified into foliage and canopy openings. The threshold value can be changed while in threshold display by pressing + (**UP THRESHOLD**) to increase the threshold and - (**DOWN THRESHOLD**) to decrease the threshold. Changes in the threshold are immediately shown on the image display monitor and the numeric value of the threshold is shown on the computer display monitor. The general classification protocol involves toggling back and forth between the continuous tone display and the threshold display, adjusting the threshold so that the canopy opening/foliage boundaries of the classified

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image best match the boundaries of the continuous tone image.

Threshold selection is among the most subjective aspects of photograph analysis, so it is important to adopt a standard, repeatable protocol for deciding upon a threshold. In general, because small canopy openings tend to be dimmer than larger canopy openings, a compromise threshold choice will tend to underestimate the area of small openings and overestimate the area of large openings. One protocol for choosing a threshold involves attempting to match edges of intermediate-size openings in the classified image as precisely as possible with the continuous tone image. Often a reasonable protocol involves performing multiple analyses of each photograph, each with an independent determination of a threshold, and then examining how well results agree. For example, a protocol can involve calculating a threshold twice, first starting well above an appropriate threshold and working down to a threshold, and next starting well below an appropriate threshold and working up to a second threshold. If results of calculations using each of the two thresholds are within reasonable agreement, the analysis can be considered acceptable; and otherwise an additional set of analyses can be performed. For a given person, consistency of threshold determination tends to improve with practice and experience. Consistency between people can be improved by adopting standard protocols, practicing on a common set of photographs, and communicating details of how decisions are made. Consistency tends to be greatest for photographs with good exposure and contrast.

Calculation

Once a threshold has been selected for an image, calculations are initiated by pressing **C** (**CALCULATE**). During calculation, first the direct sunlight distribution file and then the diffuse skylight distribution file are loaded. After calculation, tables of results are shown on a series of screens on the computer display monitor. If data file output is on, tables of results are written to a data file.

Image Editing

Images that have problems with exposure can be edited. For instance, foliage/canopy opening boundaries can be better defined and reflections on leaves can be removed. Edit mode is entered by pressing **E** (**EDIT**). The edit menu lists edit command choices. Editing is achieved by changing data values of pixels within a rectangular region defined by a rubber-band cursor. The X,Y coordinates and data intensity values of the pixels at the two diagonal corners of this rectangle cursor are displayed. X,Y coordinates range from (0,0) in the upper-left corner of the image to (511,479) in the lower-right corner, with X values increasing from left-to-right and Y values increasing from top-to-bottom. Data intensity values range from 0 to 127 (7 bits), with 0 as black in positives and white in negatives, with 127 as white in positives and black in negatives, and with intermediate values representing intermediate levels of gray.

Cursor control during image editing can be accomplished with the mouse or arrow keys on the keyboard. The mouse can be used for coarse control and the keyboard for fine pixel-by-pixel control. In general, with the mouse, movement up/down and right/left moves the cursor accordingly; the right button combined with movement of the mouse stretches the rectangular cursor to different shapes; and the left button draws a filled rectangle. On the keyboard, the arrow keys move the cursor one pixel in the corresponding direction; <**Ctrl-Left**> and <**Ctrl-Right**> move the cursor ten pixels to the left or right, respectively; and <**PgUp**> and <**PgDn**> move the cursor ten pixels up or down, respectively. Slash/toggles between this cursor movement mode and a cursor stretch mode in which the arrow keys, <**Ctrl-Left**>, <**Ctrl-Right**>, <**PgUp**>, and <**PgDn**> allow the cursor to be stretched. <**ENTER**> draws a filled rectangle, analogous to the mouse left button. Pressing **<Ctrl-V> (EDIT VALUE)** toggles the active edit value to allow editing of foliage or canopy openings. When working with positives, an edit value of 0 corresponds to foliage and an edit value of 127 corresponds to openings. When working with negatives, an edit value of 127 corresponds to foliage and an edit value of 0 corresponds to openings. The current edit value appears beside edit value menu choice. While in edit mode, it is possible to toggle between continuous tone and threshold display by pressing **F (FREEZE)** and to change the threshold by pressing **+ (UP THRESHOLD)** and **- (DOWN THRESHOLD)** while in threshold display.

Archiving Images and the DOS Shell

Digital images can be saved to disk and later reloaded. Press **A (ARCHIVE)** to bring up the archive submenu. Then press **S (SAVE)** to save an image to disk or **L (LOAD)** to load an image from disk. Images are stored as binary raster files that require approximately 1/4 megabyte per file (see Appendix C for Image File Format). A *DOS* operating system shell is provided to allow file management and to allow the user access to general commands from

DOS. Press **D (DOS SHELL)** to enter the *DOS* shell. The *DOS* shell can be used for file management and to run other programs. While in the *DOS* shell, any *DOS* command can be entered (**DIR, COPY, DEL, REN, MD, CD**, **RD**, etc.), as can any other available command. Because the program *CANOPY* remains resident in memory, only limited memory is available to run other programs from the *DOS* shell. Press **<ESC>** to leave the *DOS* shell and return to *CANOPY*.

Pseudocolor Display

Pseudocolor display capabilities are provided primarily to allow examination of direct sunlight and diffuse skylight distributions, after these distributions are loaded into the image buffer. Pseudocolor display can show each sky region in a distinct color. Press **<Alt-P> (PSEUDOCOLOR)** to toggle pseudocolor display on and off. The file *PSEUDO.LUT* specifies the pseudocolor LUT to be used, and must be accessible for pseudocolor display to be available. *PSEUDO.LUT* can be modified to specify any pseudocolor LUT (see Appendix C for Pseudocolor LUT File Format). Nothing will happen if *PSEUDO.LUT* is not present. Pseudocolor display is not used during the usual operation of *CANOPY*.

System Configuration

When *CANOPY* first begins to run, the configuration file *CANOPY.CNF* is loaded into memory. *CANOPY.CNF* specifies the default configuration for the system. Configuration of the system can be modified within the configuration mode. Configuration mode is entered by pressing **<Alt-C> (CONFIGURATION)**. In configuration mode, a configuration menu screen appears, listing choices for each of the configuration parameters that can be modified, and showing the current setting for each parameter. Details for modifying the system configuration are provided in Chapter VII (**<Alt-C> CONFIGURATION**). Any changes in system configuration are stored in *CANOPY.CNF*, and thus will remain in effect when *CANOPY* is run in the future.

CHAPTER VII. REFERENCE GUIDE TO CANOPY

The program *CANOPY* allows semi-automated digital image analysis of hemispherical canopy photographs. Control of *CANOPY* is accomplished using a series of single keystroke commands, each of which is a mnemonic for the action to be performed. The following listing is divided into four groups: primary control commands, photography counter commands, output commands, and configuration commands. Within each group, commands are listed alphabetically.

PRIMARY CONTROL COMMANDS

Primary control commands allow for digitization of images, determination of a threshold to distinguish foliage from canopy openings, calculation of the distribution of canopy openings and indirect and direct site factors, overlay of a solar grid to show sun position as a function of time of day and month, and calculation of sun paths for specific days.

C CALCULATE

Purpose
Initiate calculations.

Mode of Operation
Results are calculated and then displayed on a series of displays, showing unweighted openness, indirect site factor (ISF), unweighted openness along sun path, direct site factor (DSF), and a summary of results. Optionally, calculations can be directed to output files (**O OUTFILE**) and display of results can be toggled off (**W WAIT**)

D DIGITIZE

Purpose
Start digitization.

Mode of Operation
A standard RS-170 black and white video signal is converted into a digital image. Digitization proceeds at the rate of one frame each 1/30 second. Images are displayed on the image display monitor, with a 1/30 second delay between digitization and display. The video camera must be on and properly attached to the video input connector for digitization to proceed. Though 8 bits of intensity information per pixel are initially digitized, only 7 bits are stored with the use of a linear ramp LUT. Digitization is stopped by pressing **F (FREEZE)**.

F FREEZE

Purpose
Toggle digitization off if digitizing and toggle between continuous tone and threshold display.

Mode of Operation
In general, the user will first freeze digitization of the image and then toggle back and forth between the threshold and continuous tone display by repeatedly pressing F, while at the same time adjusting the threshold up and down with + and - (**UP THRESHOLD** and **DOWN THRESHOLD**).

G GRID

Purpose
Toggle alignment grid on and off

G GRID (continued)

Mode of Operation
When toggled on, a graphics overlay grid shows true north, south, east, west, and the magnetic north. This grid is used to determine the rotation of photographs while digitizing. Note that east and west are reversed in hemispherical photographs. Magnetic declination is specified by pressing <**ALT-C**> (**CONFIGURATION**).

+ UP THRESHOLD

Purpose
Increase threshold.

Mode of Operation
While the threshold display is in use, + increases the threshold, while showing the effect on the image in real time. The threshold is the intensity level that determines the classification of an image into foliage and canopy openings.

- DOWN THRESHOLD

Purpose
Decrease threshold.

Mode of Operation
While the threshold display is in use, - decreases the threshold, while showing the effect on the image in real time. The threshold is the intensity level that determines the classification of an image into foliage and canopy openings.

E EDIT

Purpose
Allows editing of images with an interactive rubber-band rectangle cursor. Regions of an image may be edited to be correctly counted as foliage or canopy openings. Also, this routine allows examination of individual pixel data values.

Mode of Operation
The edit menu appears, showing the cursor commands available and control information about the cursor location. A rubber-band rectangle cursor shows on the image screen. The coordinates and data values for the upper-left and lower-right corners, X1,Y1 and X2,Y2, are shown on the control screen. Cursor control on the image screen can be accomplished with the mouse or arrow keys on the keyboard. The mouse can be used for coarse control and the keyboard for fine pixel-by-pixel control. In general, with the mouse, movement up/down and right/left moves the cursor accordingly; the right button combined with movement of the mouse stretches the rectangle cursor to different shapes; and the left button draws a filled rectangle at the current cursor location. On the keyboard, the arrow keys move the cursor one pixel in the corresponding direction; press <**Ctrl-Left**> and <**Ctrl-Right**> to move the cursor ten pixels to the left or right, respectively; and press <**PgUp**> and <**PgDn**> to move the cursor ten pixels up or down, respectively. Press slash / to toggle between this cursor movement mode and a stretch cursor mode in which the arrow keys, <**Ctrl-Left**>, <**Ctrl-Right**>, <**PgUp**>, and **<PgDn>**, allow the cursor to be stretched. Press **<ENTER>** to draw a filled rectangle, analogous to the mouse left button. Press <**Ctrl-V**> to toggle the active edit value, which allows editing of either foliage or openings. When working with negatives, an edit value of 127 corresponds to foliage and an edit value of 0 corresponds to openings. When working with positives, an edit value of 0 corresponds to foliage and an edit value of 127 corresponds to openings. The keys **F**, **+**, and **-** are available within the edit routine to allow toggling between continuous tone and threshold displays and changing of the threshold.

S SUN PATH

Purpose
Plot the sun path for a given day on the canopy photograph image, and calculate the times of day when direct sunlight penetrates through canopy openings.

Mode of Operation
The user is prompted to specify a day of the year (in Julian days, 0 to 365). The sun path for a given day is shown in graphics overlay on the canopy photograph image. A results screen summarizes the times when direct sunlight will penetrate through canopy openings. If **O (OUTFILE)** is toggled on, the results will be written to the current output file. Calculation of sun paths uses the current default sun grid file to specify the latitude, solar declinations that define the boundaries of months, and lens correction coefficients (see Appendix C for Sun Grid File Format). Nothing will happen if a proper sun grid file is not present.

<Alt-O> OVERLAY

Purpose
Toggle on and off a graphics overlay of the direct sunlight distribution or diffuse skylight distribution on a canopy photograph image.

Mode of Operation
If no graphics overlay is currently on, the user is prompted whether to display a sun grid (**1**) or a sky grid (**2**). If a sun or sky grid overlay is already on, the graphics overlay will be turned off. If a choice of 1 is made, the direct sunlight distribution (sun path through the year) appears as a graphics overlay on the canopy photograph image. The overlay of the direct sunlight distribution shows the sun position at half-hour intervals through the day and month intervals through the year for any specified latitude. Calculation of the sun path uses the current default sun grid file to specify the latitude, solar declinations that define the boundaries of months, and lens correction coefficients (see Appendix C for Sun Grid File Format). Nothing will happen if a proper sun grid file is not present. If a choice of 2 is made, the diffuse skylight distribution appears as a graphics overlay on the canopy photograph image. The diffuse skylight distribution shows areas of equal illuminance. Calculation of the diffuse skylight distribution uses the current default sky grid file to specify the azimuth angles and lens correction coefficients (see Appendix C for Sky Grid File Format). Nothing will happen if a proper sky grid file is not present.

<Ctrl-R> RESET SYSTEM

Purpose
Reset the system, clear the image buffer, and reset global parameters.

Mode of Operation
The digitizer registers are reinitialized, the LUTs are reinitialized, the image buffer is cleared, and global parameters are reset. Among the global parameters, the threshold is reset to a value of 63.

<Esc> QUIT

Purpose
Exit the program.

Mode of Operation
Any active digitization is stopped, the graphics overlay positioning circle and compass grid are erased, the configuration file is updated to include any changes, and control is returned to the *DOS* operating system.

PHOTOGRAPH COUNTER COMMANDS

A photograph counter provides a number label that is attached to results. The photograph counter will autoincrement after each set of calculations for an image. It can be set to any integer value. The current value of the photograph counter is shown on the right side of the computer display.

<Ctrl-U> UP COUNTER

Purpose
Increase photograph counter.

Mode of Operation
The photograph counter is increased by 1 each time <**Ctrl-U**> is pressed.

<Ctrl-D> DOWN COUNTER

Purpose
Decrease photograph counter.

Mode of Operation
The photograph counter is decreased by 1 each time <**Ctrl-D**> is pressed.

<Ctrl-Z> ZERO COUNTER

Purpose
Reset photograph counter.

Mode of Operation
The photograph counter is reset to zero.

OUTPUT COMMANDS

Output commands allow input and output of image files, file management (with a *DOS* shell), output of data files, toggle of screen display of results on and off, and specification of labels for each set of results.

A ARCHIVE

Purpose
Loads or saves an image file, or provides a *DOS* shell.

Mode of Operation
A menu will pop up to allow choice between loading an image (**L**), saving an image (**S**), and entering *DOS* commands (**D**). After **L** or **S** is pressed, enter a valid filename. Press <**ESC**> to terminate the command choice at any point. After loading or saving an image, the filename is displayed in the lower-left portion of the control screen. Files are always loaded from and saved to the current image buffer. When an image is loaded, any image in the current image buffer will be destroyed. When an image is saved, no protection is currently included to prevent overwriting files with the same name. Images are stored in binary format with no header (see Appendix C for Image File Format). After **D** is pressed, any *DOS* operating system command can be entered. For instance this feature can be used to take directories, copy files, and erase files.

O OUTFILE

Purpose
Toggle automatic output of results to a data file on and off.

O OUTFILE (continued)

Mode of Operation
        The user is prompted as to whether to save all results (**A**) or only the summary results (**S**). Then the user is prompted to enter a filename for data output. At the prompt, enter a valid filename followed by <**ENTER**>. No protection is currently included to prevent overwriting files with the same name. After calculations for each photograph, results are saved to the specified file in ASCII format (see Appendix C for Results Output File Format). **ON** or **OFF** is displayed in the menu to indicate the current outfile status. If the outfile status is **ON**, the name of the current outfile is displayed in the left center of the control display.

W WAIT

Purpose
        Toggle wait prompt on and off during display of results.

Mode of Operation
        When the wait prompt is toggled on, calculation results are displayed in a series of screens and the user is prompted to press any key to continue from one screen to the next. This allows the user to examine results as they are calculated. When the wait prompt is toggled off, this feature is suppressed and user is not prompted to press any key to continue. The option of toggling the wait prompt off is useful if the user does not want to examine the results as they are calculated, but instead wishes to save all results directly in a data file (see **O, OUTFILE**).

P PHOTO LABEL

Purpose
        Toggle photograph label on and off.

Mode of Operation
        When the photograph label is toggled on, a unique user-specified alphanumeric label (up to 29 characters) will be attached to results of analyses, both displayed on results screen and included in data files. After each set of analyses is performed, the user is prompted for a label.

<div align="center">

CONFIGURATION COMMANDS

</div>

        Configuration commands allow the user to configure display and calculation modes for use with positive or negative input images, to display direct sunlight and diffuse skylight distributions in pseudocolor, and to specify the parameter settings for operation of the system.

<Alt-1> CON LUT

Purpose
        Toggle between positive and negative continuous display.

Mode of Operation
        NEG (negative) or **POS** (positive) is shown in the menu to indicate the active continuous tone display configuration. The continuous tone display configuration is stored in the configuration file.

<Alt-2> THR LUT

Purpose
        Toggle between positive and negative threshold display.

<Alt-2> THR LUT (continued)

Mode of Operation

    NEG (negative) or **POS** (positive) is shown in the menu to indicate the active threshold display configuration. The threshold display configuration is stored in the configuration file.

<ALT-C> CONFIGURATION MODE

Purpose

    Changes the default configuration for the digitizer in/out address, the image buffer address, the color of graphics overlay and cursors, the names of sun and sky distribution files, the names of sun and sky weighting files, the names of sun and sky correction files, the names of sun and sky grid files, the initialization command for the mouse or other locator device, the magnetic declination, the aspect ratio, and the labels for the azimuth angle ranges.

Mode of Operation

    Configuration changes are written to the configuration file *CANOPY.CNF*, so changes will remain in effect when the program is restarted (see Appendix C for Configuration File Format). The following commands are available while in configuration mode:

    0 allows specification of the digitizer/display I/O address. An incorrect address will generally cause the system to freeze. The I/O address is set in hardware using a series of jumpers (see the digitizer/display adapter manual for details).

    1 allows specification of the image buffer address. The image buffer address is set in hardware using a series of jumpers (see the digitizer/display adapter manual for details).

    2 allows specification of the cursor/graphics overlay color. The color is specified by a series of intensity values (range 0 to 255) for each of the red, green, and blue channels.

    3 allows specification of a name for a direct sunlight distribution file.

    4 allows specification of a name for the diffuse skylight distribution file.

    5 allows specification of a direct sunlight weighting file.

    6 allows specification of a diffuse skylight weighting file.

    7 allows specification of a direct sunlight correction file, generally a file for cosine correction.

    8 allows specification of a diffuse skylight correction file, generally for a cosine correction.

    9 allows specification of a direct sunlight grid file. All filenames can include a *DOS* path in standard *DOS* format.

    A allows specification of a diffuse skylight grid file.

    B allows specification of a initialization command that is automatically run when *CANOPY* starts up, for instance a batch file that loads the mouse driver.

    C allows specification of the magnetic declination for use in the grid overlay.

<ALT-C> CONFIGURATION MODE (continued)

D allows specification of the aspect ratio of individual pixels (vertical over horizontal dimensions), for fine tuning measurements due to distortion in the camera or digitizer. Without such distortion, the aspect ratio should be 0.833333.

E allows specification of the label alignment grid position. The label alignment grid appears as 3 horizontal lines in graphics overlay and is used to position photographs relative to labels imprinted by a camera databack.

F allows specification of the 21 azimuth angles used in the diffuse skylight distribution file. These azimuth angles do not affect the calculations in the program, but rather are used as labels in the tables of results. The azimuth angles used in calculating the diffuse skylight distribution file should be entered here.

<**ESC**> exits the configuration mode.

<Alt-M> CALCMODE

Purpose
Toggle between negative and positive calculation mode.

Mode of Operation
NEG (negative) or **POS** (positive) is shown in the menu to indicate the current calculation mode. When the calculation mode is positive, values greater than the threshold are counted as canopy openings and values lower than or equal to the threshold are counted as foliage. Similarly, when the calculation mode is negative, values lower than or equal to the threshold are counted as openings and values above the threshold are counted as foliage. Note that calculation direction is determined independently of how the continuous tone and threshold displays are set. The calculation mode configuration is stored in the configuration file.

<Alt-P> PSEUDOCOLOR

Purpose
Toggle pseudocolor display on and off.

Mode of Operation
Pseudocolor display capability is provided to allow examination of direct sunlight and diffuse skylight distribution files (**.DIR* and **.IND* files). Pseudocolor display is not used during the usual operation of *CANOPY*. The file *PSEUDO.LUT* must be accessible for pseudocolor display to be available. *PSEUDO.LUT* can be modified to specify any pseudocolor LUT (see Appendix C for Pseudocolor LUT File Format). Nothing will happen if *PSEUDO.LUT* is not present.

CHAPTER VIII. GUIDE TO OPERATION OF *SUN*

PURPOSE OF SUN

SUN is a utility program to produce direct sunlight distribution files, sun cosine correction files, sun weighting files, and sun zenith angle files. Direct sunlight distribution files specify 169 sky regions: one region that lies outside the sun path and 168 sky regions along the sun path. The 168 regions along the sun path are generally divided into seven one-month intervals through the year and 24 half-hour intervals through the day (Fig. 8). Sun cosine correction files weight each sun path region by the cosine of the zenith angle at the centroid of the region. Thus the sun cosine correction enables calculation of expected direct sunlight striking a flat horizontal surface. The relative direct sunlight contribution from each sky region can be weighted using a sun weighting file. Sun weighting files provide weighting coefficients that correspond to each of the 168 regions along the sun path. The weightings are calculated to account for path-length of the atmosphere as a function of zenith angle at sea level. Sun zenith angle files provide zenith angles that correspond to the centroids of each of the 168 regions along the sun path. Sun zenith angle files can be used to calculate user-specified weightings, when using weighting functions that are zenith angle dependent.

PROGRAM CONTROL

To Start *SUN*

Enter **SUN** to start the program *SUN*. A credit/copyright screen will appear on the computer display and the user prompted to press any key to continue. After any key is pressed, the menu for *SUN* will appear. As for *CANOPY*, including the option **-r** on the command line when starting *SUN* will prevent resetting and clearing of the digitizer, which is especially useful if one wishes to continue working on an image that is already loaded into the digitizer/display adapter image buffer:

> d:\pathname>**SUN -r<Enter>**

When the computer is started with a cold boot, *SUN* should be run without the **-r** option, to initialize the digitizer/display adapter registers.

Command Selection

Commands are selected from the keyboard with single keystrokes, as indicated in the menu. A simple mnemonic corresponds to each keyboard choice (see Chapter IX). In general, escape **<ESC>** will end or abort a process at any stage. Various prompts, submenu lists of choices, messages, and control information will appear at appropriate times after entering a command.

Control Information

Useful control information appears on the computer display at appropriate times. The current configuration settings are displayed on the computer display monitor, showing values for the latitude, solar declinations that define the boundaries of months, lens correction coefficients, and the maximum view angle of the lens. The current active set of display LUTs (**PSEUDOCOLOR** or **CONTINUOUS**) and the name of the current direct sunlight distribution file (if a file has been saved or loaded) are displayed in the lower-left corner.

PRODUCTION OF SUNLIGHT DISTRIBUTION FILES

Specifying Site-Specific Configuration Settings

Site-specific configuration settings first must be specified either by loading a sun grid file or by entering the settings from the keyboard. Press **I (INPUT GRID FILE)** to load a sun grid file. The user is then prompted to enter a valid sun grid filename. If the sun grid file loads properly, the configuration settings contained in the file will be shown on the computer display. Press **K (KEYBOARD INPUT)** to enter configuration settings from the keyboard. The cursor appears sequentially in the field for each configuration setting on the computer display. For each setting enter a new setting or simply press **<ENTER>** to move on to the next field without changing the current setting.

At any point pressing **<ESC>** will end keyboard input. After settings are entered, they can be saved to a sun grid file by pressing **O (OUTPUT GRID FILE)** and then specifying a valid sun grid filename.

The site-specific configuration parameters include latitude, solar declinations that define the boundaries between months, lens correction coefficients, and the maximum view angle. Latitude is expressed in degrees, to the nearest 0.01 degree, with south latitude indicated by a negative number and north latitude as a positive number. In general, the eight solar declinations should not be changed from the default settings. The default solar declinations specify boundaries of months. The solar declinations are listed in sequential order from south to north, and for special purposes can be changed to specify boundaries between times through the year that represent periods longer or shorter than one month. The lens correction coefficients correct for radially symmetrical distortions of a particular hemispherical lens. The lens correction coefficients correspond to a seventh-order polynomial that describes the expected angle position in an equal angle projection as a function of the actual observed angle (both expressed in degrees), and should be forced at zero and the maximum view angle. The maximum view angle is expressed in degrees and is a property of the hemispherical lens used. These parameters are described in greater detail in Chapter II.

Drawing Direct Sunlight Distributions

Once the site-specific configuration settings have been specified from a sun grid file or the keyboard, drawing of a direct sunlight distribution can be initiated. Before drawing a direct sunlight distribution, the image buffer should be clear. If the image buffer is not clear, press **<Alt-I> (CLEAR IMAGE)**. Press **D (DRAW SUN FILE)** to initiate drawing a direct sunlight distribution file. The message **"DRAWING SUN FILE..."** appears while the distribution is calculated and drawn. A series of sun paths will appear on the image display. It can take a long time to calculate and draw a direct sunlight distribution, so the user must have patience. The process can be aborted at any point by pressing **<ESC>**. A delay may occur after pressing **<ESC>**, as a series of calculations are completed. If drawing is aborted, the image buffer should be cleared before beginning to draw another distribution. Once drawing a direct sunlight distribution is complete, the message **"DRAWING SUN FILE..."** will turn off. Then the direct sunlight distribution file should be saved.

Saving Direct Sunlight Distribution Files

Direct sunlight distribution files are in the form of binary raster images, and as such can be loaded and saved. Press **A (ARCHIVE)** to bring up the archive submenu. Then press **S (SAVE)** to save a direct sunlight distribution file to disk as an image file or **L (LOAD)** to load an image from disk. Direct sunlight distribution files are saved as images in a binary raster format that requires 245,760 bytes per file (see Appendix C for Image File Format). A *DOS* operating system shell is provided to allow file management and to allow the user access to general commands from *DOS*. Press **D (DOS SHELL)** to enter the *DOS* shell. The *DOS* shell can be used for file management and to run other programs. While in the *DOS* shell, any *DOS* command can be entered (**DIR, COPY, DEL, REN, MD, CD, RD**, etc.), as can any other available command. Because the program *SUN* remains resident in memory, only limited memory is available to run other programs from the *DOS* shell. Press **<ESC>** to leave the *DOS* shell and return to *SUN*.

PRODUCTION OF SUN COSINE CORRECTION FILES

The site-specific configuration settings are used to calculate the sky regions to which the cosine corrections apply. Once the configuration settings are correct, press **C (COS CORRECTION)** to create a cosine correction file. The user is then prompted for a cosine correction filename. After the user enters a valid filename, the correction coefficients are calculated and output to the file.

PRODUCTION OF SUN WEIGHTING FILES

The site-specific configuration settings are used to calculate the sky regions to which the sun weighting coefficients apply. Once the configuration settings are correct, press **W (WEIGHTING FILE)** to create a sun weighting file. The user is then prompted for a weighting filename. After the user enters a valid filename, the weighting coefficients are calculated and output to the file.

PRODUCTION OF SUN ZENITH ANGLE FILES

The site-specific configuration settings are used to calculate the sky regions to which the sun zenith angles apply. Once the configuration settings are correct, press **Z (ZENITH ANGLE FILE)** to create a sun zenith angle file. The user is then prompted for a zenith angle filename. After the user enters a valid filename, the zenith angles are calculated and output to the file.

CHAPTER IX. REFERENCE GUIDE TO *SUN*

The program *SUN* allows calculation and output of direct sunlight distribution files, with specification of latitude, solar declinations that define the boundaries between months, and lens corrections either from sun grid files or keyboard input. Control of *SUN* is accomplished using a series of single keystroke commands, each of which is a mnemonic for the action to be performed. The following is a complete listing of all commands used in *SUN*.

A ARCHIVE

Purpose

Loads or saves an image file, or provides a *DOS* shell.

Mode of Operation

A menu will pop up to allow choice between loading an image (**L**), saving an image (**S**), and entering *DOS* commands (**D**). After L or S is pressed, enter a valid filename. Press <**ESC**> to terminate the command choice at any point. After an image is loaded or saved, the filename is displayed in the lower-left portion of the control screen. Files are always loaded from and saved to the current image buffer. When an image is loaded, any image in the current image buffer will be destroyed. When an image is saved, no protection is currently included to prevent overwriting files with the same name. Images are stored in binary format with no header (see Appendix C for Image File Format). After **D** is pressed, any *DOS* operating system command can be entered. For instance this feature can be used to take directories, copy files, and erase files.

C COS CORRECTION

Purpose

Create and save a sun cosine correction file.

Mode of Operation

Enter the name of the sun cosine correction file to be created. Then the cosine corrections are calculated and the file is saved (see Appendix C for Correction File Format). The sun cosine correction is calculated using the current values for the latitude, solar declinations defining boundaries of months, and the lens correction.

D DRAW SUN FILE

Purpose

Create a direct sunlight distribution file.

Mode of Operation

A direct sunlight distribution file is calculated and displayed on the image display monitor. Calculations are made using the current values for the latitude, solar declinations defining boundaries of months, and the lens correction. Creation of the file may take quite a long time, depending on the speed of the computer being used. Do not interrupt the process once it is started unless you wish to start over again. The direct sunlight distribution file should be saved as an image file using the archive save command (**A, S**) Press <**Esc**> to abort the process at any point. A slight delay may occur after pressing <**Esc**>, while a series of calculations are completed. The image buffer should be cleared before creating another direct sunlight distribution file.

I INPUT SUN GRID

Purpose

Input a sun grid file that specifies the latitude, solar declinations defining boundaries of months, and the lens correction to be used in calculations.

I INPUT SUN GRID (continued)

Mode of Operation
    Enter a valid filename for a previously created sun grid file. The file is then loaded and the latitude, solar declinations, and lens correction coefficients are then updated and shown on the display monitor. These values are used when calculating direct sunlight distribution files and sun cosine correction files.

K KEYBOARD INPUT

Purpose
    Specify the latitude, solar declinations defining boundaries of months, and the lens correction to be used in calculations.

Mode of Operation
    The cursor appears in the latitude field and can be moved to enter new values for the latitude, solar declinations defining boundaries of months, and the lens correction. For each value enter the new value, or press <**Enter**> with no other characters to move on to the next value field without making a change. Press **<Esc>** at any point to stop changing values. These values are used when calculating direct sunlight distribution files and sun cosine correction files.

O OUTPUT SUN GRID

Purpose
    Output a sun grid file that specifies the latitude, solar declinations defining boundaries of months, and the lens correction.

Mode of Operation
    Enter a valid filename for a sun grid file to be saved to disk. A sun grid file is saved containing the latitude, solar declinations, and lens correction coefficients currently in use, as shown on the display monitor. The values of these parameters may be modified using the keyboard input command (**K**). These values are used when calculating direct sunlight distribution files and sun cosine correction files.

W WEIGHTING FILE

Purpose
    Create and save a sun weighting file.

Mode of Operation
    Enter the name of the sun weighting file to be created. Then the cosine corrections are calculated and the file is saved (see Appendix C for Weighting File Format). The sun weighting file is calculated using the current values for the latitude, solar declinations defining boundaries of months, and the lens correction. A sun weighting file is used to account for effects of path-length of the atmosphere at sea level as a function of zenith angle.

Z ZENITH ANGLE FILE

Purpose
    Create and save a zenith angle file.

Mode of Operation
    Enter the name of the zenith angle file to be created. Then the zenith angles are calculated and the file is saved (see Appendix C for Zenith Angle File Format). The zenith angle file is calculated using the current values for the latitude, solar declinations defining boundaries of months, and the lens correction.

1 CONTINUOUS LUT

Purpose
    Toggle continuous tone display on.

Mode of Operation
    Continuous tone capability is provided to allow examination of intensity values of direct sunlight distribution files; however, direct sunlight distribution files are generally produced while in pseudocolor display.

2 PSEUDOCOLOR LUT

Purpose
    Toggle pseudocolor display on.

Mode of Operation
    Pseudocolor display capability is provided to allow examination of direct sunlight distribution files. Direct sunlight distribution files are generally produced while in pseudocolor display. The file *PSEUDO.LUT* must be accessible for pseudocolor display to be available. *PSEUDO.LUT* can be modified to specify any pseudocolor LUT (see Appendix C for Pseudocolor LUT File Format).

<ALT-C> CONFIGURATION MODE

Purpose
    Changes the default configuration for the digitizer in/out address and the image buffer address.

Mode of Operation
    Configuration changes are written to the configuration file *SUN.CNF*, so changes will remain in effect when the program is restarted (see Appendix C for Configuration File Format). **0** allows specification of the digitizer/display I/O address. An incorrect address will generally cause the system to freeze. **1** allows specification of the image buffer address. Press <**ESC**> to exit the configuration mode.

<Alt-I> CLEAR IMAGE

Purpose
    Clear the image buffer.

Mode of Operation
    The image buffer is cleared, erasing any image currently in the buffer. If the image buffer is not clear, it should always be cleared before drawing a direct sunlight distribution file.

<Ctrl-R> RESET SYSTEM

Purpose
    Reset the system, clear the image buffer, and reset global parameters.

Mode of Operation
    The digitizer registers are reinitialized, the LUTs are reinitialized, the image buffer is cleared, and global parameters are reset. If an input sun grid file is being used, it must be reloaded after resetting.

<Esc> QUIT

Purpose
    Exit the program.

Mode of Operation
    The configuration file is updated to include any changes and control is returned to the *DOS* operating system

CHAPTER X. GUIDE TO OPERATION OF *SKY*

PURPOSE OF SKY

The program SKY is a utility program to produce diffuse skylight distribution files and sky cosine correction files. The diffuse skylight distribution files specify 161 sky regions: one region that lies outside the hemispherical photograph and 160 sky regions that define regions of equal expected illuminance from diffuse skylight. The 160 sky regions are divided into 20 ranges of zenith angle and 8 ranges of azimuth angle (Fig. 7). SKY is limited to producing radially symmetrical diffuse skylight distribution files; however non-symmetrical distributions can be accounted for using sky weighting files. A sky cosine correction file weights each sky region by the cosine of the zenith angle at the centroid of the region. Thus the sky cosine correction enables calculation of expected diffuse skylight striking a flat horizontal surface. The relative diffuse skylight contribution from each sky region can be weighted using a sky weighting file.

PROGRAM CONTROL

To Start SKY

Enter **SKY** to start the program *SKY*. A credit/copyright screen will appear on the computer display and the user prompted to press any key to continue. After pressing any key the menu for *SKY* will come up. As for *CANOPY*, including the option **-r** on the command line when starting *SKY* will prevent resetting and clearing of the digitizer, which is especially useful if one wishes to continue working on an image that is already loaded into the digitizer/display adapter image buffer:

> d:\pathname>**SKY -r<Enter>**

When the computer is started with a cold boot, SKY should be run without the -r option, to initialize the digitizer/display adapter registers.

Command Selection

Commands are selected from the keyboard with single keystrokes, as indicated in the menu. A simple mnemonic corresponds to each keyboard choice (see Chapter XI). In general, <**ESC**> will end or abort a process at any stage. Various prompts, submenu lists of choices, messages, and control information will appear at appropriate times after entering a command.

Control Information

Useful control information appears on the computer display at appropriate times. The current configuration settings are displayed on the computer monitor, showing values for the zenith angles and lens correction coefficients. The current active set of display LUTs (**PSEUDOCOLOR** or **CONTINUOUS**) and the name of the current direct sunlight distribution file (if a file has been saved or loaded) are displayed in the lower-left corner.

PRODUCTION OF SKYLIGHT DISTRIBUTION FILES

Specifying Site-Specific Configuration Settings

Site-specific configuration settings first must be specified either by loading a sky grid file or by entering the settings from the keyboard. Press **I (INPUT GRID FILE)** to load a sky grid file. The user is then prompted to enter a valid sky grid filename. If the sky grid file loads properly, the configuration settings contained in the file will be shown on the computer display. Press **K (KEYBOARD INPUT)** to enter configuration settings from the keyboard. The cursor appears sequentially in the field for each configuration setting on the computer display. For each setting enter a new setting or simply press <**ENTER**> to move on to the next field without changing the current setting. At any point pressing <**ESC**> will end keyboard input. After settings are entered, they can be saved to a sky grid file by pressing **O (OUTPUT GRID FILE)** and then specifying a valid sky grid filename.

The site-specific configuration parameters include 21 zenith angles that define sky regions and lens correction coefficients. Zenith angles are expressed in degrees, to the nearest 0.01 degree. Zenith angles should always be

listed with values in sequential order, from the image center to the outside, always beginning with 0 (straight up) and ending with the maximum view angle of the image (as determined by the hemispherical lens). The lens correction coefficients correct for radially symmetrical distortions of a particular hemispherical lens. The lens correction coefficients correspond to a seventh-order polynomial that describes the expected angle position in an equal angle projection as a function of the actual observed angle (both expressed in degrees), and should be forced at zero and the maximum view angle. These parameters are described in greater detail in Chapter II.

Drawing Diffuse Skylight Distributions

Once the site-specific configuration settings have been specified from a sky grid file or the keyboard, drawing of a diffuse skylight distribution can be initiated. Before drawing a diffuse skylight distribution, the image buffer should be clear. If the image buffer is not clear, press **<Alt-I> (CLEAR IMAGE)**. Press **D (DRAW SKY FILE)** to initiate drawing a diffuse skylight distribution file. The message "**DRAWING SKY FILE...**" appears while the distribution is calculated and drawn. Graphics drawing will appear on the image display. It can take a long time to calculate and draw a diffuse skylight distribution, so the user must have patience. The process can be aborted at any point by pressing **<ESC>**. A delay may occur after pressing <ESC>, as a series of calculations are completed. If drawing is aborted, the image buffer should be cleared before beginning to draw another distribution. Once drawing a diffuse skylight distribution is complete, the message "**DRAWING SKY FILE...**" will turn off. Then the diffuse skylight distribution file should be saved.

Saving Diffuse Skylight Distribution Files

Diffuse skylight distribution files are in the form of binary raster images, and as such can be loaded and saved. Press **A (ARCHIVE)** to bring up the archive submenu. Then press **S (SAVE)** to save a diffuse skylight distribution file to disk as an image file or **L (LOAD)** to load an image from disk. Diffuse skylight distribution files are saved as images in a binary raster format that requires 245,760 bytes per file (see Appendix C for Image File Format). A *DOS* operating system shell is provided to allow file management and to allow the user access to general commands from *DOS*. Press **D (DOS SHELL)** to enter the *DOS* shell. The *DOS* shell can be used for file management and to run other programs. While in the *DOS* shell, any *DOS* command can be entered (**DIR, COPY, DEL, REN, MD, CD**, **RD**, etc.), as can any other available command. Because the program *SKY* remains resident in memory, only limited memory is available to run other programs from the *DOS* shell. Press <**ESC**> to leave the *DOS* shell and return to *SKY*.

PRODUCTION OF SKY COSINE CORRECTION FILES

Diffuse skylight cosine correction files can be produced using *SKY*. The site-specific configuration settings are used to calculate the sky locations to which the cosine corrections apply. Once the configuration settings are correct, press **C (COS CORRECTION)** to create a sky cosine correction file. The user is then prompted for a cosine correction filename. After the user enters a valid filename, the correction coefficients are calculated and output to the file.

CHAPTER XI. REFERENCE GUIDE TO SKY

The program *SKY* allows calculation and output of diffuse skylight distribution files, with specification of ranges of azimuth angles and lens corrections either from sky grid files or keyboard input. Control of SKY is accomplished using a series of single keystroke commands, each of which is a mnemonic for the action to be performed. The following is a complete listing of all commands used in *SKY*.

A ARCHIVE

Purpose
Loads or saves an image file, or provides a *DOS* shell.

Mode of Operation
A menu will pop up to allow choice between loading an image (**L**), saving an image (**S**), and entering *DOS* commands (**D**). After **L** or **S** is pressed, enter a valid filename. Press <**ESC>** to terminate the command choice at any point. After loading or saving an image, the filename is displayed in the lower-left portion of the control screen. Files are always loaded from and saved to the current image buffer. When an image is loaded, any image in the current image buffer will be destroyed. When an image is saved, no protection is currently included to prevent overwriting files with the same name. Images are stored in binary format with no header (see Appendix C for Image File Format). After **D** is pressed, any *DOS* operating system command can be entered. For instance this feature can be used to take directories, copy files, and erase files.

C COS CORRECTION

Purpose
Create and save a sky cosine correction file.

Mode of Operation
Enter the name of the sky cosine correction file to be created. Then the cosine corrections are calculated and the file is saved (see Appendix C for Correction File Format). The sky cosine correction is calculated for using the current values for the zenith angles and the lens correction.

D DRAW SKY FILE

Purpose
Create a diffuse skylight distribution file.

Mode of Operation
A diffuse skylight distribution file is calculated and displayed on the image display monitor. Calculations are made using the current values for the zenith angles and the lens correction. Creation of the file may take quite a long time, depending on the speed of the computer being used. Do not interrupt the process once it is started unless you wish to start over again. The diffuse skylight distribution file should be saved as an image file using the archive save command (**A**, **S**) Press <**Esc>** to abort the process at any point. A slight delay may occur after pressing <**Esc>**, while a series of calculations are completed. The image buffer should be cleared before creating another diffuse skylight distribution file.

I INPUT SKY GRID

Purpose
Input a sky grid file that specifies the zenith angles and the lens correction to be used in calculations.

I INPUT SKY GRID (continued)

Mode of Operation
     Enter a valid filename for a previously created sky grid file. The file is then loaded and the zenith angles and lens correction coefficients are then updated and shown on the display monitor. These values are used when calculating diffuse skylight distribution files and sky cosine correction files.

K KEYBOARD INPUT

Purpose
     Specify the zenith angles and the lens correction to be used in calculations.

Mode of Operation
     The cursor appears in the latitude field and can be moved to enter new values for the zenith angles and the lens correction. For each value enter the new value, or press <**Enter**> with no other characters to move on to the next value field without making a change. Press <**Esc**> at any point to stop changing values. These values are used when calculating diffuse skylight distribution files and sky cosine correction files.

OUTPUT SKY GRID

Purpose
     Output a sky grid file that specifies the zenith angles and lens correction coefficients.

Mode of Operation
     Enter a valid filename for a sky grid file to be saved to disk. A sky grid file is saved containing the zenith angles and lens correction coefficients currently in use, as shown on the display monitor. The values of these parameters may be modified using the keyboard input command (**K**). These values are used when calculating diffuse skylight distribution files and sky cosine correction files.

1 CONTINUOUS LUT

Purpose
     Toggle continuous tone display on.

Mode of Operation
     Continuous tone capability is provided to allow examination of intensity values of diffuse skylight distribution files; however, diffuse skylight distribution files are generally produced while in pseudocolor display.

2 PSEUDOCOLOR LUT

Purpose
     Toggle pseudocolor display on.

Mode of Operation
     Pseudocolor display capability is provided to allow examination of diffuse skylight distribution files. Diffuse skylight distribution files are generally produced while in pseudocolor display. The file *PSEUDO.LU*T must be accessible for pseudocolor display to be available. *PSEUDO.LUT* can be modified to specify any pseudocolor LUT (see Appendix C for Pseudocolor LUT File Format).

<ALT-C> CONFIGURATION MODE

Purpose
     Changes the default configuration for the digitizer in/out address and the image buffer address.

ALT-C> CONFIGURATION MODE (continued)

Mode of Operation
Configuration changes are written to the configuration file *SKY.CNF*, so changes will remain in effect when the program is restarted (see Appendix C for Configuration File Format). **0** allows specification of the digitizer/display I/O address. An incorrect address will generally cause the system to freeze. **1** allows specification of the image buffer address. Press <**ESC**> to exit the configuration mode.

<Alt-I> CLEAR IMAGE

Purpose
Clear the image buffer.

Mode of Operation
The image buffer is cleared, erasing any image currently in the buffer. If the image buffer is not clear, it should always be cleared before drawing a diffuse skylight distribution file.

<Ctrl-R> RESET SYSTEM

Purpose
Reset the system, clear the image buffer, and reset global parameters.

Mode of Operation
The digitizer registers are reinitialized, the LUTs are reinitialized, the image buffer is cleared, and global parameters are reset. If an input sky grid file is being used, it must be reloaded after resetting.

<Esc> QUIT

Purpose
Exit the program.

Mode of Operation
The configuration file is updated to include any changes and control is returned to the *DOS* operating system.

ACKNOWLEDGMENTS

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APPENDIX A. MENU SCREENS

```
MAIN MENU                                             CANOPY version 1.3
                              COMMANDS

                         DIGITIZE        D
                         FREEZE          F            photo #23
CON LUT      <Alt-1>  NEG GRID           G
THR LUT      <Alt-2>  NEG UP THRESHOLD   +
CALCMODE     <Alt-M>  NEG DOWN THRESHOLD  -      UP COUNTER    <Ctrl-U>
OUTFILE      O        ON  CALCULATE       C      DOWN COUNTER  <Ctrl-D>
WAIT         W        ON  EDIT            E       ZERO COUNTER  <Ctrl-Z>
PHOTO LABEL  P        ON  ARCHIVE         A       RESET SYSTEM  <Ctrl-R>
                         SUN PATH        S       PSEUDOCOLOR   <Ctrl-P>
                         OVERLAY        <Alt-O>  CONFIGURE     <Ctrl-C>
                         QUIT           <ESC>

                           ENTER CHOICE: _



BUFFER 1: image.img
THRESHOLD DISPLAY          THRESHOLD 63
```

```
CONFIGURATION MENU                                    CANOPY version 1.3

    I/O ADDRESS          0        300 hex           AZIMUTH ANGLE F
    IMAGE BUFFER         1        D0000000             0:  0
    GRAPHIC COLOR        2        r=0 g=0 b=220        1:  5
    SUN FILE             3        1043.DIR             2:  9
    SKY FILE             4        ISO.IND              3:  14
    SUN WEIGHT FILE      5        SUN.WGT              4:  18
    SKY WEIGHT FILE      6        SKY.WGT              5:  23
    SUN COR FILE         7        SUN.COR              6:  27
    SKY COR FILE         8        SKY.COR              7:  32
    SUN GRID FILE        9        SUN.GRD              8:  36
    SKY GRID FILE        A        SKY.GRD              9:  41
    INITIALIZATION       B        INITCAN             10: 45
    MAGNETIC DEC         C        2.5                 11: 50
    ASPECT RATIO         D        0.83333             12: 54
    NUMBER GRID LOC      E        406 415             13: 59
                                                      14: 63
              ENTER CHOICE: _                         15: 68
                                                      16: 72
                                                      17: 77
                                                      18: 81
                                                      19: 86
                                                      20: 90
```

```
EDIT MENU                                              CANOPY version 1.3

         COMMANDS                   KEYBOARD           MOUSE

    CHANGE EDIT VALUE            <Ctrl-V>
    TOGGLE MOVE/STRETCH          /                  right button
    DRAW RECTANGLE               <ENTER>            left button
    MOVE ONE PIXEL               <ARROWS>           movement
    MOVE TEN PIXELS              <Ctrl-Left>
                                 <Ctrl-Right>
                                 <PgUp>
                                 <PgDn>
    QUIT                         <ESC>

                                                              EDIT VALUE
CURSOR:    X1,  Y1   X2,  Y2                                     127
LOCATION  255, 239  259, 243
VALUE          32        119

CONTINUOUS DISPLAY            THRESHOLD 63
```

```
                                                       SUN version 1.3



       COMMANDS
                                                          LENS
   INPUT GRID FILE     I                                CORRECTION
   OUTPUT GRID FILE    O    LATITUDE   DECLINATION       COEFFICIENT
   KEYBOARD INPUT      K      10.43      -23.45       0:  +0.000000e+000
   DRAW SUN FILE       D                 -22.58       1:  +1.000000e+000
   COS CORRECTION      C                 -16.21       2:  +0.000000e+000
   WEIGHTING FILE      W                  -5.73       3:  +0.000000e+000
   ZENITH ANGLE FILE   Z                  +5.73       4:  +0.000000e+000
   ARCHIVE             A                 +16.21       5:  +0.000000e+000
   CONTINUOUS LUT      1                 +22.58       6:  +0.000000e+000
   PSEUDOCOLOR LUT     2                 +23.45       7:  +0.000000e+000
   CLEAR IMAGE         <Alt-I>
   RESET SYSTEM        <Ctrl-R>                        MAXIMUM ANGLE
   QUIT               <ESC>                                90.00
                           ENTER CHOICE: _

PSEUDOCOLOR DISPLAY
```

```
                                                                SKY version 1.3


    COMMANDS                                                          LENS
                                                                  CORRECTION
    INPUT GRID FILE      I       AZIMUTH    ANGLE                  COEFFICIENT
    OUTPUT GRID FILE     O         4.50    49.50        0:     +0.000000e+000
    KEYBOARD INPUT       K         9.00    54.00        1:     +1.000000e+000
    DRAW SKY FILE        D        13.50    58.50        2:     +0.000000e+000
    COS CORRECTION       C        18.00    63.00        3:     +0.000000e+000
    ARCHIVE              A        22.50    67.50        4:     +0.000000e+000
    CONTINUOUS LUT       1        27.00    72.00        5:     +0.000000e+000
    PSEUDOCOLOR LUT      2        31.50    76.50        6:     +0.000000e+000
    CLEAR IMAGE          <Alt-I>  36.00    81.00        7:     +0.000000e+000
    RESET SYSTEM         <Ctrl-R> 40.50    85.50
    QUIT                 <ESC>    45.00    90.00

                                  ENTER CHOICE: _


 PSEUDOCOLOR DISPLAY
```

APPENDIX B. HARDWARE SPECIFICATIONS[*]

VIDEO DIGITIZER/DISPLAY ADAPTERS

Imaging Technology[**] *PCVISION*: This framegrabber has a resolution of 512 (horizontal) X 480 (vertical) pixels with 8 bits of information per pixel, 8-bit digitization of RS-170 video, digitization of a single frame in 1/30 second, pseudocolor RGB display capabilities, four hardware input LUTs, four hardware display LUTs. This adapter can store a single frame and the image buffer can be accessed by the host CPU while it is displaying images. The bus is IBM *XT* compatible. The *PCVISION* will not synchronize properly with a video tape recorder without time base correction. The I/O address generally should be set to hexadecimal FF00 and the image buffer to hexadecimal A0000 or D0000. Three hardware configuration changes are necessary for the *PCVISION* adapter to operate correctly with *IMAGE*: 1) remove chip ICA85 (ALF374R) and reinstall it in the upper position of its socket; 2) move jumper J66 to position B; and 3) move jumper J65 to upper position (jumper J65 is under the piggyback memory module).

Imaging Technology** *PCVISION*plus: This framegrabber has a resolution of 512 (horizontal) X 480 (vertical) (or optionally 640 X 480 resolution) with 8 bits of information per pixel, 8-bit digitization of RS-170 video (CCIR video optional), digitization of a single frame in 1/30 second, pseudocolor RGB display capabilities, 8 hardware input LUTs, 8 hardware display LUTs, and hardware zoom (2X) and pan capabilities. This adapter can store two frames (2 image buffers) (only 1 buffer if in 640 X 480 configuration) and can be accessed by the host CPU while it is displaying images. The bus is IBM *XT* or *AT* compatible. The *PCVISION*plus will generally synchronize properly with a video tape recorder. The I/O address should generally be set to hexadecimal 300 and the image buffer to hexadecimal A0000 or D0000.

Data Translation[***] *DT2853*: This framegrabber has a resolution of 512 (horizontal) X 480 (vertical) with 8 bits of information per pixel, 8-bit digitization of RS-170 video, square pixels produced by sampling only the center portion of each video line, digitization of a single frame in 1/30 second, pseudocolor RGB display capabilities, 8 hardware input LUTs, 8 hardware display LUTs, and feedback LUT capabilities. This adapter can store two frames (2 image buffers) and can be accessed by the host CPU while it is displaying images. The bus is IBM *AT* compatible. The DT2853 will generally synchronize properly with a video tape recorder. The I/O address should generally be set to hexadecimal 300 and the image buffer to hexadecimal D00000 (in extended memory).

ANALOG RGB VIDEO DISPLAY MONITOR

Sony[†] *PVM 1271Q*: This high resolution analog RGB video display monitor has underscan capability (to show full images) and has external synchronization. The red, green, and blue channels of the digitizer/display adapters should be connected to the respective red, green, and blue RGB input channels of the video display monitor, and the synchronization cable (brown) should be connected to the external synchronization input. All connections should be properly terminated with the resistance switches in the on position.

VIDEO CAMERA AND LENS

Cohu[††] 4800 Solid State Camera: This solid state RS-170 video camera uses a CCD (charge-coupled device) array with a resolution of 754 (horizontal) by 488 (vertical) pixels, high sensitivity, broad spectral response, and

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[*] Reference herein to specific commercial products does not necessarily constitute or imply endorsement, recommendation, or favoring by the United States Government, or by any agency thereof, or by the authors. Product information is provided for informational purposes only.

[**] Imaging Technology Incorporated, 600 West Cummings Park, Woburn, MA 01801; telephone (800)532-3500 or (617)938-8444.

[***] Data Translation Incorporated, 100 Lock Drive, Marlboro, MA 01752; telephone (508)481-3700.

[†] Sony Corporation of America, Headquarters, 1600 Queen Anne Road, Teaneck, NJ 07666; telephone (201)833-5200

[††] Cohu Incorporated, 575 Kearny Villa Road, P. O. Box 85623, San Diego, CA 92123; telephone (619)277-6700.

excellent signal-to-noise ratio. I use this camera with a Nikon Nikkor 55mm micro lens fitted with an F to C mount adapter.

Nikon[*] *Nikkor 2.8 55mm micro lens*: This macro lens provides excellent image input, with essentially no geometric distortion. The manual model AI lens should be used, rather than the autofocus model AF lens. An F-to-C mount adapter is required to attach the lens to the video camera.

FILM HOLDER AND BACKLIGHTING

Marron Carrel[**] *Slide Positioner Compound*: This film holder allows precision positioning of negatives or transparencies. The slide positioner compound comes with a standard 2x2 mounted slide carrier and the optional 35mm pin-registered carrier should be purchased for use with negatives or unmounted slides. A custom stand with adjustable level feet[***] should be built for the film holder.

Aristo[†] *Model V-56 Light Head*: This lamp provides very even backlighting, for use with either negatives or transparencies. The unit should be equipped with a model 7452 standard color fluorescent lamp.

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[*] Nikon Inc., 623 Stewart Avenue, Garden City, NY 11530; telephone (516)222-0200.
[**] Marron Carrel, 2640 West 10th Place, Tempe, AZ 85281; telephone (602)966-2189.
[***] Adjustable leveling feet for use on optical benches, Model #20-22-005, available from Oriel Corporation, 250 Long Beach Boulevard, Stratford, CT 06497; telephone (203)377-8282.
[†] Aristo Grid Lamp Products, Incorporated, P.O. Box 769, Port Washington, NY 11050; telephone (516)944-3030.

APPENDIX C. FILE FORMATS

CONFIGURATION FILE FORMAT

The configuration file CANOPY.CNF must be present and accessible for *CANOPY* to run. The configuration file is an ASCII file with the following format of configuration parameters separated by blank spaces or carriage returns:

digitizer register in/out address (in hexadecimal)
image buffer address (in segment offset hexadecimal)
the continuous LUT (0 for positive, 1 for negative)
the threshold LUT (2 for positive, 3 for negative)
the calcmode (0 for positive-openings above threshold, 1 for negative-
openings below or equal to threshold)
the intensity of red in the graphics/cursor (range 0 to 255)
the intensity of green in the graphics/cursor (range 0 to 255)
the intensity of blue in the graphics/cursor (range 0 to 255)
filename for direct sunlight distribution
filename for diffuse skylight distribution
filename for direct sunlight distribution weighting
filename for diffuse skylight distribution weighting
filename for direct sunlight distribution correction
filename for diffuse skylight distribution correction
filename for the sun grid
filename for the sky grid
initialization command at startup
the magnetic declination in degrees
the aspect ratio
the label grid position (upper-left corner in device X,Y coordinates)
and 21 azimuth angle labels that specify bounds of the zenith angles
used in the diffuse skylight distribution, rounded to the nearest
degree (note: for label of data only--precise angles are used in SUN to calculate the diffuse
skylight distribution)

For example,

300 D0000000 1 3 1 0 0 220
1043.SUN ISO.SKY SUN.WGT SKY.WGT SUNC.COR SKYC.COR
SUN.GRD SKY.GRD INITCAN.BAT
2.500000 0.833333 406 415
0 5 9 14 18 23 27 32 36 41 45 50 54 59 63 68 72 77 81 86 90

specifies:

I/O register address to be 300 hex
image buffer address to be D000:0000 hex
continuous LUT to be negative
threshold LUT to be negative
graphics/cursor color to be blue (red 0, green 0, blue 220)
1043.SUN as filename for direct sunlight distribution
ISO.SKY as filename for diffuse skylight distribution
SUN.WGT as filename for direct sunlight distribution weighting
SKY.WGT as filename for diffuse skylight distribution weighting

SUNC.COR as filename for sun cosine correction
SKYC.COR as filename for sky cosine correction
SUN.GRD as filename for sun grid
SKY.GRD as filename for sky grid
INITCAN.BAT as the initialization command
magnetic declination to be 2.25 degrees
aspect ratio to be 0.833333
(406,415) as the X,Y coordinates of the label grid position
and labels of azimuth angles that vary every 4.5 degrees (rounded off).

CORRECTION FILE FORMAT

Corrections can be specified in separate ASCII files for the direct sunlight distribution and the diffuse skylight distribution (*.COR* files). A sun correction file consists of a list of corrections for each of the 168 regions specified in a direct sunlight distribution file; and a sky correction file consists of a list of corrections for each of the 160 sky regions specified in a diffuse skylight distribution file. Each correction coefficient should be entered on a separate line. The most common correction is a cosine correction, in which each region is weighted by the cosine of the zenith angle. Cosine corrections are expressed as the cosine of the azimuth angle for the centroid of the region. Each correction coefficient is listed on a separate line in ASCII format. Cosine correction files can be generated using the programs *SUN* and *SKY*. Corrected results are tabulated separately in the summary result tables following calculations in the program *CANOPY*.

DIRECT SUNLIGHT DISTRIBUTION FILE FORMAT

Direct sunlight distribution files characterize the sun path as consisting of 168 regions within the sky. Each pixel is assigned a one-byte value between 0 and 168, with 0 corresponding to regions outside the sun path or outside the image and each of the values from 1 to 168 corresponding to a region representing a particular time interval through the day and a particular time interval through the year. In general, the regions are defined to correspond to half-hour intervals through the day and month intervals through the year (see figs. 6 and 8). A correction for lens distortion, for example, a radially symmetrical deviation from an equal angle projection, can be included in a direct sunlight distribution file. Direct sunlight distribution files in this format can be produced using the utility program *SUN*. Direct sunlight distribution files are saved as image files (see Image File Format). These raster binary files can be displayed as images and are best viewed in a pseudocolor display mode. For certain specialized purposes, regions that correspond to periods less than one half hour through the day and less than one year through the year can be defined and used for calculations.

IMAGE FILE FORMAT

Images are stored as raster binary files, with one byte of information per pixel, typically with a spatial resolution of 512 by 480 pixels. Some digitizer/display adapters produce images with other resolutions (512 by 512 pixels, 640 by 480 pixels, or 640 by 512 pixels). Each image is a list of pixel values, each one byte long, with pixels listed from left to right across rows of pixels and from top to bottom between rows. A typical 512 by 480 image requires 245,760 bytes per file. For each byte of information, one bit contains graphics overlays and seven bits contain the intensity value of the pixel (i.e., 128 levels, 0 to 127 possible). For the Imaging Technology digitizer/display adapters, the most-significant bit is used for graphics overlay and the seven least-significant bits are used for data; whereas, for the Data Translation digitizer/display adapters, the least-significant bit is used for graphics overlay and the seven most-significant bits are used for data. For use in other programs, it may be necessary to bit-shift data one bit to the left or to adjust LUTs accordingly. Direct sunlight distribution files and diffuse skylight distribution files are stored as image files, but do not include a seven-bit image and a one-bit graphic plane, but rather a series of one-byte values that define to which region a pixel corresponds.

PSEUDOCOLOR LUT FILE FORMAT

The pseudocolor LUT file *PSEUDO.LUT* consists of an ASCII list of the red, green, and blue display values (range 0 to 255) corresponding to each of the data values. There are 256 lines with three integers per line. Each line corresponds to a data value and the three integers correspond to display value intensities of red, green, and blue, respectively. Thus if line 33 is 20 200 50, data value 32 will be displayed as the color with intensity red 20, green 200, and blue 50. Note that line 1 corresponds to data value 0 and line 256 corresponds to data value 255. Any user-specified LUT file can be specified, whether it genuinely specifies a pseudocolor LUT or some other possible LUT.

DIFFUSE SKYLIGHT DISTRIBUTION FILE FORMAT

Diffuse skylight distribution files divide the sky into 160 regions. Each pixel is assigned a one-byte value between 0 and 160, with 0 corresponding to regions outside the image and each of the values from 1 to 160 corresponding to a particular sky region. In general, the regions are defined to correspond to areas of equal illuminance from diffuse skylight (see figs. 6 and 7). Diffuse skylight distribution files in this format can be produced using the utility program SKY. A correction for lens distortion, for example a radially symmetrical deviation from an equal angle projection, can be included in a diffuse skylight distribution file. Diffuse skylight distribution files are saved as image files (see Image File Format). These raster binary files can be displayed as images and are best viewed in a pseudocolor display mode.

RESULTS OUTPUT FILE FORMAT

Results output files consist of ASCII lists of results of calculations. Three types of output can be included in a results output file: 1) tables of results from calculations--that include unweighted openness as a function of zenith and azimuth angles, indirect site factor (ISF) as a function of zenith and azimuth angles, unweighted openness along the sun path as a function of time of day and month, direct site factor (DSF) as a function of time of day and time of month, and summary results of the overall direct and ISF and DSF by year and month, both uncorrected and correct; and 2) tables of summary results--that include only the overall ISF and DSFs by year and by month, both uncorrected and corrected; and 3) results for a sun path calculated for a particular day--that list the times of day for which direct sunlight can be expected to penetrate through canopy openings. Each set of calculations is automatically assigned a unique numeric label and optionally can be assigned a unique alphanumeric label. Programs can readily be written that read result output files and extract particular results for additional processing (for example, for statistical analysis or graphics production) or to perform additional calculations (for example, calculation of gap frequencies and leaf area index from unweighted openness results).

SUN GRID FILE FORMAT

Sun grid files specify the parameter values to be used when calculating sun paths for individual days or when producing a graphics overlay of the sun path on a canopy photograph image. Sun grid files can be produced using the program SUN. Sun grid files consist of an ASCII list of parameter values that specify the latitude, eight solar declinations that define the boundaries between times through the year (generally months), the coefficients for a seventh-order polynomial corresponding to a radially symmetrical lens correction, and the maximum view angle of the image (as determined by the hemispherical lens). The latitude and solar declinations are specified in degrees, with negative values below the equator and positive values above the equator. The solar declinations are listed in sequential order from south to north. Lens correction coefficients correspond to a polynomial that describes the expected angle position in an equal angle projection as a function of the actual observed angle, and should be forced at 0 and the maximum view angle. The maximum view angle is given in degrees. One floating point value is specified per line in the following format:

latitude
solar declination 1
solar declination 2
...
solar declination 7
solar declination 8
lens correction coefficient 0
lens correction coefficient 1
...
lens correction coefficient 6
lens correction coefficient 7
maximum zenith angle.

For example,

10.43
-23.45
-22.58
-16.21
-5.73
+5.73
+16.21
+22.58
+23.45
1.3352e-03
1.0905e00
3.4868e-04
-4.0904e-05
9.6861e-07
-1.6526e-07
1.1671e-10
-6.4179e-13
89.9

corresponds to a sun grid file for 10.43 degrees north latitude (La Selva Biological Station, Costa Rica), with standard one-month intervals through the year, and with a correction for the Nikkor 8mm hemispherical lens.

SKY GRID FILE FORMAT

Sky grid files specify the parameter values to be used when producing a graphics overlay of the diffuse skylight distribution on a canopy photograph image. Sky grid files can be produced using the program SKY. Sky grid files consist of an ASCII list of parameter values that specify 20 zenith angles in degrees (that define 20 ranges of zenith angles) and the coefficients for a seventh-order polynomial corresponding to a radially symmetrical lens correction. Zenith angles should always be listed with values in sequential order, from the image center to the outside. The first zenith angle range is always assumed to begin with 0 (straight up), and the last zenith angle must be the maximum view angle of the image (as determined by the hemispherical lens). Lens correction coefficients correspond to a polynomial that describes the expected angle position in an equal angle projection as a function of the actual observed angle, and should be forced at 0 and the maximum view angle. One floating point value is specified per line in the following format:

zenith angle 1
zenith angle 2
...
zenith angle 20 (always the maximum view angle)
lens correction coefficient 0
lens correction coefficient 1
...
lens correction coefficient 6
lens correction coefficient 7.

For example,

4.5
9.0
13.5
18.0
22.5
27.0
31.5
36.0
40.5
45.0
49.5
54.0
58.5
63.0
67.5
72.0
76.5
81.0
85.5
89.9
1.3352e-03
1.0905e00
3.4868e-04
-4.0904e-05
9.6861e-07
-1.6526e-07
1.1671e-10
-6.4179e-13

corresponds to a sky grid file for equal zenith angle ranges and with a correction for the Nikkor 8mm hemispherical lens.

WEIGHTING FILE FORMAT

Weightings are specified in separate ASCII files for the direct sunlight distribution and the diffuse skylight distribution (*.*WGT* files). A sun weighting file consists of a list of weightings for each of the 168 regions along a sun path specified in a direct sunlight distribution file; and the diffuse skylight distribution weighting file consists of a list of weightings for each of 160 regions specified in a diffuse skylight distribution file. Some regions of the direct sunlight distributions have two weighting coefficients, one for each of the corresponding 2-month periods, for a total of 288 weightings. Weightings for diffuse skylight follow the order shown in Fig. 7 and weightings for direct sunlight follow the order shown in Fig. 8 for December through June and continue in the order July (169-192),

August (193-216), September (217-240), October (241-264), and November (265-288). The weightings can be any floating point number. Weightings are normalized within the program: weighted relatively by calculating each weighting value divided by the mean weighting value. Note that weightings are applied in all calculations, whereas corrections (for instance cosine corrections) are only tabulated in the summary result tables following calculations.

ZENITH ANGLE FILE FORMAT

Sun zenith angle files consist of an ASCII list of zenith angles for each of the 168 regions along a sun path specified in a direct sunlight distribution file. Sun zenith angle files can be used to calculate user-specified weightings when using functions that are zenith angle dependent.

APPENDIX D. LISTING OF FILES

FILES FOR USE WITH *CANOPY*

CANOPY.EXE	the executable program *CANOPY*.
CANOPY.CNF	the configuration file for the program *CANOPY*.
1043N.SUN	a direct sunlight distribution file for 10.43 degrees north, with a correction for the Nikkor 8mm lens.
1043.SUN	a direct sunlight distribution file for 10.43 degrees north, with a correction for the Nikkor 8mm lens.
1043.SUN	a direct sunlight distribution file for 10.43 degrees north, with no lens correction.
3690.SUN	a direct sunlight distribution file for 36.90 degrees north, with no lens correction.
3690N.SUN	a direct sunlight distribution file for 36.90 degrees north, with a correction for the Nikkor 8mm lens.
ISO.SKY	a diffuse skylight distribution file for equal zenith angle ranges, with no lens correction.
ISON.SKY	a diffuse skylight distribution file for equal zenith angle ranges, with a correction for the Nikkor 8mm lens.
NOSUN.WGT	a direct sunlight distribution weighting file, with equal weighting for all sun regions.
NOSKY.WGT	a diffuse skylight distribution weighting file, with equal weighting for all sky regions.
1043C.COR	a direct sunlight distribution cosine correction file for 10.43 degrees north latitude, with no lens correction.
1043CN.COR	a direct sunlight distribution cosine correction file for 10.43 north latitude, with a correction for the Nikkor 8mm lens.
ISOC.COR	a diffuse skylight distribution cosine correction file for equal zenith angle ranges, with no lens correction.
1043.GRD	a sun grid file for 10.43 degrees north latitude, with no lens correction.
1043N.GRD	a sun grid file for 10.43 degrees north latitude, with a correction for the Nikkor 8mm lens.
ISO.GRD	a sky grid file for equal zenith angle ranges, with no lens correction.
ISON.GRD	a sky grid file for equal zenith angle ranges, with a correction for the Nikkor 8mm lens.
PSEUDO.LUT	the pseudocolor display LUT file.

FILES FOR USE WITH SUN

SUN.EXE   the executable program *SUN*.

SUN.CNF   the configuration file for the program *SUN*.

FILES FOR USE WITH SKY

SKY.EXE   the executable program *SKY*.

SKY.CNF   the configuration file for the program *SKY*.

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