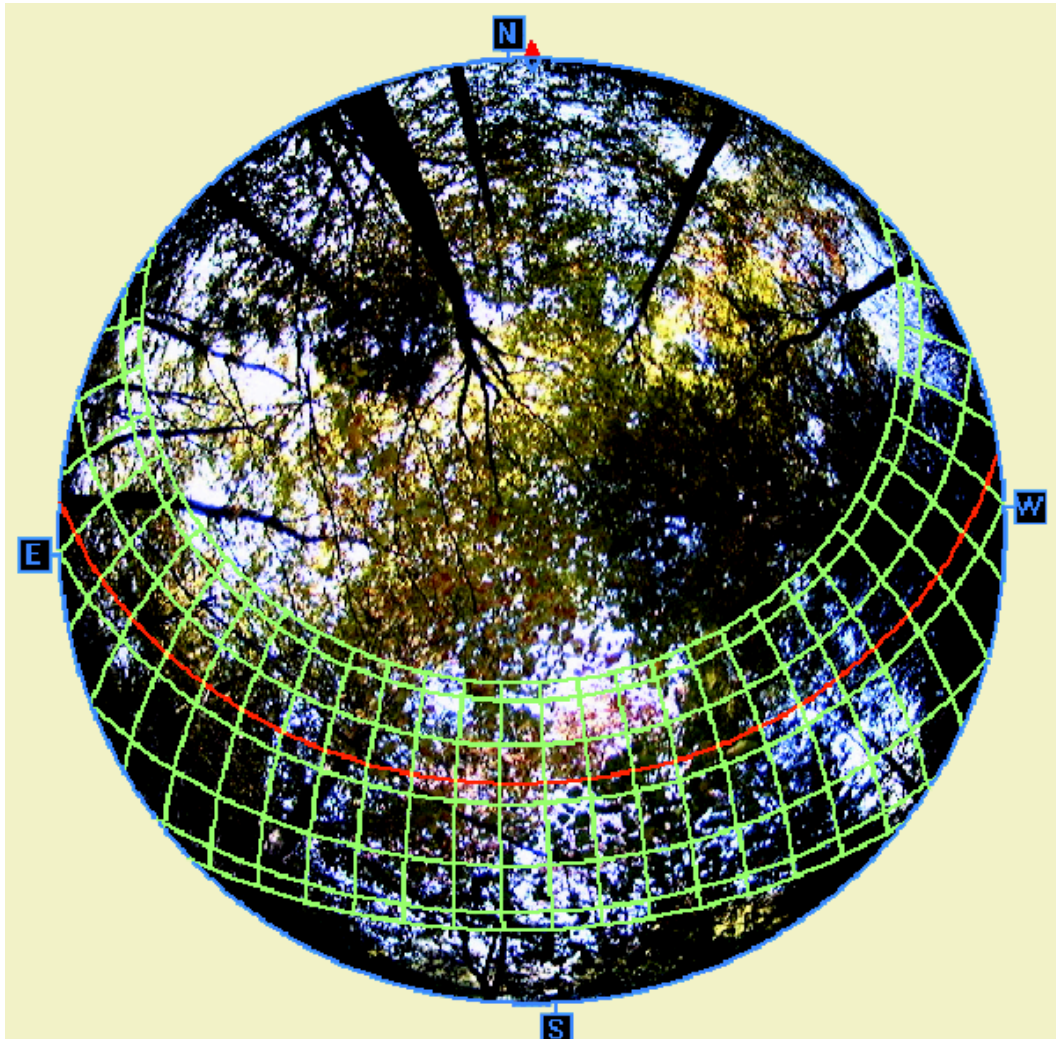

User Manual for

HemiView



Version 2.1

AT

DELTA-T DEVICES

Notes:

HemiView Manual Revision Number: 2.1

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Introduction

About this Manual

Use this manual to get started with HemiView.

It covers the following

Getting Started: Installing the software

Tutorial 1: Introduction to Hemispherical Photography – essential background for understanding and using HemiView effectively.

Tutorial 2: Using the HemiView Software – supplemented by comprehensive on-line help.

Tutorial 3: Field Protocols - about good experimental techniques.

Tutorial 4: Case Studies

Technical Support

Glossary of Terms

In addition to the above, the on-line Help includes sections on

Windows and Menu Commands

Calculations Theory

Files.

Features of HemiView

HemiView is a Windows-based program designed for convenient image analysis of hemispherical photography.

HemiView supports the following image file formats: Windows or OS/2 BMP (*.bmp), JPEG (*.jpg), PC Paintbrush PCX (*.pcx), TIFF (*.tif), TARGA (*.tga) and Photo CD(*.pcd).

Full Windows compatibility enables the user to place digital images and analysis results in the clipboard and to paste graphics and data directly in documents or graphics presentations.

Image display toggles between original and classified views, permits real-time display of negatives as positive images, and provides for overlay of skymaps, sunmaps, and daytrack maps.

A horizon circle marked with cardinal points and magnetic North, along with an interactive alignment mode enables precise registration of images with the hemispherical co-ordinate system.

Interactive image classification allows the user to adjust a threshold intensity value that distinguishes visible sky from sky obstructions, producing a classified image. The user can toggle instantaneously between a full colour display of the canopy photograph and a threshold display of the classified image.

Rapid calculations are made possible by HemiView's use of advanced algorithms to calculate gap fraction, contributions of direct and diffuse solar radiation from each sky direction, site factors, and leaf area index (LAI). Computation and results output generally require less than one minute on a Pentium computer. Typically, each image can be analysed in two to five minutes, including all steps of input, alignment, selection of a threshold, calculation, and output of results.

The results of analysis are output to a fully functional spreadsheet where they can be further analysed within the HemiView environment. Alternatively, the spreadsheet can be saved to disk as an Excel 5.0 compatible workbook for archiving or further analysis.

A large selection of options for calculated results permits users to custom design output suited to particular needs.

HemiView is fully configurable, such that a user can specify detailed site and lens characteristics for use in calculations.

Install HemiView

System Requirements

HemiView runs on 486 and Pentium computers. The following is a listing of system requirements:

Operating System:

Microsoft Windows NT v.4.0, Windows 95, Windows 98.

Memory (RAM):

Minimum: 16 Mbytes. **Recommended:** 32 Mbytes of RAM to improve calculation performance. Larger images require more RAM.

Storage (hard disk):

Minimum: HemiView requires approximately 10 Mbytes of free space for installation. **Recommended:** 20 Mbytes to 2 Gbytes. Considerable disk space can be required for handling images.

Video Display:

Minimum: 16 colour VGA **Recommended:** 800 x 600 24-bit true colour or 16-bit high colour display adapter with hardware accelerated panning. Superior operation can be achieved with a higher resolution adapter (e.g. 1024 x 768 true colour).

Other Features:

Mouse, trackball, or other pointer device (required); CD ROM drive (essential); writeable CD, tape backup, or other mass storage device (optional for archiving large image files)

Installing or Removing HemiView

The HemiView files include a program called Setup.exe which automatically installs HemiView on your computer. Once installed, a HemiView installation can be removed by following the simple procedure described below.

Installing HemiView

To run the installation program Setup.exe, which is provided on the HemiView distribution CD, do the following:

1. Start Windows. Insert the HemiView CD in an appropriate drive.
2. From the Start Menu, select Settings, Control Panel.
3. In Control Panel, double click on AddorRemove Programs.
4. In the Install/Uninstall tab, click the Install button and follow the on-screen instructions.

You will be prompted to enter the serial number. This can be found on the HemiView CD.

Uninstalling HemiView

To uninstall Hemiview:

1. From the Start Menu, select Settings, Control Panel.
2. In Control Panel, double click on Add/Remove Programs.
3. In the Install/Uninstall tab, highlight HemiView in the list of installed programs, click the Add/Remove button and follow the on-screen instructions.

Tutorial 1: Introduction to Hemispherical Photography

What is Hemispherical Photography?

Hemispherical photography provides an upward-looking view of all or part of the sky. Typically hemispherical images are acquired with either a standard film camera or a digital camera fitted with a hemispherical (fisheye) lens pointed upward. The resulting photographs provide a permanent record that can be analysed to determine which parts of the sky are visible and which parts are obstructed by landscape features, plant canopies, or human-built structures. Based on these measurements of the geometry of sky visibility and sky obstruction, hemispherical photographs can be used to calculate solar radiation regimes and plant canopy characteristics such as Leaf Area Index (LAI). Hemispherical photography can greatly expand the number of field sample measurements that are possible as compared with direct solar radiation sensor measurements or direct leaf area measurements. Computer analysis with HemiView, involving advanced digital image analysis techniques, enables efficient analysis of large numbers of photographs.

Hemispherical Photography as “Upside Down” Remote Sensing

Hemispherical photography can be thought of as “upside down” remote sensing. Hemispherical photographs can be analysed by hand or automated digital image analysis to precisely measure geometry and its implications. Once properly classified, hemispherical photographs literally provide a detailed map of sky visibility and obstruction. In turn, solar radiation regimes and canopy characteristics can be inferred from this map of sky geometry. In the case of plant canopies, a hemispherical photograph can be interpreted as a map of the directions of canopy openings relative to the location from which the photograph is taken. They can be inspected to provide insight into heterogeneity within a given canopy and to compare canopies at different sites.

Some Applications of Hemispherical Photography

Herein the term hemispherical photograph is used to refer to any extremely wide-angle, upward-looking image, generally with a 180-degree field of view, whether it is obtained from a film camera, a digital camera, or from a theoretical model. While this manual tends to emphasise using hemispherical photography to analyse plant canopies, and in particular forest canopies, the same principles apply for many other uses. For example, hemispherical photography can be used to analyse the influence of human structures such as buildings, to analyse the influence of topographic features such as mountains, or even to analyse the

influence of window placement within a room inside a building. Applications can be classified into two main categories:

environmental monitoring, modelling, and research for agriculture, forestry, micrometeorology, ecology, environmental science, and remote sensing;

design and site evaluation for architecture, planning, and engineering;

Hemispherical Images as Permanent Records of Sky Visibility and Obstruction

Hemispherical photographs provide a permanent record of the geometry of sky visibility and obstruction. Hemispherical photographs can be stored as negatives or transparencies, and/or as digital images. Film media have distinct advantages of relatively low cost and high resolution. Recent advances in digitisation methodology and storage devices, along with decreasing storage media costs now make it practical to create digital archives of hemispherical photographs. New technology (e.g. Kodak PhotoCD) provides a convenient, low-cost means for producing digital archives. As permanent records, hemispherical photographs can be studied using existing analytical methodology and saved for future study. Analogous to the way voucher specimens are collected for vegetation or floristic studies, hemispherical photographs can be collected and archived for comparative study of plant canopies.

Brief History of Hemispherical Photography

Hill (1924) first designed the hemispherical (fisheye) lens for view of the whole sky to study cloud formation. Later, architects used hemispherical photographs to assess “site factors” that estimate the solar radiation regimes at different positions within or near buildings. Foresters and forest ecologists conceived of using photographic techniques to study the light environment under forest canopies. In particular, Evans and Coombe (1959) estimated solar radiation penetration through forest canopy openings by overlaying diagrams of the sun track on hemispherical photographs. Anderson (1964, 1971) provided a thorough theoretical treatment for calculating the penetration of solar beam (direct) and scattered (diffuse or indirect) components of solar radiation from visible sky directions as determined using hemispherical photographs.

In recent years, many researchers have successfully used hemispherical photography to study solar radiation regimes and plant canopy architecture (see reviews in Chazdon and Field 1987, Rich 1988, 1989, Becker *et al.* 1989). Detailed treatments of field and analytical methodology have been provided by Pearcy (1989) and Rich (1989).

Until relatively recently, interpretation of hemispherical imagery has required tedious manual analysis using sampling grids. Jupp *et al.* (1980) first developed a computer program, PISCES, for analysis of hemispherical photographs, but PISCES still required manual photograph analysis and data entry. Automated image analysis was 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. Integrated image analysis systems based on DOS computers, in particular the systems CANOPY (Rich 1988) and SYLVA (Becker *et al.* 1989), were developed to use video for direct input of negatives. Most recently several Windows-based software packages have been developed, for example the program HEMISP (Vieglaiss unpublished).

HemiView benefits from and has many advantages over these prototype systems. These advantages include full Windows compatibility, lack of requirement for expensive specialised hardware, support of a full spectrum of standard image

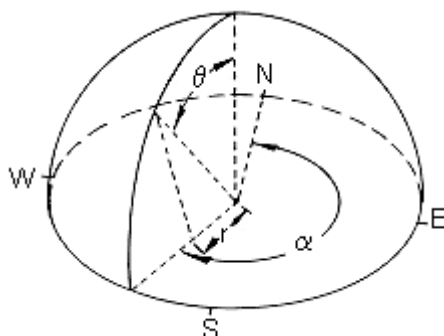
formats, rapid and accurate calculation, configurable output to spreadsheets, flexibility for incorporating site-specific information, expert technical support, and ongoing commitment to the research and development required for improvements and new capabilities.

Hemispherical Co-ordinate System

How Are Sky Directions Represented?

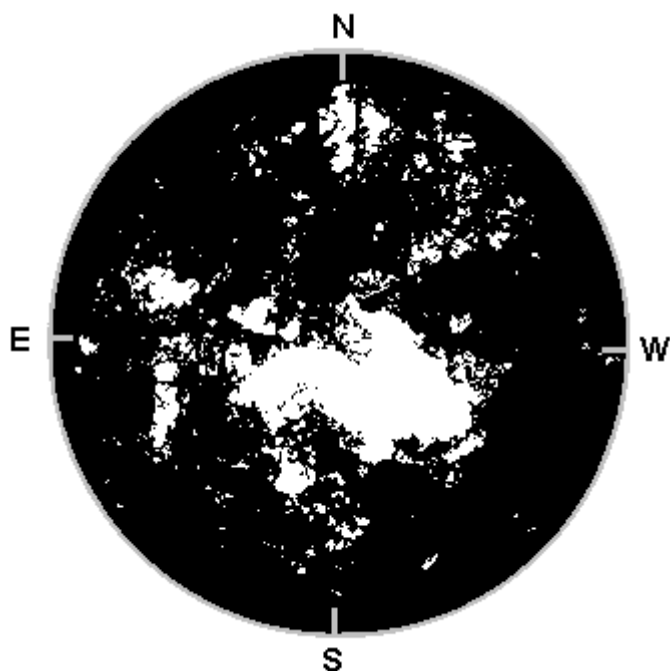
Hemispherical Viewsheds

Hemispherical photographs provide a hemispherical field of view, which, when looking directly upwards, corresponds to a “viewshed” of all sky directions. This hemispherical viewshed can be represented as an image by projecting the hemisphere of directions on a plane. Each position of the image corresponds to a sky direction. Sky directions are represented by two angles: the zenith angle θ (angle relative to the zenith) and the azimuth angle α (angle relative to true north). As its standard reference, HemiView uses an equiangular projection for a full 180-degree field of view.



Hemispherical Projections

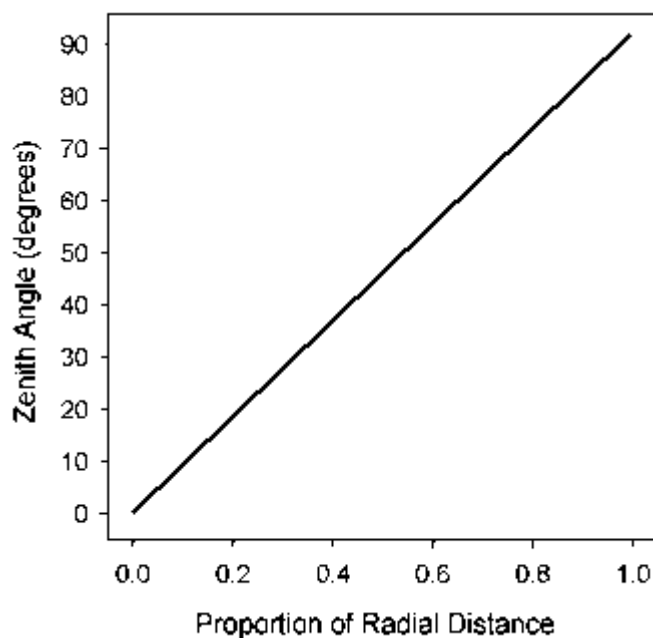
The resulting circular image (looking upward from beneath the hemisphere shown above) gives a complete view of all sky directions, with the zenith in the centre of the image and the horizons at the edges.



The hemispherical image above was taken in a treefall gap in the tropical rain forest of Costa Rica. Note that 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 the usual convention in maps because the view is upward rather than downward.

Equiangular Projections

In 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 axis within the image.



Other Hemispherical Lens Projections

More generally, any hemispherical lens produces an image in which the zenith is in the centre of the image, the maximum view angle is at the edges of the image,

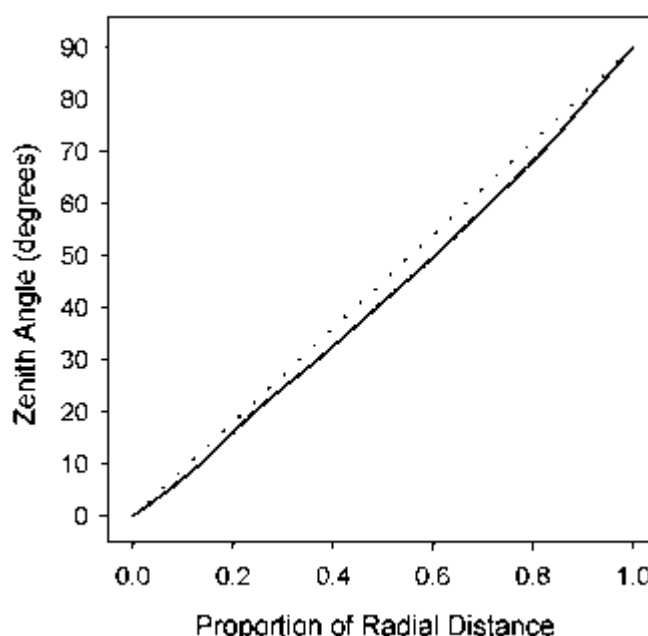
and intermediate locations represent intermediate zenith angles. It is possible to precisely locate any intervening sky direction in the resulting hemispherical photographs. HemiView accounts for the projection used by a particular lens by fitting a polynomial that translates location within the photograph to sky direction (represented by zenith and azimuth angle).

Lens Calibration

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 HemiView a polynomial is used to calculate the proportion of radial distance from the centre of the image as a function of zenith angle. The curve is constrained to pass through 0 and 90 degree zenith angles at radial distances of 0 and 1 respectively.

The following graph shows the lens calibration for the Sigma hemispherical lens. Note that the dotted line shows a perfect equiangular projection, while the solid line shows the Sigma lens projection.

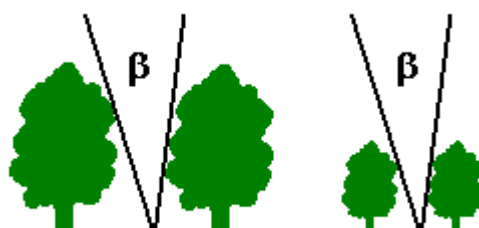
Note: The HemiView lens equations are expressed in radians not degrees



Why Hemispherical Photographs Represent Angles, Not Distance

Simply stated, each position in a hemispherical photograph represents a direction from the location where the photograph was acquired. Each position corresponds to a zenith, azimuth angle co-ordinate in a hemispherical co-ordinate system. Actual distance, such as heights of trees or diameters of treefall gaps can only be calculated if additional information is available, such as the height of the canopy. Distance in a hemispherical photograph corresponds to angles, not to actual distance. Within a photograph, the radial component of distance is proportional to zenith angle, and the distance in an arc at a fixed radius is proportional to azimuth angle. Area in a hemispherical photograph corresponds to angular area or along a hemisphere of directions. With supplementary measures of distance, or hemispherical photographs taken at known distances from each other, it is possible to determine distances using

standard trigonometry. Note how two canopies of different heights can have similar angles of openings, as shown below.



Basic Steps of Hemispherical Photography

The three basic steps of digital image analysis of hemispherical photography are image acquisition, digitisation, and analysis:

Image acquisition typically involves taking hemispherical photographs using a film camera looking upward from a location of interest (e.g. from beneath a plant canopy). Images may also be “acquired” by calculation using a simulation model that accounts for three-dimensional geometry.

Image digitisation typically involves conversion of a film photograph (an analogue format) into digital format. In the case of HemiView, film negatives can be digitised using a negative scanner, a video framegrabber, or other analogue to digital conversion device. In the case of digital cameras or video cameras connected to a framegrabber, image acquisition and digitisation are combined into one step, the analogue to digital conversion occurring at the time the image is acquired.

Image analysis involves four steps:

1. **classification of images** to distinguish visible and obscured sky directions (e.g. for canopies, to distinguish canopy openings from foliage);
2. **calculation of sky visibility and obstruction** as a function of sky direction;
3. **calculation of solar radiation and/or canopy indices** using this information about sky visibility and obstruction;
4. **output** of results.

Image Acquisition and Digitisation

Typically hemispherical photographs are acquired through standard film cameras and then negatives or positives are digitised using scanners, video digitizers, or other analogue to digital conversion technologies. Recently digital cameras present the possibilities to combine acquisition and digitisation in one step.

A primary challenge in image acquisitions is to obtain high contrast images with excellent distinction between visible sky and obscured sky directions. Another challenge is to ensure that the camera is properly oriented, such that the axis of the lens is pointed directly upward and the camera is oriented with magnetic north in a known direction.

See "

Classification of Images

Classification of images involves using digital image processing to distinguish visible and obscured sky directions. In the case of plant canopies this means distinguishing canopy opening from foliage.

Threshold Method

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, above which is classified as visible, and below which is classified as obscured. This technique is also known as segmenting an image, in that it divides a set of grey levels (intensity values) into a binary classification. The technique has the advantage that it is relatively simple to understand and use, but has problems that can result because of unevenness in the light conditions within images.

Successful classification depends upon having high contrast photographs in which foliage or other sky obstruction is consistently darker than visible sky directions. Problems arise if parts of the visible sky are darker than obscured sky directions (for example, dark clouds) or if parts of the obscured directions are brighter than the visible sky (for example, reflections on leaves). In practice, for canopies the technique involves a compromise between overestimating large areas of visible sky (large canopy openings) near the zenith and underestimating small areas of visible sky (small canopy openings) near the horizon. Within reason, images can be edited to compensate for dark sky regions or bright obscured regions using commercial image editing software such as the Paint program provided with Windows 95. This typically involves manually changing values for regions of an image and using flood routines to assist in classifying problematic portions of images.

In HemiView thresholds are determined interactively, such that a 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 visible or obscured sky edges of the continuous tone image. Subjectivity in the choice of thresholds is minimised by adopting strict protocols for deciding thresholds, by practice, and by use of high contrast images taken under even lighting conditions.

Other Methods

Other methods for image classification are various, and include the following. These are not provided by HemiView:

- modified threshold techniques that produce local thresholds for different portions of an image;
- modified threshold techniques that account for systematic differences in lighting conditions within different parts of the image (in particular brighter lighting in the centre as opposed to the edges);
- colour techniques, that use colour indices and/or advanced lookup table algorithms to classify images.

Compounding of Errors

For hemispherical photography, errors can occur at any stage of image acquisition, digitisation, or analysis. 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

performed with little error. Strict protocols should be developed and followed to prevent cumulative errors.

Sources of Error in Hemispherical Photography:

Camera position:

- horizontal and vertical position
- film plane levelling
- azimuth rotation

The degree of alignment accuracy required can be quite complicated to predict and depends on the application. The following can be intended to be used as a rough guide.

For LAI, site factors and global measurements the effect of 1 degree out from level or North alignment are going to be pretty small. Cosine corrections will be in error determined by the number of degrees out of level, and that part of the image below the horizon will not be measured or will be measured incorrectly.

If you are studying sunflecks and trying to match predicted and actual sunfleck patterns on a particular day then you have to be very accurately aligned. If your alignment is out by the equivalent of one solar disk (half a degree) then you will be in error for the calculated times and position of the sunfleck. In practice it is quite difficult to achieve half a degree accuracy in horizontal alignment, and so you should be as careful as possible.

The main point to remember is that you need a higher alignment accuracy for accurate sunfleck predictions than for broad global measurements such as LAI, site factors and gap fractions.

Exposure:

- sky lighting evenness
- foliage lighting evenness.

Reflections can occur if the sun is lighting-up the underneath of some of the leaves. This is one reason for taking pictures when the sun is just below the horizon. Glossy leaves can give reflections from bright portions of sky even when the direct sun is not visible.

Optical distortion

To a large extent Hemiview takes out optical distortions for the recommended lenses.

Image quality, resolution and digitisation

For a given image, the highest achievable resolution and colour depth are best. Digitising film will add some noise and lose resolution, but even so, good quality 35 mm film combined with the use of a high resolution scanner can be better than a lower resolution digital camera. This must be balanced against the benefit of real-time feedback from the use of digital cameras.

Alignment with co-ordinate system:

- horizon circle size
- x,y translation of horizon circle
- rotation relative to North

The error considerations are similar to those mentioned above for aligning the camera. The accurate registration of the horizon circle on screen requires some care.

Image Analysis:

- classification—distinguishing visible sky from obscured sky
- image editing/enhancement
- calculation assumptions.

The interactions between all sources of error are complicated and so it is not possible to give guidance on accuracy requirements for individual applications.

Indices Derived from Hemispherical Photographs

Hemispherical photographs can be analysed to derive a variety of useful indices:

geometric indices of visible sky and sky obstruction, in particular gap fraction as a function of sky direction;

solar radiation indices based on geometry and fundamental physical properties of solar radiation;

canopy indices such as leaf area index (LAI).

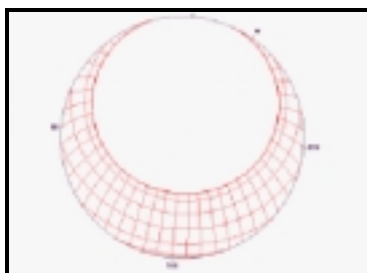
Gap Fraction

What is Gap Fraction?

Gap fraction is the proportion of visible sky within a given sky sector, where a sky sector is defined by a range of zenith and azimuth angles. All calculations, whether for solar radiation regimes or for canopy characterisation, ultimately depend upon dividing the sky into sectors and calculating gap fraction for each sky sector. A gap fraction of zero (0) means that the sky is completely blocked (obscured) in that sky sector. A gap fraction of one (1) means that the sky is completely visible (not obscured) in that sky sector.

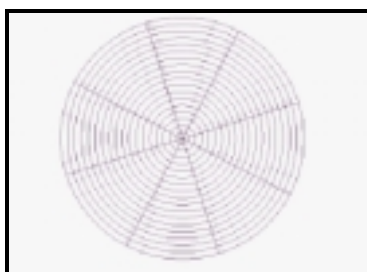
Gap Fraction for the Sunmap

Gap fraction along the path of the sun is derived by overlaying a series of solar tracks to produce a Sunmap of sky sectors defined by time of day and day of year and calculating the proportion of sky visible in each sky sector:



Gap Fraction for the Skymap

Gap fraction for any sky direction is derived by overlaying a grid of sky sectors defined by zenith and azimuth angle ranges to produce a Skymap and calculating the proportion of sky visible in each sky sector:



What do the Skymap and Sunmap represent

Although the Sunmap and Skymap are similar overlays, they have some important differences when used by Hemiview, especially for calculating radiation values.

The Skymap divides the hemiphoto into areas representing different directions, so shows variations in **space**. When combined with the incident diffuse radiation, it shows how the available diffuse light varies in space, and can be applied to either instantaneous radiation values, or values integrated over some time interval.

The Sunmap matches the track of the sun throughout the day, and through the year, so it divides the hemiphoto into areas representing **time**. When combined with incident direct radiation values it shows how direct radiation varies over time.

It is because of these differences that the Sunmap and Skymap use different units when radiation values are calculated.

Solar Radiation Indices

What are the Main Types of Solar Radiation?

Incoming solar radiation (insolation) can potentially originate from a visible sky direction as either of two types:

direct radiation – radiation passing unimpeded through the atmosphere from the sun; and

diffuse radiation – solar radiation that is scattered by the atmosphere.

One consequence of having visible sky in a given direction is that direct and diffuse solar radiation can pass unimpeded from that direction. On the other hand, obscured sky directions represent directions where solar radiation can not be transmitted directly, however reflected radiation can originate from canopy elements in those directions. Global radiation is defined as the sum of direct, diffuse, and reflected radiation reaching a particular location. Under most circumstances, the majority of insolation reaching a given location originates as direct or diffuse solar radiation transmitted from visible sky directions, as opposed to reflected radiation from surfaces in obscured sky directions.

Direct radiation for a particular site depends upon the relative position of the sun as it changes through the day and through the year, as well as upon atmospheric conditions. Diffuse radiation for a particular site depends upon the amount of incoming radiation that scatters from each sky direction. For any given period of time, global radiation reaching a location under a plant canopy is defined within HemiView as the sum of direct and diffuse radiation entering through canopy openings, and does not include reflected radiation off of surfaces in obscured sky directions. Analyses of hemispherical photographs commonly use indices expressed as the proportion of direct or diffuse solar radiation for a given location, relative to that in the open, known as direct and diffuse site factors respectively.

The Basic Model for Estimation of Solar Radiation

A reasonable estimate of radiation from direct radiation can be obtained by looking at the intersection between visible sky directions and the amount of direct radiation that can be expected from those sky directions. Similarly, a reasonable estimate of radiation from diffuse radiation can be obtained by looking at the intersection between visible sky directions and the amount of diffuse radiation that can be expected from those sky directions.

In this basic model, as viewed from beneath a plant canopy, foliage absolutely blocks incoming radiation and canopy openings allow radiation to pass unimpeded. Radiation reflected by or transmitted through foliage is ignored. Direct radiation is calculated by multiplying the gap fraction of a sunmap sector by the radiation originating from that sky sector, and correcting for angle of incidence. Similarly, diffuse radiation is calculated by multiplying the gap fraction of a skymap sector by the radiation originating from that sky sector, and correcting for the angle of incidence.

What is Angle of Incidence?

The angle of incidence is the angle between a surface and incoming radiation reaching the surface, measured relative to the direction normal to the surface. The amount of radiation reaching the surface is proportional to the cosine of the angle of incidence. Thus radiation originating at a right angle to the surface has an angle of incidence equal to zero, a cosine of one, and receives the full amount of radiation; whereas radiation originating parallel to a surface has an angle of incidence of 90-degrees, a cosine of zero, and receives no radiation from that direction. HemiView accounts for angle of incidence by multiplying radiation originating from each sky sector (diffuse or direct) by the cosine of the angle of incidence from the centroid of the sky sector to the surface.

Within HemiView, the intercepting surface can be set to any orientation. It would typically be set to horizontal (Zenith = 0, Azimuth = 0) to give results comparable to measurements made with levelled cosine-corrected sensors. However there are cases, e.g. modelling the response of individual leaves, where it is appropriate to set the intercepting surface to the same orientation as the surface being studied.

What are the Units of Solar Radiation?

Solar radiation flux can be variously expressed, in terms of energy flux or in terms of Photon Flux Density (PFD):

Energy flux is commonly measured in units of megajoules per square meter per second ($\text{MJm}^{-2}\text{s}^{-1}$).

PFD is commonly measured in micromoles per square meter per second ($\mu\text{mol m}^{-2}\text{sec}^{-1}$). These are also known as microEinsteins (μE)

PAR and Other Wavelengths of Interest

For study of energy balance, it is common to study all wavelengths of solar radiation, termed **total radiation**. 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)**.

Site-Specific Solar Radiation Values

Considerable variation in solar radiation regimes occurs between sites, even at the same latitude. Further, energy flux, PFD for total radiation, and PPFD are not always linearly proportional. Site-specific distributions of diffuse and direct radiation can be formulated accordingly using empirical or theoretical insolation values appropriate for a particular site. Long-term monitoring of direct and diffuse radiation for a given site can be accomplished using pyranometers (for total radiation) or quantum sensors (for PAR) attached to data loggers. For detailed studies, two sensors are required, one to monitor global radiation flux and a second to monitor diffuse radiation. The diffuse radiation sensor must be fitted with a shadowband to block radiation along the sun path. Direct radiation is calculated as the difference between observed global radiation flux and diffuse radiation flux. The Delta-T BF2 Sunshine Sensor has been designed specifically for this purpose.

Site Factors from Hemispherical Photographs

What are Site Factors?

Site factors are indices of the proportion of radiation reaching a given location. Values range from 0 to 1, with 0 being no radiation (complete sky obstruction) and 1 being the radiation for an open location (complete sky visibility = no sky obstruction).

Indirect site factor (ISF) is the proportion of diffuse solar radiation reaching a given location, relative to a location with no sky obstructions (“diffuse site factor” of Anderson 1964).

Direct site factor (DSF) is the proportion of direct solar radiation reaching a given location, relative to that in a location with no sky obstructions.

Global site factor (GSF) is the proportion of global radiation (direct plus diffuse) under a plant canopy relative to that in the open (“total site factor” of Anderson 1964).

ISF and DSF can readily be estimated from canopy photographs, given assumptions about the contribution of diffuse and direct radiation from each sky sector. GSF can be estimated if we have an estimate of the relative proportions of diffuse and direct radiation in the open, either determined empirically or theoretically.

Converting Site Factors to Energy Flux, PFD, or PPFD

ISF, DSF, and GSF can be considered to be proportional estimates of energy flux, PFD for total radiation, or PPFD, and 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.

Leaf Area Index from Hemispherical Photographs

What is Leaf Area Index?

Leaf area index (LAI) is widely used to describe the photosynthetic and transpirational surface of plant canopies. LAI can be simply defined as the amount of leaf surface area per unit ground area, and has broad applications in ecophysiology, water balance modelling, and characterisation of vegetation-atmosphere interactions. In recent years, many researchers have adopted the definition of LAI as half of the total leaf area per unit ground surface area (Lang et al. 1991 and Chen and Black 1992), as opposed to the projected area, which does not work well for all leaf shapes.

Hemiview algorithms will estimate LAI as half of the total leaf area per unit ground area.

LAI Models

Inversion Models

Calculation of LAI involves use of Beer’s Law, which can be expressed as follows:

$$G(\theta) = e^{-K(\theta)L}$$

where:

G is gap fraction,

K(θ) is the extinction coefficient at angle θ, and

L is LAI, θ is zenith angle.

Calculation of LAI involves a kind of iterative “inversion” model, whereby LAI is inferred from the observed distribution of gap fraction as a function of zenith angle. These models are termed inversion models because they work backwards, in that instead of inferring a pattern of gap fraction resulting from a particular distribution of leaves in a canopy they infer the pattern of leaf distribution from the pattern of gap fraction. While the former (forward) model can be solved analytically, the latter (inverted) model requires an iteration of approximate solutions that converge upon a satisfactory solution.

Assumptions of LAI Models

Calculations of LAI assume a random distribution of canopy elements, such that gap fraction should be observed for a small enough annulus that randomness can be assumed. LAI calculated in this manner is sometimes termed “effective LAI” (LAI_{eff}), since it does not account for non-random distribution of foliage. Chen et al. (1991) suggests that a clumping factor can be used to account for this non-random distribution, such that LAI_{eff} is simply multiplied by a stand-specific clumping factor to calculate a more realistic LAI. In practice, LAI and LAI_{eff} are nearly identical in broadleaf canopies (i.e., clumping factors are near unity); however, in conifer canopies, where there is strong clumping, it becomes necessary to estimate the clumping factor by either direct or indirect means (Chen and Cihlar 1995, Chen et al. 1995).

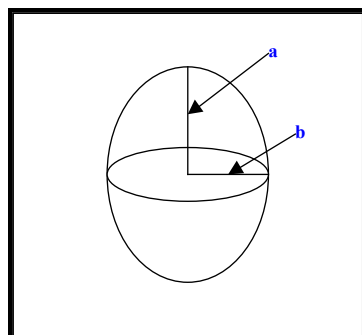
The LAI estimated by the inversion process may not be an exact measure of the LAI of the real canopy, even if that could be measured accurately. However, an ideal canopy with the LAI estimated will behave in a very similar way to the real canopy as far as radiation interception is concerned.

Leaf Angle Distribution

The same models that permit calculation of LAI also permit calculation of leaf angle distribution. Leaf angle distribution refers to the distribution of LAI between leaves of each angular orientation.

HemiView LAI Calculations

Introduction



Campbell(1986) derived an equation for the extinction coefficient of canopy elements distributed in the same proportions and orientation as the surface of an ellipsoid of revolution, symmetrical about a vertical axis. The semi vertical axis is **a** and the semi horizontal axis is **b**. There is symmetry about the vertical axis. He relates these to a single parameter $x=b/a$. (x is the Ellipsoidal Leaf Angle Distribution Parameter, or ELADP). The extinction coefficient also depends on the zenith angle of the incoming direct beam. Canopy elements are assumed to be completely black, and randomly distributed in a horizontal slab extending to infinity in all directions. This model can be used to represent a wide variety of different canopies by choosing an appropriate LAI and ELADP. An ELADP greater than 1 represents a canopy where the elements are predominantly horizontal, and less than 1 represents a canopy where the elements are predominantly vertical.

Hemiview LAI Inversion

Hemiview finds the values of LAI and ELADP for an ellipsoidally distributed theoretical canopy that give the best fit to the measured gap fraction values from the hemiphot. These best fit values are then used as a basis for subsequent calculations in the LAI group. This gives a robust and widely applicable result, but will not necessarily accurately reflect particular cases, such as bimodal distributions (where the canopy is a mix of two very different types of canopy element).

HemiView estimates the effective LAI, so this value may need to be multiplied by a clumping factor to give an accurate estimate of actual LAI.

Analysis of partial images

There are situations where users may wish to ignore part of an image from the analysis, e.g. if the horizon is not entirely within the image area, or part of a building or crane is visible, or to exclude trunks and branches from a LAI estimate. Hemiview allows you to paint parts of an image in a colour which is then ignored by the hemiphot analysis. Areas ignored in this way can be visualised as an additional mask between the sky hemisphere and HemiView. Gap fractions, site factors and LAI are calculated using only the information in the valid part of the image. Radiation values, both above and below the canopy, are reduced by the amounts that would have come from the ignored areas.

Tutorial 2: Using HemiView

Set up your work folders

The HemiView installation program creates a directory named Samples under the HemiView installation directory, and a Windows shortcut which will start up HemiView in the Samples directory.

The Samples directory contains the files you will need for this tutorial. Two of them are image files: Sample1.jpg, and Sample2.jpg.

There is also a third file in your Sample folder, called Sample2.hvs. This is not an image file. Later in the Tutorial you will be asked to load it. It is a 'HemiView Settings' file created by using the **File, Save** command. It contains information about the Sample2.jpg image file, but does not actually contain a copy of the image itself.

A point to remember when organising your work folders: HemiView always needs the image file to be available in the same folder as the .hvs file.

Starting HemiView in your Working Directory

When you are working on "real projects" it is good practice to create a working directory on your hard drive for your work. That is, keep your data separate from the actual HemiView program.

You will probably want to create or modify a HemiView icon which starts up HemiView in your working directory.

1. Highlight the HemiView icon and click the right mouse button to display the icon's popup menu.
2. From the popup menu select Properties.
3. Select the Shortcut tab, and enter the name of your working directory in the Start In box.

Start up

HemiView can also be started by double clicking a .hvs file, in Windows Explorer or dragging and dropping an image, .hvs or .xls file icon onto a HemiView icon (or its shortcut) icon

Start HemiView either by choosing HemiView in the **Start, Programs** Menu or by double-clicking on a desktop shortcut to HemiView.

Toolbars



Toolbars provide quick mouse access to many tools used in HemiView. Typically toolbars are displayed across the top of the application window, below the menu bar. Toolbars can also be moved by dragging the border of the toolbar to the desired location while holding down the left mouse button.

To display or hide toolbars, choose **View, Toolbar** and click toolbars to be displayed or hidden. A check mark or tick appears next to each toolbar that is displayed.

Standard Toolbar

Contains buttons for file management, editing, printing and help:



New – create a new workbook (menu command: **File, New**).



Open an existing workbook or image. HemiView displays the Open dialog box, in which you can locate and open the desired file (menu command: **File, Open**).



Save the active image or workbook with its current name. If you have not named the document, HemiView displays the Save As dialog box (menu command: **File, Save**).



Cut highlighted cells from the workbook and store it on the clipboard (menu command: **Edit, Cut**).



Copy the image or highlighted workbook cells to the clipboard (menu command: **Edit, Copy**).



Paste the contents of the clipboard into a workbook at the insertion point (menu command: **Edit, Paste**).



Print the active workbook or image (menu command: **File, Print**).



About HemiView. Displays version number, your serial number, license and copyright information.



What's This? Displays context sensitive help about the program area under the mouse when you click the left mouse button.

View Toolbar

Contains buttons for controlling the display of images:



Toggle the displayed **Image** on and off (menu command: **View, Show Image**).



Toggle between **Negative** and normal images display (menu command: **View, Negative**).



Toggle between **Classified** and full colour image display (menu command: **View Classified**).



Toggle the **Skymap** overlay on or off (menu command: **View, Skymap**).



Toggle the **Sunmap** overlay on or off (menu command: **View, Sunmap**).



Toggle the **Daytrack** overlay on or off (menu command: **View, Daytrack**).



Toggle the **Alignment** overlay on or off (menu command: **View, Alignment**).

Calculate Toolbar

Contains buttons for working with calculations:



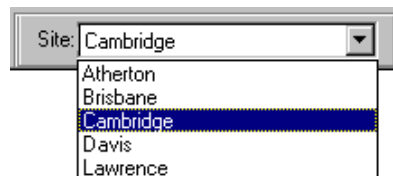
Calculate results using the selected image, current alignment, and other settings.ns, fcheck you have an image open and selected.



Toggle between the **Image** and an associated **Workbook** (menu command: **Window, Image** and **Window, Workbook**).

Site List Toolbar

Typical view of Site List toolbar:



The Site List toolbar allows you to select a site for the image in image window provided that image window is active (menu command: **Settings, Site, Select**).

Click on the toolbar with the right mouse button to bring up a menu which allows you to add and delete sites to the site list, and to examine and modify the properties of the current site.

Lens List Toolbar

Typical view of Lens List toolbar:



The Lens List toolbar allows you to select a lens name from the list of available lenses (menu command: **Settings, Lens, Select**).

Click on the toolbar with the right mouse button to bring up a menu to examine and change lens properties.

Day of Year Toolbar

Typical view of the Day of Year toolbar:



The Day of Year toolbar allows you to select an active day of year for drawing daytracks and performing time series or sunfleck calculations (menu command: **Settings, DayTrack tab**).

Drag the slider, or click the up or down buttons, or type a Day of Year value directly into the edit box.

The day is part of the current output configuration, so using the Day of Year toolbar modifies the current output configuration.

Threshold Toolbar

Typical view of the Threshold toolbar:



The Threshold toolbar allows you to decrease or increase the classification threshold for the active image (menu command: **Settings, Classifier**).

Alternatively you can click the up or down buttons, or type a threshold value directly into the edit box.

Whenever the active window is an image window, you can also use the **+** and **-** shortcut keys to change the threshold. Hold down **Ctrl** and press **+** or **-** to change the threshold in larger steps.

Solar Models Toolbar

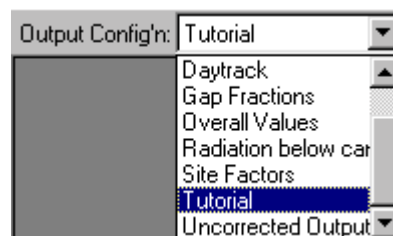
Typical view of the Solar Models toolbar.



The Solar Models toolbar allows you to select a choice of solar models representing the transmission of solar radiation through the earth's atmosphere. These can be edited and inspected in detail via the menu command **Settings, Solar Model**.

Output Configuration Toolbar

Typical view of the Output Configuration Toolbar

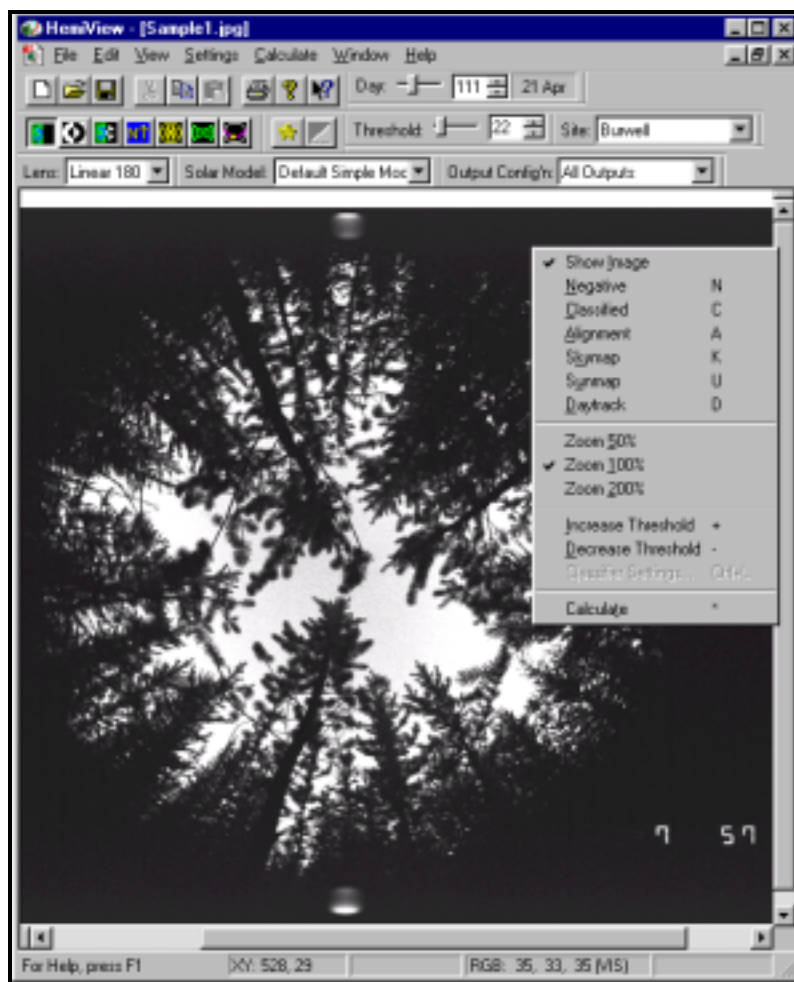


The Output Configuration Toolbar allows you to select from a predetermined list of Output Configurations, each of which may represent a different combination of calculation settings and Output Sheets. These may be inspected in detail and edited via the menu command **Settings, Output Configuration**.

Open an Image

HemiView can handle several standard image file formats. Choose **File, Open**. Select the file **Sample1.jpg** from the Samples directory (under the HemiView installation directory) and open it. (This is a greyscale image from a JPEG format file scanned in from a 35 mm black and white film.)

The image opens in its own image window.



Sample1.jpg also showing a pop-up menu enabled by clicking right mouse button.

Observe that various toolbars have now become available for the display and analysis of images.

Reduce the size of the image window. Try reducing the image down to an icon.

Enlarge the image window to fill the entire available area.

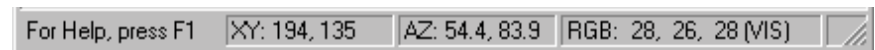
Right click somewhere on the image and observe the pop-up menu appear, as shown above. This pop-up menu duplicates some of the commands in the main menu, and also shows shortcut keys as follows.

Negative	N
Classified:	C
Alignment:	A
Skymap:	K
Sunmap:	U
Daytrack:	D

The visible sky in this image is fairly uniform. Later in this tutorial, when you come to "classify" the image by setting a threshold grey scale level representing the boundary between clear and obstructed sky, you will need the sky illumination to be as uniform as possible. When classifying the image you will not want large variations in brightness in the sky, and so you particularly will not want to see the sun in the photo! The problem is that an obstruction, such as a leaf, in bright sunlight in one part of the sky may appear brighter than a dull part of the visible sky somewhere else.

The best time to take pictures is before sunrise or after sunset or on a day when the sky is uniformly overcast with cloud.

Move the mouse pointer over the image and observe the values changing in the Status Bar at the bottom of the window:

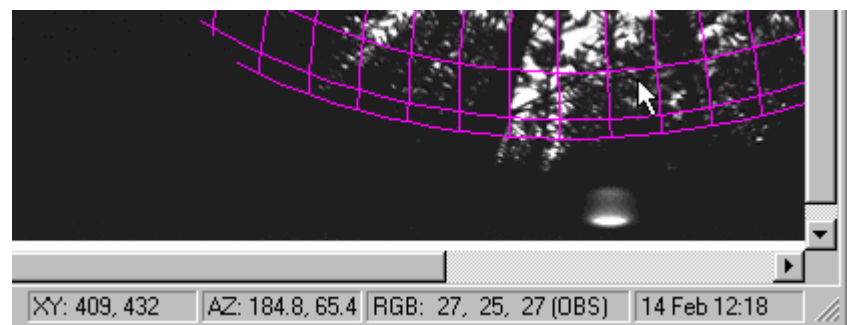


The status bar presents detailed information about each pixel under the pointer.

- **XY:** X,Y co-ordinate of the cursor (shown as 194,135 pixels from the top left of the picture).
- **AZ:** azimuth and zenith angle co-ordinates, in degrees.
- **RGB:** Red, Green, Blue intensity value (0,0,0 is black, 255,0,0 is bright red, 255,255,255 is white), plus an indication of whether the pixel, when classified, represents obscured (OBS) or visible (VIS) or ignored (IGN) sky.

Display the **Sunmap** and move the pointer over it.

- If the pointer is over over a section of the sky covered by the sunmap, then a date and time is displayed representing the time of year when the sun would appear at that location. Of the two times in the year when the sun will appear at each location, the date and time is shown for the half-year which contains the day of year shown in the Day of Year toolbar.



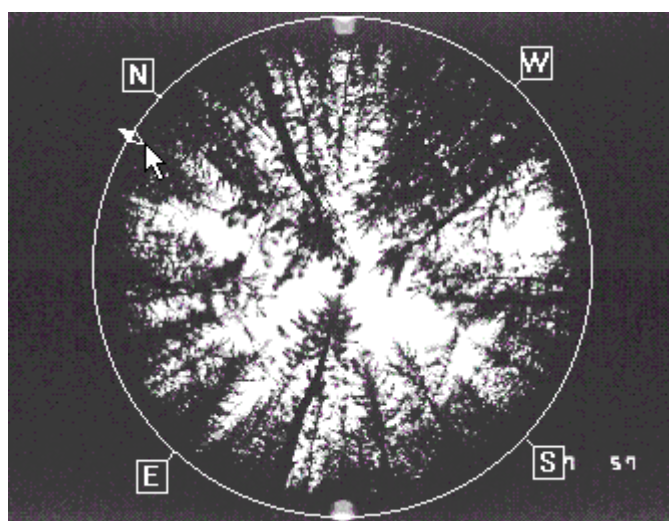
Next we need to align the image.

Align Image

It is necessary to align the image with the hemispherical co-ordinate system, so that HemiView knows where to find North and the horizon. This is all needed for the calculations.

The alignment overlay shows the location and geographic orientation of the horizon circle.

1. Turn the alignment overlay on. There are several ways of doing this:
 - Press the **A** shortcut key.
 - Right click on the image and left click on Alignment in the pop up menu.
 - Click on the toolbar button 
 - Select the **View, Alignment** command.



Alignment overlay, as it might appear before aligning. It shows the horizon circle, with the four cardinal points N,S,E & W and the magnetic North symbol - next to the pointer at about 10 o'clock. The LEDs are clearly visible at 12 and 6 o'clock. The digits at bottom right, added by the camera can be very useful for identifying pictures.

The actual horizon is defined as a circle at the 90 degree zenith angle.

The alignment overlay shows a horizon circle marked with the four compass directions (N, E, S & W) and a compass needle indicating magnetic north.

Note that East is to the left of North and West to the right in hemispherical photographs, since they are taken looking upward.

If you cannot see the alignment overlay it may simply be the wrong colour.

To change the colour of the horizon circle:

- a) Select the menu command **Settings, Appearance**
 - b) In the **Appearance** tab click on **Alignment**
 - c) In the **Color** dialog select a bright colour such as yellow
 - d) Click **OK** to return from the **Color** dialog to the **Alignment** tab, and **OK** again to return to the image.
2. Move the mouse pointer around the circle and observe how the symbol changes.

Every 45 degrees from the top of the circle the pointer becomes a double-headed arrow pointing towards and away from the centre of the circle. This indicates that you can now resize the horizon circle.

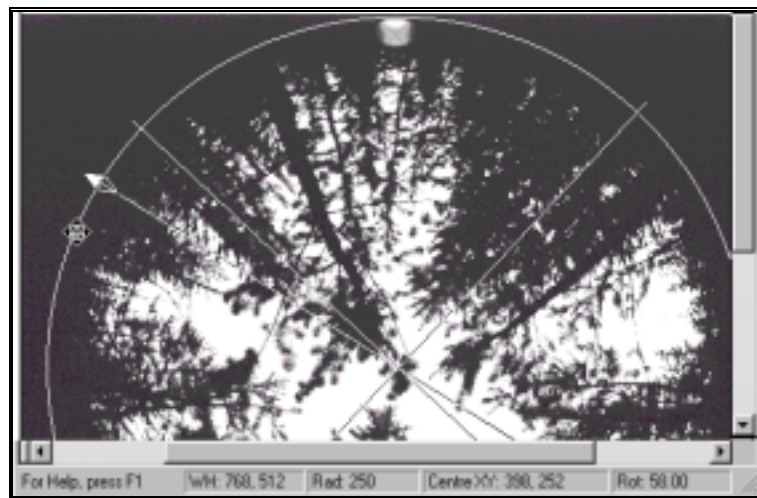
3. Hold down the left mouse button and drag the horizon circle to the required size.

In between, the pointer becomes a 4-headed arrow symbol indicating you can move the circle by dragging.

Immediately outside the horizon circle on the compass needle and on the N, E, S, W markers, the pointer changes to a double headed arrow pointing along the circumference of the circle. This indicates that you can rotate the horizon circle by dragging.

Try these operations, holding down the left mouse button and dragging the horizon circle.

4. While dragging the horizon circle, observe how the status bar changes to present detailed information about the image alignment:



WH: width and height of the image

Rad: radius of the horizon circle

Centre XY: X,Y co-ordinates of the centre of the horizon circle

Rot: the rotation of the image, measured in the direction of increasing azimuth angle, i.e. anti-clockwise when looking up at the sky.

You can also adjust the size and position of the horizon circle using shortcut keys, as follows:

5. Hold down the **Shift** key and press one of the keyboard **arrow** keys to move the horizon circle.

6. Hold down **Shift** and **Alt** and press the **up** or **down arrow** keys to adjust the size of the horizon circle

7. Hold down **Shift** and **Alt** and press the **left** or **right arrow** keys to adjust the rotation of the horizon circle.

8. Add the **Ctrl** key to the above key strokes to make larger movements

In the picture file Sample1.jpg the direction of magnetic North and South is indicated by two small dome-shaped lights on the horizon. In this picture these were created by two LEDs (Light Emitting Diodes) mounted on the camera's self-levelling mount.

Unfortunately, in this picture, both LEDs look the same, so it is impossible to figure out which one is North!

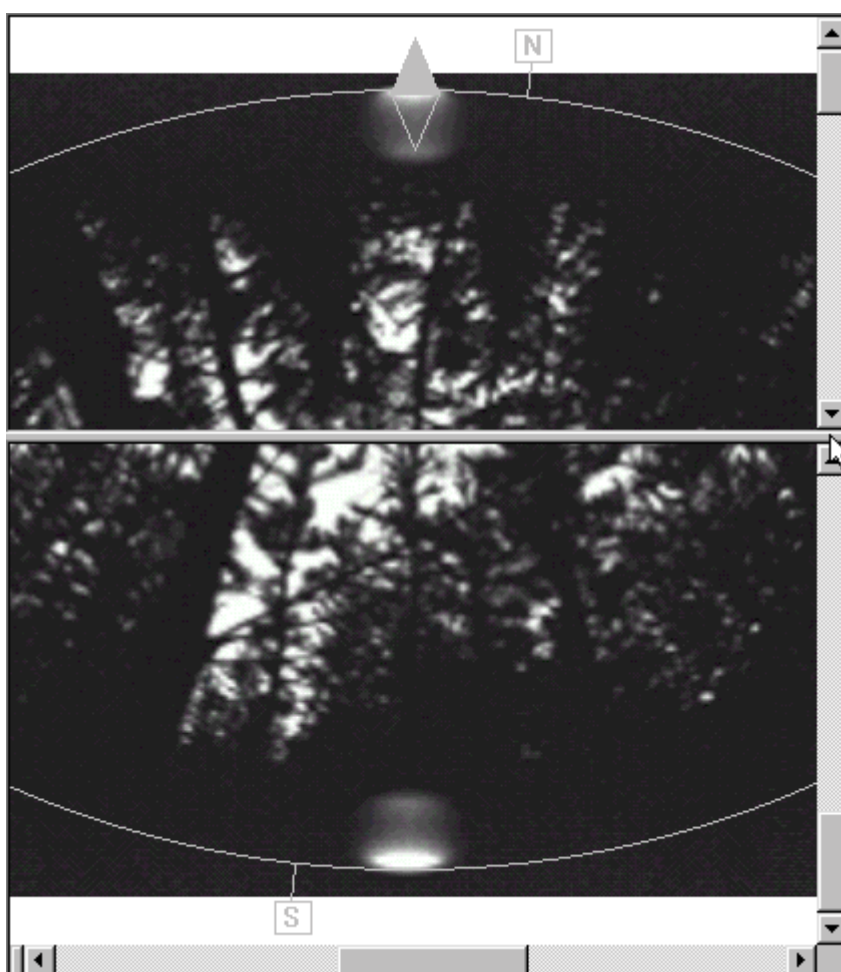
For the purposes of the tutorial we will assume that the LED at 12 o'clock was oriented towards Magnetic North with a compass.

For future reference - if you have two identical LEDs on your camera, do not remove the south light, because it helps define the horizon circle. Instead, change the shape in some way, for instance, by wrapping a wire around it, or using a dab of paint, or carefully filing it.

Note: North is indicated by the triangular shaped light source on digital photos created using the Delta-T self-levelling mount for the Nikon Coolpix camera.

9. Rotate the image, dragging the triangular compass indicator around to the light at 12 o'clock.

When aligning images you may find it helpful to use magnify the image using the **View, Zoom** command and to split the Window into two using the **Window, Split** command., as shown below.



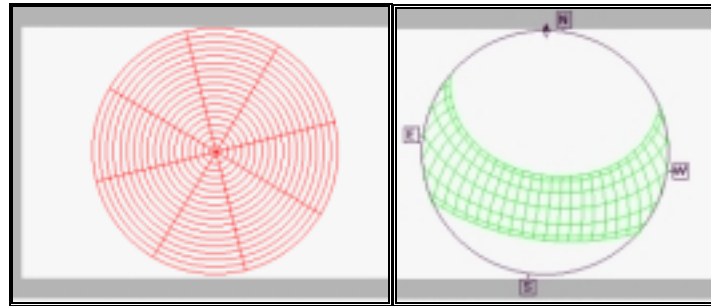
10. Adjust the size and location of the circle so that it is centred, correctly marks the horizon, and is correctly oriented to the compass directions.

The angle between magnetic and true North, the magnetic declination, is a property of the site selected for the image and is defined via the **Settings, Site Properties** command. We will come to this later in the tutorial.

HemiView stores information about the alignment of an image in its associated .hvs file.

Overlay Skymap, Sunmap and Daytrack

HemiView can overlay various types of graphics on hemispherical images, including the alignment overlay, skymap overlay, sunmap overlay, and daytrack overlay.



The skymap (left) covers the whole sky. The sunmap (right) covers the path of the sun through the whole year (the alignment overlay is also shown)

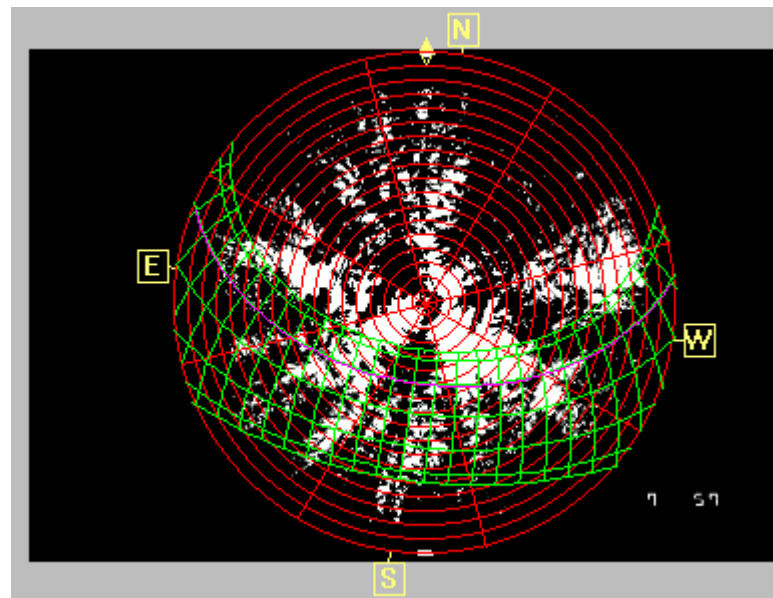
The daytrack overlay (not displayed here) shows the path of the sun on one day

These overlays are useful for examining patterns in the images, for example: how the sunmap coincides with canopy openings.

In addition, HemiView allows you to display:

- negative images as positives
- overlays without images
- classified images.

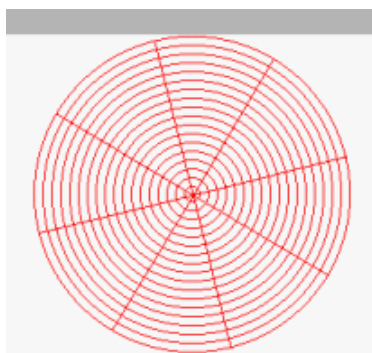
Overlays are useful when producing illustrations, which can then be copied and pasted in other applications or printed.



All overlays shown

1. Select **View, Negative**. Observe that a negative of the image is displayed. Uncheck the negative mode and observe that the display changes back to a positive display.

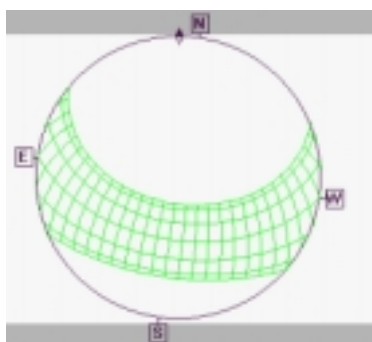
2. Select **View, Alignment** . Observe that this choice toggles off the alignment overlay. Turning this off can be useful when producing graphical illustrations. Toggle the alignment overlay on again.



3. Toggle on the skymap overlay using .

The Skymap divides the whole sky into sky sectors, and is used for calculations of diffuse solar radiation, ISF, and LAI, all of which require information about all sky directions.

Select **Settings, Skymap** and observe the current settings. Set the azimuth divisions to 16 and the zenith divisions to 30 and click **OK**. Observe how the skymap overlay changes. Set the azimuth divisions to 8 (45-degree divisions) and zenith divisions to 18 (5-degree divisions) and click **OK**. This is the setting typically recommended for analysis of hemispherical photographs. Observe how the skymap overlay changes. Toggle the skymap overlay off.



4. Select **View, Show Image** to toggle the image display off. Observe that the Sunmap Overlay remains on. This feature can be useful to produce graphical illustrations of overlays without having to load a blank image. Select **View, Show Image** again to redisplay the image.

Toggle off the Sunmap Overlay using the  button.

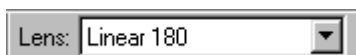


5. Toggle on the daytrack overlay using the  button. Observe the value in the Day of Year toolbar. Toggle the daytrack overlay off. Experiment with entering different values in the Day of the Year toolbar and their effect on the daytrack overlay. The daytrack overlay enables examination of the path of the sun on any given day through the year.

Lens Selection

Lens information is used by HemiView to correct for any distortions in mapping from the zenith angle in 3 dimensions to the radius on the two dimensional image.

HemiView allows you to specify the type of lens used to create the image, either by using the Lens toolbar, or by using the **Lens** command in the **Settings** menu.



1. Select the **Settings, Lens** command. In the Select Lens dialog observe which lens is currently selected. If not already selected, highlight "Linear 180" from the list and click **OK**. This is suitable for a Nikon SLR 8mm lens.

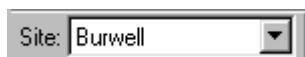
2. Toggle on the skymap overlay with the  button. Observe the pattern of annuli. Leave the skymap overlay on.

3. Select the Sigma 8 mm lens from the Lens List. Observe as the image overlay is updated and redrawn. The Linear 180 and Sigma lenses differ only slightly in their characteristics. Can you detect a difference in the position of the annuli? Leave the setting with the on Sigma 8 mm lens selected.

Site Properties

In this section we select a site and observe the effect of changing site properties.

These include latitude, longitude, magnetic declination and altitude. Use the commands in the **Settings, Site** menu or the Site List Toolbar to choose the site for an image, change the properties of a site, or add a new site to HemiView's Site List .



1. From the Site List select the “Burwell”. Bring up the Site List popup menu by placing the mouse pointer on the Site List toolbar and clicking the right mouse button. From the popup menu select **Properties**. Examine its properties. Press Cancel after you have finished examining the properties.



2. Turn on the sunmap by clicking the  button.
3. Select other sites from the Site List toolbar. Examine the properties of each, and observe how the sunmap changes, depending on the latitude.
4. Observe how the magnetic north marker remains fixed on the LED while the position of true north varies with the magnetic declination of the site.
5. Select the **Settings, Site** command and choose **New**. Enter the following settings: Site Name: Wild Place, Latitude: 10.5 West, Longitude: 20.3 South, magnetic declination: 30.1 West , altitude: 200, Description: test location. Click **OK** and examine how the sunmap overlay shifts.
6. Scroll through the Site List using the Site List toolbar and observe that Wild Place has been added to the list.
7. To delete the site, select Burwell for the active image (HemiView won't allow you delete a site which is in use by an image). From the Site List popup menu select **Delete**. In the **Delete Site** dialog, highlight Wild Place and click **OK**. Scroll through the sight list and observe that Wild Place is no longer in the list.



8. Turn off the sunmap overlay by clicking the  button again.

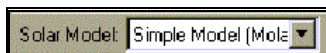
Solar Model

HemiView uses a model to estimate how much solar radiation will be received, both directly from the sun and diffuse radiation from the whole sky, and over the whole period of interest. This could be a day, a month or a year.

HemiView's solar model calculates solar radiation conditions from the 'solar constant' (the quantity of solar radiation incident on the surface of the earth's atmosphere), and two numerical values which characterise local atmospheric conditions: the fraction transmitted to the earth's surface (sea level, with the sun at the zenith), and the proportion scattered to become diffuse light (the remainder being reflected).

Combining these with the latitude, altitude and date and time, HemiView calculates how much of the direct beam will be scattered or absorbed on its way to the surface and how much will be seen as scattered light from the rest of the sky.

As with sites and lenses, use either the commands in the **Settings, Solar Model** menu, or the Solar Models toolbar to choose a solar model, change the properties of a solar model, or create a new solar model.



1. From the Solar Models toolbar select Default Simple Model.
2. Bring up the Solar Models popup menu by placing the mouse pointer on the Solar Models toolbar and clicking the right mouse button. From the popup menu select **Properties**. Examine the three tabs in the **Solar Model Properties** dialog.
3. Observe that Energy units are selected on the **Solar Model** tab. You may choose Molar units, which are appropriate for many plant scientists. Alternatively you may prefer to select Energy in Watts m⁻².
4. Select the **Solar Transmission** tab and observe that the simple transmittance model requires three values: a transmittivity value - the amount of direct beam transmitted through unit atmospheric depth (typically between 0.4 and 0.9), a proportion of external solar flux scattered as diffuse radiation (typically between 0.1 and 0.6), and a value for the external solar radiation flux incident on the outside of the atmosphere, also known as the solar constant (The currently accepted value is 1370 Wm⁻²).
5. Select the **Diffuse Distribution** tab and observe that you can choose between a Standard Overcast Sky model and a Uniform Overcast Sky model. These describe the pattern of diffuse illumination from a clear sky (not actually overcast).
6. Select the Uniform Overcast Sky (UOC) model, which assumes that equal amounts of diffuse radiation originate from all sky directions. Click **OK**.

See also:

"The Basic Model for Estimation of Solar Radiation" on page 15

Classify Image

HemiView needs your help deciding which part of the sky is visible and which is obscured. We call this classifying the image.

HemiView uses the total intensity (ie the sum of the red, green and blue values) of each pixel to determine whether it should be counted as obstructed or visible sky. Pixels which are brighter than a 'Threshold' intensity value are counted as visible. Darker pixels are counted as obstructed.

Your job is to choose an intensity value which best separates the visible sky pixels from obstructed pixels (leaves, tree trunks, buildings or whatever).

To enable HemiView to accurately classify an image, it is essential to have a uniformly lit or overcast sky when taking photographs for analysis by HemiView. Otherwise, it is possible for areas of visible sky to appear darker than obstructed canopy.

HemiView provides a Threshold toolbar which allows you to select a suitable threshold value for the image, and a classified view of the image which is updated immediately when you change the threshold. You can easily switch between classified and full colour views of the image, or display both views side by side, to observe the effect of changing the threshold value.

You can also designate a colour value which will be ignored in HemiView's calculations. Thus you can paint out prominent obstructions such as tree trunks in the designated colour, and exclude those areas of the image from calculated results.

Display the Classified View

1. Use one of the following methods to display the classified view of the image:

- Select the **View, Classified** command
- Press the **C** shortcut key
- Click the Classified toolbar button 
- Right click on the image and select **Classified** from the popup menu
- Right click on the Threshold toolbar and select **Classified** from the popup menu.

The classified view of the image shows obstructed pixels as black, visible sky as white, and ignored pixels (if any) in the ignored colour.

The image is not degraded by this action. Repeating any of the above actions restores the original view of the image.

Toggling the Classified view on and off, whilst adjusting the Threshold, is a good way of deciding the best Threshold setting

2. To determine the best threshold setting, you may find it useful to display classified and full colour views side by side. Select the **Window, New** command. Change the classified state of one of the windows, and re-size and arrange the two images side by side.

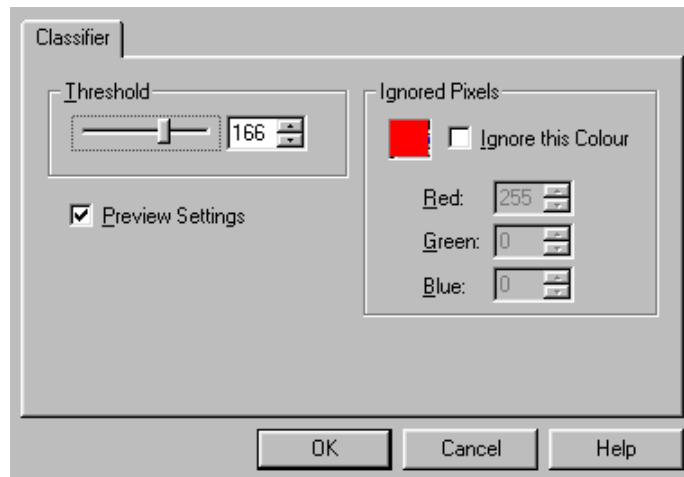
Change the Threshold

3. Adjust the threshold. Experiment with each of the following methods:



- Press **+** or **-** keyboard shortcut keys to increase or decrease the threshold value.
- Hold down **Ctrl** while pressing **+** or **-** to increase or decrease the threshold value in larger steps.
- Drag the Threshold toolbar slider with the mouse.
- Click the up and down buttons of the Threshold toolbar
- Enter a numeric value directly into the Threshold toolbar
- Choose the **Settings, Classifier** command and select a threshold value in the Classifier Settings dialog (as in the Threshold toolbar).

Note that the Classifier Settings dialog allows you to preview (and cancel) any changes you make to the threshold value. Also, the Classifier Settings dialog allows to select a colour value for HemiView to ignore.



4. Toggle Classified on and off using the **C** shortcut key. Examine how well the two views match in terms of visible and obscured sky directions. Adjust the threshold to better match the original image view. Repeat these steps until you are satisfied that the image is well classified.

Note that consistency in choosing a threshold takes practice, and is among the most challenging issues when analysing hemispherical photographs. Consistency in image classification depends upon using high quality photographs and adopting consistent criteria for trade-offs between best representing distinctions between foliage and visible sky in different parts of the image. For many projects a set of 10-20 reference photographs is used to train users and periodically to evaluate whether repeated analyses are consistent. In addition, many users of hemispherical photographs repeat analyses of all photographs two or more times until consistently repeatable results (e.g., ISF or DSF values) are obtained.

Inspect Results

HemiView can compute a wide range of results, placing each type of result in its own worksheet within an Excel 5.0 compatible workbook.

First we select an existing output configuration so we can have a quick look at some results.

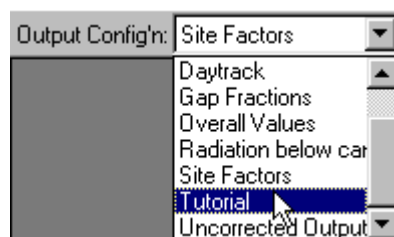
1. Open Sample2.hvs using the **File, Open** command.

Observe that HemiView has also loaded the alignment and threshold setting.

2. Check to see if you agree with the threshold setting.

We will now define what results we want to see.

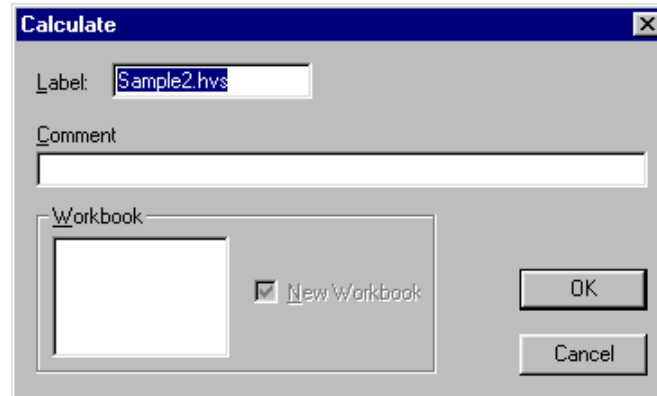
3. From the **Output Configurations** toolbar, select Tutorial.



4. Click the  Calculate toolbar button.

Note that the Calculate button is only enabled if the active window is an image window. If you have a workbook window open (for example if you are repeating this section of the tutorial, or have been experimenting with HemiView and have created a workbook window), first ensure that the active window is an image window (click on its title bar, or select it from the Windows menu).

The Calculate dialog will appear as follows:



We will not change anything this time, but whilst we are here, note that you may type anything you like into the Label and Comment boxes. The Label will appear in every results sheet - the default offered is the image file name. The Comment appears only on one sheet, called Comments .

The Workbook section of this dialog will appear blank the first time. On subsequent occasions it will offer you the choice of appending results to an existing workbook, or starting a new one. (Appended results are always added below previous results).

5. Click **OK** in the **Calculate** dialog.

An Excel 5.0 -compatible workbook will appear containing several worksheets of results, as shown below:

	A	B	C	D	E	F	G
1	Summary						
2	SeqNo	Label	HVSFile	Lens	Site	SolrModl	Config
3	1	Sample2.jpg	C:\Program Files\Hemiview\Samples\Sample2.jpg	Linear 180	Burwell	Default Simple Model	Tutorial
4							
5							
6							

The **Summary**, **Comments** and **Image** sheet contain input information, ie information which you, the user, has provided as inputs to HemiView's calculations.

Click on each in turn and inspect them.

In this example the first sheet with results in is the fourth tab along – the Values sheet.

6. Click on the **Values** tab:

	A	B	C	D	E	F
1	Overall Values					
2	SeqNo	Label	ISF	DSF	GSF	
3	1	Sample2.hvs	0.177	0.242	0.232	
4						
5						
6						

Results in the Values sheet reflect the whole canopy or the whole image. In general, most entries in the Values sheet represent a summation over all positions in the sky or over time. In contrast, most of the other sheets are tabulated according to position in the sky or by time.

The abbreviation ISF stands for Indirect Site Factor – the proportion of diffuse solar radiation reaching a given location, relative to a location with no sky obstructions. Values range from 0 to 1, with 0 representing complete sky obstruction, and 1 representing open sky.

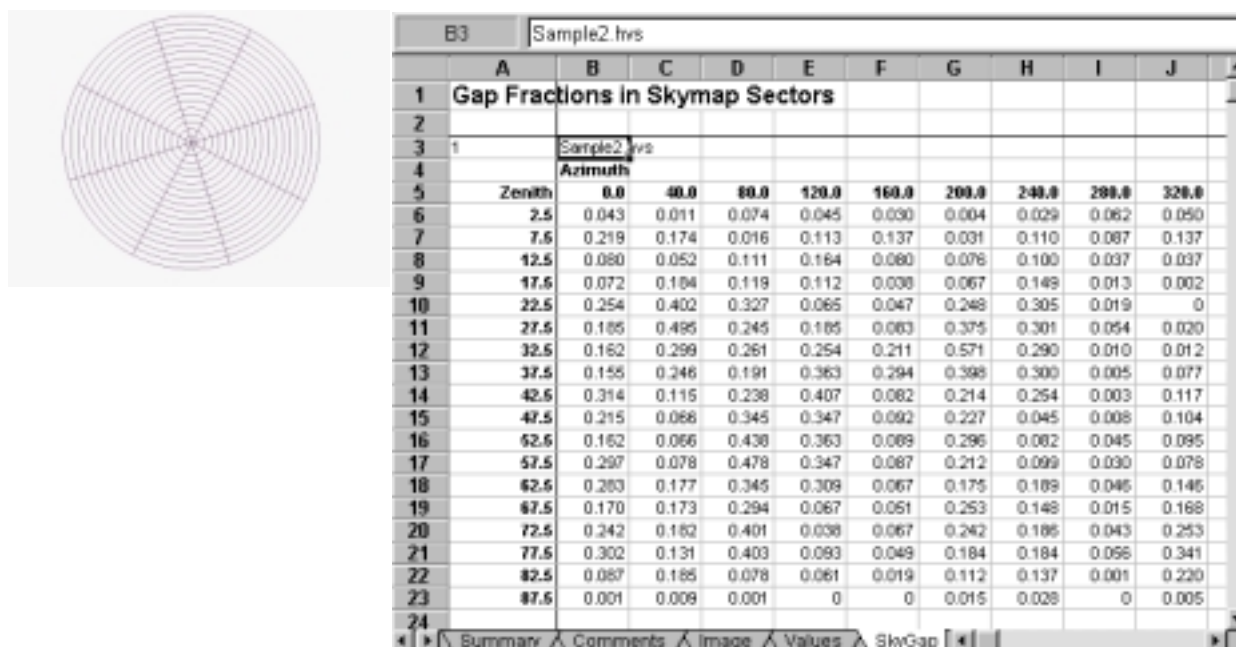
To find out definitions, see the "Appendices, Calculations Theory" section in the on-line Help and Glossary of Terms.

In the Glossary of Terms you will find the following definition:

Global Site Factor (GSF): The proportion of global radiation under a plant canopy relative to that in the open ("total site factor" of Anderson 1964). Typically, calculated as direct plus diffuse radiation, with reflected radiation ignored.

You should similarly be able to find on-line definitions for direct site factor (DSF) and indirect site factor (ISF).

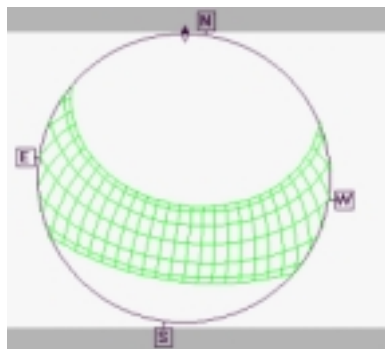
7. Click on the **SkyGap** tab.



The SkyGap sheet shows how much of each cell in the sky map appears obstructed, expressed as a decimal fraction. Each column maps onto a radial section of the SkyMap, starting at North (about 1 o'clock) and proceeding anticlockwise.

The Zenith angle starts in the centre, i.e. up, and proceeds out to the horizon at 90 degrees.

8. Inspect the SunGap sheet:



B3	Sample2.hvs									
1	A	B	C	D	E	F	G	H	I	J
2	Gap Fractions in Sunmap Sectors									
16	05:15	-1	-1	-1	0	0.029	0.351	0.351	0.027	0
17	05:45	-1	-1	0	0.040	0.172	0.759	0.756	0.171	0.030
18	06:15	-1	-1	0	0.174	0.541	0.120	0.144	0.540	0.153
19	06:45	-1	0	0.098	0.358	0.468	0.378	0.381	0.467	0.343
20	07:15	-1	0	0.064	0.317	0.289	0.354	0.346	0.296	0.304
21	07:45	0	0.002	0.044	0.080	0.616	0.450	0.452	0.595	0.073

The SunGap table shows how much of each sector in the sunmap appears obstructed.

The sunmap is derived by overlaying a series of solar tracks for the given site.

The sectors in the sunmap show the suntrack defined by the time of day and time of year. Each sector in the sunmap is the area traversed by sun over a half-hour period, on consecutive days of a month.

Each cell in the SunGap table corresponds to a sector in the sunmap.

The values in each cell of the SunGap table, derived directly by counting pixels, give the proportion of sky visible in that sector, where 1.0 represents all the sky is visible, and 0.0 represents no visible sky.

The value -1 in any cell in the results indicates that no meaningful value is available for the cell. In the SunGap sheet, this occurs for sectors which lie below the horizon.

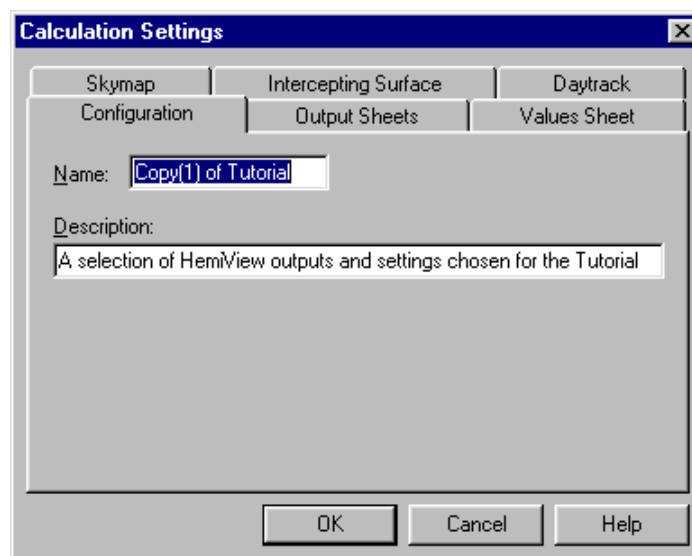
The SkyGap and SunGap sheets are special in that they incorporate no models making assumptions about the effects of the atmosphere, the amount of radiation or the structure of plants. HemiView simply counts pixels, and uses site and lens information to apportion the numbers to each sector.

Next we customise the Calculations Settings.

Change Calculation Settings

1. Bring up the Output Configurations popup menu by placing the mouse pointer on the Output Configurations toolbar and clicking the right mouse button. From the popup menu select **New**.

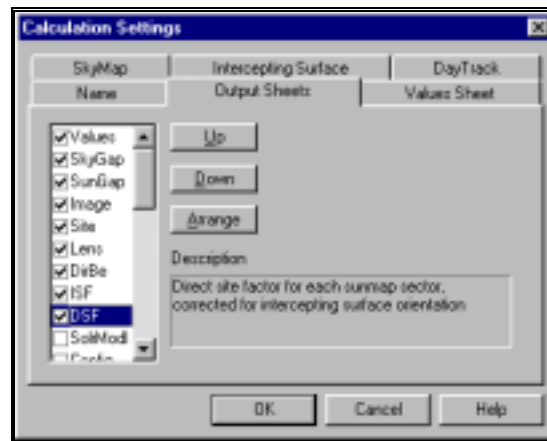
The **Calculations Settings** dialog appears:



2. Type in a new name for the output configuration, such as MyTutorial.
3. Click on the **Output Sheets** tab
4. Scroll through the output sheet options and select the following:

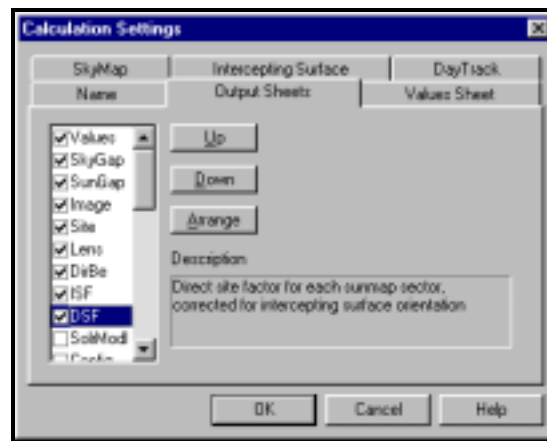
Output Sheet name	What it will display
Values	Overall values calculated for the whole sky or canopy.
SkyGap	Gap fraction in each skymap sector.
SunGap	Gap fraction in each sunmap sector
Image	Image information
Site	Site information
Lens	Lens information
ISF	Indirect site factor for each skymap sector, corrected for intercepting surface orientation.
DSF	Direct site factor for each sunmap sector corrected for intercepting surface orientation.
DirBe	Direct radiation below the canopy for each sunmap sector, corrected for intercepting surface orientation
Comment	Comments entered by the user.

5. Click on **Arrange**. Observe all the selected sheets are now at the top of the list.



6. Experiment with changing the output list order by highlighting items in the list and clicking the **Up** and **Down** buttons.

To highlight an item without unchecking it, click on the text of the item – not the check box. Hold down Shift or Ctrl keys to highlight multiple items within the list.



7. Click on the **Values Sheet** tab and in addition to the defaults offered, add TotBe.

8. Click on the **Skymap** tab and ensure that the number of Azimuth divisions is set to 9 and the number of Zenith divisions is set to 18.

9. Click on and inspect the **Intercepting Surface** tab.

HemiView allows you the choice of calculating what radiation would be received on a perfectly absorbing flat surface or aperture oriented at any angle.

The tilt of a surface can be conveniently described by the zenith and azimuth angles of a normal or perpendicular line to the surface.

Azimuth: The angle in degrees for the normal to the intercepting surface (0 = North, 90 = East, 180 = South, 270 = West...)

Zenith: The zenith angle, in degrees, for the normal to the intercepting surface (0 = horizontal, 90 = vertical...)

10. We wish to perform a calculation that includes solar radiation interception by a horizontal surface - so set the zenith angle to 0 (the azimuth angle is immaterial, or undefined, in this instance).

Note that calculations for non-horizontal surfaces can be useful for calculating solar radiation interception by leaves in different orientation and for calculating solar radiation interception for non-horizontal slopes.

11. Select Single-Sided. In general select Double-Sided if you are interested in sensors which are sensitive to radiation received on both upper and lower surfaces, such as most plant leaves.

12. Click on the **Daytrack** tab. The information in this tab is used for time series calculations of the radiation and sunflecks on any day of the year, not just the day of the photo. Values are calculated every Time Series Increment throughout the day.

We do not need to enter any values in the Daytrack tab because we have not chosen either a TimeSer or Sunfleck sheet.

You have now finished configuring the settings for the results. Before progressing to Results here is an announcement!

Uncorrected ('U', as in DSFU) does not mean horizontal surface!!

If you want the radiation on a horizontal surface it is a mistake to use the uncorrected radiation values. You should use corrected values and declare the surface orientation (zenith angle 0). The reason is as follows:

Radiation is described in two ways in HemiView - corrected and uncorrected.

The uncorrected radiation values presented in HemiView represent the intensity of the radiation source, in other words the brightness of the sky at different points over the hemisphere, and the corrected readings represent the how that is absorbed by a flat surface at a specified angle.

The conversion from one to the other involves a simple cosine correction - but you need to cosine-correct the incident uncorrected radiation values from each part of the sky even when the surface is horizontal.

Scientists normally work with radiation readings as they would be received by a perfect flat black body surface or aperture at a given orientation.

Most people will expect to receive cosine corrected results. If you are unsure, assume you are with the majority and choose the corrected, i.e. cosine-corrected, results.

All HemiView outputs with the U suffix, e.g. DSFU are not cosine corrected. "U" is for Uncorrected and for Unusual. When would you use it? If you were interested in modelling the radiation absorbed by a non flat surface, such as human or animal, you may wish to take the raw uncorrected data and project it onto a cylinder, or map it directly onto a hemispherical object – such as a ladybird.

Calculate Results

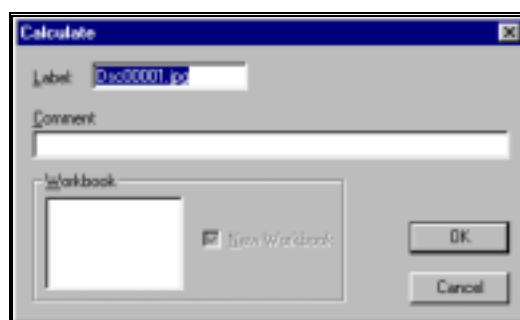
In previous sections we opened, aligned and classified the image and specified which calculations HemiView will perform.

1. Ensure that your image window is the active window: click on its title bar if in doubt, or select it from the Window menu. (Note that the Calculate button is only enabled if the active window is an image window).

2. Use one of the following to start the HemiView calculation:

- Select Calculate from the menu bar
- Click the Calculate  toolbar button.

Before proceeding with the calculation, HemiView pops up the Calculate dialog:



The Calculate dialog allows you to provide a label to identify the results of each calculation you perform, and a comment to annotate the calculation (for example, to describe why you have chosen particular settings for this calculation).

The label appears on each of HemiView's output sheets together with a sequence number, alongside the calculated results.

The comment appears on the Comments sheet – but only if you have selected the Comments sheet as one of the output sheets in the calculation settings (as we have in this tutorial). Otherwise HemiView ignores any comment which you enter in the Calculate dialog.

The Calculate dialog also allows you direct the results to an existing workbook window, or to create a new one.

3. Enter a label and comment, highlight Book1 in the Workbook list (to append a new set of results to the existing workbook) and click **OK**.

4. Examine the results sheets. Observe how a row of values has been added to the Values, Image, Site and Lens sheets, and how tables of values have been added to each the other selected output sheets.

Notice also how the arrangement of output sheets in the workbook matches the order of the selected items in the Output Sheets tab, and that no results have been appended to the Summary or other sheets which you de-selected in the Output Sheets tab.

The ISF (Indirect Site Factor) and DSF (Direct Site Factor) are the proportions of direct and diffuse radiation, respectively, relative to that outside the canopy; whereas, the diffuse and direct radiation values are expressed in solar radiation units.

5. Examine the SkyGap and SunGap tables to see if you can identify the effects of openings in the canopy.

6. Click the Image/Workbook toolbar button  to switch quickly between image and workbook windows.
7. Click on the image, and press the – (minus) shortcut key several times until you can see the difference on the image.
8. Click  to recalculate, and inspect the results. Observe that the new results are appended below the previous ones, and that each output sheet has scrolled down so as to display the most recent set of results.
9. Observe on the Image sheet that your selected threshold setting has been recorded for each calculation.
10. With the results workbook active select the **File, Save As** command and save the workbook to the file **tutorial.xls** in your working directory.

That's it! Next we look at file handling.

Using .hvs (HemiView Settings) Files

Previous sections of Tutorial 2 covered opening, aligning and classifying the image and displaying and saving results.

HemiView allows you to save alignment and classification information, together with the lens and site names, and the name of the original image file in a .hvs (or 'HemiView Settings') file. Information about whether the image is a negative or positive is also kept in the .hvs file.

So *additional* information about the image, that affect the calculation of results, is stored in the .hvs file, but not the actual image itself.

Information about whether the overlays are to be displayed is *not* saved in the .hvs file.

The actual properties of the site and lens are not saved in the .hvs file.

HemiView saves the site and lens properties separately in files named Sites.csv and Lenses.csv in the HemiView installation directory.

HemiView also saves solar model and output configuration information in files named Models.csv and Config.csv in the HemiView installation directory.

Learn about .hvs (HemiView Settings) files.

1. If they are not already visible, display the site, lens and threshold toolbars with the **View, Toolbar** command.
2. If the image that you were working on previously is still open, use that. If not, use **File, Open** and select and open Sample1.jpg.
3. If you have a workbook open, click anywhere on the image to select it.
4. Save the image as a .hvs file using **File, Save As** .
5. **Close** the image window.
6. Make a note of the current settings in the Lens, Site and Threshold toolbars.
7. Change these settings. Hint: Drag the Threshold slider to one side with the mouse.
8. Reopen the .hvs file, using **File, Open** and observe all the original toolbar settings restored.

Note: the Day of Year is not image information, and is not saved in the .hvs file, and so is not altered when you open a.hvs file. It is part of the Output Configuration

Next time you Open an image

Output configurations (ie sets of calculation settings), solar models, sites and lenses are available for use by all images. HemiView saves them in configuration files (Config.csv, Models.csv, Sites.csv, Lenses.csv) in the HemiView installation directory when you exit HemiView, so they are preserved for the next time you run HemiView.

The names of the image, site and lens, are saved to a .hvs (HemiView Settings file) whenever you save an image in HemiView, so that when you open a .hvs file, HemiView automatically locates the image file, and the appropriate lens and site in its lens and site lists.

The .hvs file contains the name of an image file only, and *not* the image itself, so the image needs to remain alongside the .hvs file in your working directory.

The .hvs file contains the names of the site and lens, and *not* the site or lens properties, so if you delete or modify the properties of the site or lens within HemiView, you will not be able to reproduce earlier results when you next open the .hvs file.

The .hvs file does not contain solar model properties or calculation settings. HemiView always uses the currently selected solar model and output configuration for its calculations.

Calculating Time Series and Sunfleck Duration

HemiView can plot the track of the sun across the sky on any chosen day of the year (the daytrack) and calculate the visibility of the solar disk and associated solar radiation values throughout the course of the day.

The results can be presented as a 'time series' (a sequence of instantaneous 'snapshots' taken at regular intervals) in the TimeSer sheet, or they can be summarised in the Sunfleck sheet, as a list of sunflecks with a start and stop times, and radiation values integrated over the sunfleck's duration.

The calculation settings for daytrack calculations are entered in the **Daytrack** tab of the **Calculation Settings** dialog. The day of interest can also be selected using the Day of Year toolbar, and the daytrack can be viewed by selecting the **View, Daytrack** command or by clicking the Daytrack toolbar button.

For the Sunfleck sheet, you just need to select the day of interest. For the TimeSer sheet you also need to specify the time interval between results.

Daytrack time series calculations are used as input by YPlant©, a computer program for simulating physiological processes in plants (Pearcy et al. 1997).

1. Display the daytrack using one of the following methods:
 - Select the **View, Daytrack** command
 - Press the **D** shortcut key
 - Click the Daytrack toolbar button
 - Click the right mouse button on the image and select Daytrack from the image popup menu
2. Use the Day of Year toolbar to change the day of year and observe how the position of the daytrack moves across the sky during the course of the year.
3. Toggle the View, **Classified** command to show the classified image. Observe where the daytrack intersects with visible sky directions. These intersections correspond to times when sunflecks will occur.
4. Select **Settings, Output Configuration, Properties**. Click on the Daytrack tab and observe that the Day of Year matches the value in the Day of Year toolbar.
5. Set the Time Series Increment to 10 minutes. This means that the TimeSer sheet will contain values for every 10 minutes through the day between sunrise and sunset. This interval can be reduced to 1 minute, which is equivalent to the time it takes for the sun to move half of one diameter.
6. Click on the **Output Sheets** tab and select TimeSer and Sunfleck.
7. Close the **Calculation Settings** dialog and initiate calculations with the **!** shortcut key.
8. Inspect the TimeSer sheet. Compare the values in the table to the pattern you see in the image.

The TimeSer sheet contains the following values:

- day of year selected for calculation
- time (in this case, at 10 minute intervals)
- sun's positions, zenith and azimuth
- visibility of the sun's disc
- radiation above and below the canopy, both corrected and uncorrected. These are instantaneous values for the stated time.

9. Inspect the Sunfleck sheet.

The Sunfleck calculation scans the the daytrack from sunrise to sunset at 30 second intervals (i.e. at a resolution of one quarter of a solar diameter). The sunfleck calculation gives the start and stop times of any sunfleck and the amount of radiation during that sunfleck.

The Sunfleck sheet contains the following values:

- day of year selected for calculation
- start and stop times of each sunfleck
- maximum peak radiation value during the sunfleck
- integrated radiation values over the whole of the sunfleck.

Inspect the classified image and confirm that the calculated sunflecks coincide with intersections of the daytrack with visible sky regions.

Tutorial 3: Field Protocols

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 analyse 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 difficult to obtain and represent the primary weakness of the technique. In general, it is best to take photographs under conditions with even back-lighting, in particular just before dawn or just after sunset, and on days with evenly overcast skies.

Camera System

A high quality hemispherical lens should be used. High quality hemispherical lenses and rugged cameras are manufactured by several companies, including Sigma, Canon, Minolta, and Nikon. The Sigma 8mm lens represents excellent value, in terms of quality relative to price. Other components include a camera body (e.g., Nikon FM2), a databack that automatically imprints a unique number in the corner of each negative (e.g., Nikon MF16). A camera fitted with an internal meter can facilitate determination of exposure.

Film

For quality hemispherical canopy photographs, excellent results have been obtained with either black-and-white (e.g. T-Max 400, Ilford HP5) or colour film (e.g. Ektachrome 400).

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-Levelling Camera Mount

A self-levelling camera mount can greatly facilitate photograph acquisition. A self-levelling mount is essential for situations where hemispherical canopy photographs are taken high above the ground or in awkward positions. However, even when acquiring photographs near ground level, a self-levelling mount makes photograph acquisition much easier. In terms of design, 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. An set of weights secured to the bottom of the mount can be adjusted to level the film plane. The mount assembly can be supported on a tripod or monopod.



Delta-T can supply self-levelling mounts suitable for tripods or monopods. Mounts can be supplied for the Sigma 8mm fisheye lens with the Nikon FM2 camera and the Nikon Coolpix950 digital camera and lens. These include lights, a compass and bubble level for aligning pictures. An adaptor is also available for the Nikon SLR 8mm lens but due to its large size this mount does not have lights, bubble level or compass.

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 quicker set-up and simpler transport between sites. When using a monopod, it is best to also use a self-levelling 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.



In addition, a monopod and self-levelling mount set-up can be used from ladders to take photographs at greater heights using tall folding aluminium step ladders.



Similarly, a monopod and self-levelling mount set-up enables work at even greater heights using such techniques as Swedish climbing ladders and a climbing harnesses.



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 digitisation. 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 digitisation.

Protocol for Image Acquisition

A standardised field protocol should be adopted for acquisition of hemispherical canopy photographs, thus ensuring uniform quality of photographs for analysis.

Field protocol for photograph acquisition:

1. Set up—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 camera assembly to magnetic north.
4. Set exposure time and aperture.
5. Take photograph using the camera self-timer.

6. Repeat steps 2-4.

Preparations Prior to 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 labelled 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, levelled, 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 levelled, if a self-levelling mount is not used. After the camera is positioned and levelled 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

An internal camera light meter can be used to obtain consistent exposures. First the ASA should be properly set on the camera. When working with black-and-white film, photographs should be taken using a blue filter to enhance contrast between visible and obscured sky direction. Red filters can also help to increase contrast in a desirable way. However yellow filters should be avoided because they tend to increase contrast within the sky, in particular accentuating clouds and uneven lighting. Blue and 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 often 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. Generally, excellent exposures can be obtained using the internal camera meter.

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 stabilised 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.

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 auto-incrementing 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 labelling 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 digitisation.

Field Records

Field records should contain 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 or sky conditions, and additional notes can be recorded. Weather or sky conditions can include such categories as sunny, partly cloudy, overcast, sprinkling, and raining. Some researchers prefer to write with indelible pens; others prefer mechanical pencils that will not fail in the rain. Waterproof notebooks are especially useful for humid or rainy study locations. Pre-printed data sheets can minimise 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 at predawn or post sunset, when no direct sunlight is visible. 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 foliage or structures. 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, Paul Rich 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

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. Many commercial film processors now offer services to scan photographs and place them directly in Kodak PhotoCD format at reasonable costs.

Typical Film Processing Protocol

1. Load film into developing tank (in dark room or film loading bag).
2. Fill tank with 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 indicator).
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 labelled. Typically it is best 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 examined without removal from the storage sheets. Negatives that are to be analysed can be temporarily removed. As with any photographic materials, negatives should be stored in a cool, dark location.

Tutorial 4: Case Studies

Solar radiation regimes below the canopy

Most of the early work with hemispherical photography, and much of the current work, involves calculation of site indices or solar radiation regimes beneath plant canopies. Commonly, hemispherical photographs are used as a means to evaluate differences between study locations. Photographs have various advantages over solar radiation sensors, including the ability to gather data relatively quickly, without need for long-term set-up of sensors with data logger, which also has the implication that hemiphotos can be acquired for a broader range of spatial locations than is practical for sensors. Unlike most sensors, hemispherical photographs provide direct information about the geometry of the canopy above a site, which can be used for understanding causal factors for observed temporal and spatial patterns. Further, hemiphotos represent a permanent record that can be analysed to obtain many solar radiation and site indices. Spatial patterns can be examined by taking photographs at distance intervals in 1) horizontal or 2) vertical transects. Temporal patterns can be examined either 1) by calculating future regimes under the assumption that the canopy does not change or 2) by taking repeated photographs at a given location at intervals through time.

Solar radiation regimes and site indices for treefall gaps versus closed-canopy locations.

Rich, P.M., D.B. Clark, D.A. Clark, and S.F. Oberbauer. 1993. Long-term study of solar radiation regimes in a tropical wet forest using quantum sensors and hemispherical photography. Agricultural and Forest Meteorology 65(1-2):107-127.

One of the primary ways that hemispherical photographs have been used involves comparison of solar radiation regimes or site indices at select sample locations within a forest or at different times for the same sample location. This study involved taking hemispherical photographs at a series of seven fixed sample locations at ground level within a recent treefall gap and under nearby closed-canopy forest of a tropical wet forest. Photographs were acquired at each of the sample locations at month intervals through the course of a year, which enabled characterisation of changes over time. PAR sensors were installed at each of the sample locations and used to monitor insolation continuously over the course of the year. The sensor data enabled calibration and validation of PAR estimates from the hemispherical photographs. The hemiphoto data enabled understanding of the geometric basis for variation in solar regimes through the year. Changes in solar radiation with time were related to seasonal shifts in solar angle with respect to canopy openings, variation in atmospheric conditions (month-to-month difference in cloudiness), and changes in canopy geometry (in particular growth of trees into the gap).

Solar radiation regimes or site indices as they relate to plant ecophysiology and growth.

Oberbauer, S.F., D.B. Clark, D.A. Clark, P.M. Rich, and G. Vega. 1993. Light environment, gas exchange, and annual growth of saplings of three species of rain forest trees in Costa Rica. Journal of Tropical Ecology 9(4):511-523.

Hemispherical photographs taken above individual plant crowns can be used to estimate solar radiation regimes or site indices from the perspective of and individual, and, in turn, related to physiological or ecological measurements. This study examined relations between solar radiation regimes above saplings, gas exchange (carbon uptake), and annual growth for three species of tropical trees with different life histories. Measurements of annual growth were correlated with indices of both direct and diffuse radiation, expressed as ISF and DSF, and with the strongest relationship with ISF.

Site factors as they relate to habitat suitability for animal species.

Weiss, S.B., P.M. Rich, D.D. Murphy, W.H. Calvert, and P.R. Ehrlich. 1991. Forest canopy structure at overwintering monarch butterfly sites: measurements with hemispherical photography. Conservation Biology 5(2):165-175.

Hemispherical photographs can also be used to characterise habitat for animal species. This study examined site factors (indirect and direct site factors) as they relate to suitability of different stands as overwintering sites for monarch butterflies. Suitable habitat corresponded to a limited range of ISF and DSF that relates to the physiology of the butterflies. Sites with too much solar radiation would cause butterfly metabolism to increase and deplete fat reserves, while too little solar radiation would cause metabolism to be so low that butterflies would not become active at the appropriate time for migration in the spring. The butterflies select overwintering sites that have a suitable canopy structure to protect them from wind, rain, and major temperature fluctuations, while also allowing sufficient solar radiation in the spring. Hemispherical photography proved to be a valuable tool for habitat assessment and use in conservation management decisions. By simulating potential impacts of tree removal on butterfly habitat, it was possible to assess different management scenarios concerning proposed modifications to forest stands.

Solar radiation regimes along transects, and soil moisture in heterogeneous canopies.

Breshears, D.D., P.M. Rich, F.J. Barnes, and K. Campbell. 1997. Overstory-imposed heterogeneity in solar radiation and soil moisture in a semiarid woodland. Ecological Applications 7:1201-1215.

Hemispherical photographs taken along horizontal transects can be used to determine variation in solar radiation regimes as it relates to variation in canopy structure, and also to examine ecosystem measurements that correspond with this spatial heterogeneity. This study examined relations between the overstory, solar radiation regimes, and soil moisture for photographs taken every meter along a one-hundred meter transect. Solar radiation and soil moisture showed autocorrelation at spatial scales that correspond to heterogeneity of canopy versus intercanopy patches. A complex set of factors (interception, evapotranspiration, insolation...) lead to predictable patterns of soil moisture as a function of canopy position (south edge of canopy, under canopy, north edge of canopy, and intercanopy). In essence, this study enabled characterisation of distinct gradients of microclimate that occur in predictable ways, depending upon position beneath the canopy.

Vertical transects, and changes in available light with height growth.

Lerdau, M.T., Holbrook, N.M., H.A. Mooney, P.M. Rich, and J.L. Whitbeck. 1992. Seasonal patterns of acid fluctuations and resource storage in the arborescent cactus *Opuntia excelsa* in relation to light availability and size. *Oecologia* 92:166-171.

Hemispherical photographs taken along vertical transects can be used to determine differences in solar radiation regimes experienced by plants growing at different heights within the canopy. This study involved taking photographs at a series of heights within a deciduous forest, with transects repeated during leaf-on and leaf-off periods. Additional sets of photographs were taken to characterise the light available to tree cactuses growing at different heights within the canopy. The forest displayed an exponential increase in light availability with height, and a marked increase in light available to the understory during the leaf-off period. Cactuses growing at a particular height were found to have higher light levels than the forest in general at that height. Acquiring photographs in vertical transects is challenging, especially for tall canopies, but has been accomplished successfully by various researchers.

Using multiple transects to compare spatial patterns in different forest stands.

Clark, D.B., D.A. Clark, P.M. Rich, S.B. Weiss, and S.F. Oberbauer. 1996. Landscape-scale evaluation of understory light and canopy structure: methods and application in a neotropical lowland rain forest. *Canadian Journal of Forest Research* 26:747-757.

Photographs taken at intervals along multiple long transects can be used to assess spatial patterns and assess the distribution of understory light environments at a landscape level. This study involved taking hemispherical photographs along fifteen 100-m long transects to sample variation in a tropical wet forest (photos taken at 2.5-m intervals for heights of one and three m above the ground, and at 0.6 and five m heights at five stations for each transect). Photographs were analysed to determine GSF. Spatial autocorrelation (Moran's I test) was observed to be significant for GSF at distances of about 20 m (under a canopy that was observed to have a median height of 23 m). Values for the random background understory light environment of the forest at large proved useful as the reference when evaluating the conditions observed for saplings of tree species with different life histories. Two pioneer species occurred in microsites with solar radiation levels that were significantly higher than the forest at large; whereas five species of nonpioneer (shade tolerant) species occurred in microsites with solar radiation levels below that of the forest at large.

Two-dimensional maps of solar radiation from arrays of photographs (multiple transects).

Galo, A.T., P.M. Rich, and J.J. Ewel. 1992. Effects of forest edges on the solar radiation regime in a series of reconstructed tropical ecosystems. *American Society for Photogrammetry and Remote Sensing Technical Papers*. pp 98-108.

By acquiring hemispherical photographs in arrays it is possible to produce two-dimensional maps. This study used hemispherical photographs taken in a series of fifteen transects from the forest edge into an eight-hectare clearing to produce maps of direct radiation. ISF, monthly DSF, and hours of direct beam radiation were calculated from the photographs. In general east and west forest edges modify daily regimes of solar radiation, while north forest edges modify seasonal regimes (south edges in the southern hemisphere, and both north and south edges within the tropics). As a rule of thumb, the influence of the forest edge was strongest up to a distance approximately equal to the canopy height (30 to 40 m, in this case). Isoline maps of the duration of direct beam radiation were derived for the summer solstice, equinox, and winter solstice. Based on these

maps it was possible to assess the influence of the forest edge on experimental growth plots being set up in the clearing. While it is practical to produce such maps in gaps or clearings, maps under forest canopies are more challenging, because high variation of conditions under canopies often occurs at very fine spatial scales, and interpolation between point samples may not be valid.

Monitoring temporal changes in solar radiation regimes after major disturbance events.

Bellingham, P.J., E.V.J. Tanner, P.M. Rich, and T.C.R. Goodland. 1996. Changes in light below the canopy of a Jamaican montane rainforest after a hurricane. Journal of Tropical Ecology 12:699-722.

Major disturbances, such as hurricanes or forest fires, can cause a mosaic of forest patches at different successional states. Hemispherical photography has proven useful for monitoring changes that occur after disturbances. This study examined landscape-scale changes in understory solar radiation after Hurricane Gilbert in 1988. Hemispherical photographs were taken at permanent sampling locations at four sites during the course of 33 months after the hurricane. A total of 25 sample locations were distributed among the four sites, and photographs were acquired at ten time intervals between seven and 33 months after the hurricane. PAR was calculated for each photograph, with calculated values calibrated to long-term sensor measurements above the canopy. During the first 24 months after the hurricane PAR beneath the canopy was significantly greater in sites that were defoliated as compared with sites that were not heavily impacted. By 33 months most site differences had disappeared. Hemispherical photography represents an effective method for examination of temporal patterns of change.

Sunfleck studies

Hemispherical photographs can be used to study variation in solar radiation over small space and time scales. In particular, various studies have focused on sunflecks as they influence ecophysiology and growth. Calculation of sunfleck regimes can be more challenging than calculation of integrated measures of solar radiation because the exact timing and duration of sunflecks is related to accurate alignment and image classification. While accurate alignment and image classification are always of importance when using hemispherical photography, these considerations are of even greater concern when small differences in timing or duration may affect results. Typically, sunfleck studies focus on an individual plant or a single leaf. When focusing on a single planar leaf, it is most appropriate to perform a calculation for a double-sided surface of interception. This enables accounting for solar radiation that intercepted by either side of the leaf surface.

Using sunfleck regimes as an input to ecophysiological models of plants.

Pearcy, R.W. and W. Yang. 1996. A three-dimensional crown architecture model for assessment of light capture and carbon gain by understory plants. Oecologia 108:1-12.

This study used hemispherical photographs as input for an individual crown model for light capture and carbon gain by understory plants (YPlant model). Either empirical or simulated hemispherical photographs can be used for simulations with the model. In essence, light capture was calculated using gap fraction in each sky direction as input to a diffuse radiation submodel, and timing of sunflecks along the sun track as input in a direct radiation submodel. The three-dimensional distribution of all leaves on a plant are specified, along with physiological parameters, such as light response curves. Interception

efficiencies and carbon gain were compared under different light regimes for an understory species and a forest edge species. The edge species had more self-shading within the crown, while the understory species was more efficient at capturing light from directly above. The YPlant model has been enhanced significantly since this study, and has been rewritten as a Windows program that uses the HemiView TSeries and TSkyGap as input. This modelling approach opens a new frontier for understanding ecophysiology, crown architecture, and life history strategies.

Solar radiation interception by canopies

Solar radiation interception involves the same calculations as do analyses of solar radiation regimes beneath the canopy, but with a focus on what radiation is blocked rather than what radiation penetrates the canopy. An intercepted direct site factor (IDSF) can be calculated as $1 - \text{DSF}$ and an intercepted indirect site factor (IISF) can be calculated as $1 - \text{ISF}$. The perspective of interception is especially common for studies that wish to examine function of the canopy as a whole, in terms of considerations such as carbon uptake, transpiration, energy balance, or ecological implications. Many of the studies placed in the “Solar radiation regimes below the canopy” could equally well be placed here.

Solar radiation interception in forest canopies as it relates to succession.

Canham, C.D., A.C. Finzi, S.W. Pacala, and D.H. Burbank. 1994. Causes and consequences of resource heterogeneity in forests: interspecific variation in light transmission by canopy trees. Canadian Journal of Forest Research 24:337-349.

Solar radiation intercepted by the canopy is potentially available for growth of the individual plants that intercept the radiation and made unavailable for individuals growing beneath. This study examined the influence of interception (and transmission) characteristics of crowns on succession in temperate deciduous forest. Hemispherical photographs were used to gather species-specific light extinction coefficients, by using maximum likelihood techniques along with detailed measurements of the identity, location, and geometry of trees in the neighborhood of each photograph. Later successional, shade tolerant trees cast the deepest shadows, while earlier successional, less shade-tolerant trees allowed greater transmission. The study is consistent with models that explain secondary succession as a process driven by interspecific differences in resource uptake and tolerance. Solar radiation uptake (interception) restricts growth to later successional species that are tolerant (able to grow in their shade).

Solar radiation interception in three-dimensional reconstructions of forest canopies.

Fournier, R.A., P.M. Rich, and R. Landry. 1997. Hierarchical characterisation of canopy architecture for boreal forest. Journal of Geophysical Research, BOREAS Special Issue 102(D24):29445-29454.

Reconstruction of the three-dimensional geometry of forest canopies is practical using modern computers, but challenging because of the difficulty of obtaining data concerning the distribution of canopy elements. Once a three-dimensional construction is available, it can be used to simulate solar radiation interception, regimes beneath the canopy, and relations between canopy properties and observed structure from beneath. This study presents a hierarchical methodology for reconstruction of the three-dimensional geometry of forest stands, and compares simulated versus empirical hemispherical views of a forest stand. The three-dimensional geometry of individual trees is reconstructed based

on 1) sub-sampling of branch and leaf elements to enable simulation of individual trees (tree vectorization) and 2) mapping the size, diameter, and height of trees simulated within the stand. There was a strong correspondence between simulated and empirical hemispherical photographs.

Recording and analysing structure

Hemispherical photographs can be used to calculate various indices concerning the physical structure of plant canopies (canopy architecture). LAI is the most common index. Associated with LAI are such measures as mean tip angle (MTA).

Comparison of leaf area index of forest stands.

Chen, J.M., P.M. Rich, S.T. Gower, J.M. Norman, and S. Plummer. 1997. Leaf area index of boreal forests: theory, techniques, and measurements. Journal of Geophysical Research, BOREAS Special Issue 102(D24):29429-29444.

In recent years various studies have begun to provide comparative data concerning LAI. This study reviews LAI calculation theory and compares four methods for field measurement of LAI: TRAC, LAI-2000, sunfleck ceptometer, and hemispherical photography. All of the instruments underestimate LAI of boreal forest stands because of clumping of foliage. Foliage clumping coefficients were determined using a video camera and rotational light table system. Surface area of conifer shoots was measured using a volume displacement method. Hemispherical photography was observed to have the advantage of providing a permanent record of canopy geometry.

Challenges and Opportunities

HemiView is a powerful tool that can be used in many ways. The case studies supplied above represent a sampling of the range of uses of hemispherical photography, but can not be comprehensive. New uses will continually be developed, and depend upon the problems being addressed as well as on ingenuity. Clearly more research is needed in all of the areas mentioned above. The technique is sufficiently well developed, that with care it can yield excellent results. At the same time, neither the limitations nor the opportunities of the technique have been fully explored.

From a technique standpoint, much work is still needed. Systematic studies are needed to compare results from HemiView with other software used for analysis of hemispherical photography; to compare results according to image resolution; and to compare results with different films and camera settings. Further research is needed concerning alternative algorithms for image classification; alternative direct and diffuse models; sensitivity to incorporation of month-to-month variation in cloudiness; importance of diffuse radiation anisotropy (non-uniform distribution according to sky direction); and alternative LAI models. Rigorous measures of errors need to be developed, and standards need to be established, to enable comparisons of results from different study sites. Finally, studies of hemispherical statistics promise to prove fruitful.

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Glossary of Terms

analogue

Information stored in a continuous form. For example, photographic negatives and video images (which are stored as a voltage wave form) are both analogue images. See also digital.

azimuth angle

The angle used to measure compass direction. Generally azimuth angle is measured relative to true North via East. Any sky direction can be represented as a pair of zenith angle, azimuth angle co-ordinates. See also zenith angle

bearing

Equivalent to azimuth angle.

degrees

A unit used to measure angles. There are 360 degrees in a circle. Degrees can be converted to radians by multiplying by $\pi/180$. See also radians

diffuse proportion

The proportion of above atmosphere solar radiation that appears as diffuse light, integrated over the hemisphere.

diffuse site factor

equivalent to indirect site factor (ISF).

diffuse solar radiation

Solar radiation scattered by the atmosphere, including blue sky, reflections from clouds, and the bright aureole surrounding the sun. See also direct solar radiation.

digital

Information stored as a series of discrete units, such that each unit is represented as a numerical (binary) value in a computer. For example, standard computer image formats (e.g., bmp, tiff, jpeg) are stored as an array of discrete values corresponding to brightness or colour. See also analogue.

digitize

The process of converting an analogue signal into digital (binary) form. For example, a negative scanner converts photographic negatives (analogue) to standard computer image formats (digital). See also analogue and digital.

direct radiation

Direct radiation arrives from the direction of the solar disc and includes a small component scattered directly forward.

direct site factor (DSF)

The proportion of direct solar radiation reaching a given location, relative to that in a location with no sky obstructions. Values range from 0 to 1, with 0 being no direct radiation (complete sky obstruction) and 1 being the direct radiation for an open location (no sky obstruction). See also indirect site factor (ISF) and global site factor (GSF).

elevation angle

The angle above the horizon. See also zenith angle and azimuth angle.

equiangular projection

A hemispherical projection in which zenith angle is linearly proportional to radial position. The resulting circular image has the zenith in the centre, the horizons toward the edges, and zenith angle increasing linearly from the centre to the edge.

format

Image file format defines how image information is saved to file. HemiView handles bit mapped pictures, in which the value for each pixel is stored separately. Up to 24 bits may be used to represent each pixel, depending on the colour depth, the simplest being monochrome.

framegrabber

Devices that convert (digitise) video signals (analogue) into digital form. See digitize, analogue, digital.

global site factor (GSF)

The proportion of global radiation under a plant canopy relative to that in the open (“total site factor” of Anderson 1964). Typically, calculated as direct plus diffuse radiation, with reflected radiation ignored. See also direct site factor (DSF) and indirect site factor (ISF).

global solar radiation

The sum of the energy flux densities for direct, diffuse, and reflected radiation is known as total or global radiation.

hemispherical photograph

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 180 degree field of view. The photographs can be analysed to determine the geometry of canopy openings, and in turn, to estimate light beneath the canopy. Thus, canopy photographs can be used to assess local light environments 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.

incoming solar radiation

For any given location at the Earth's surface, the incoming solar radiation, or insolation, consists of three components: 1) direct radiation, which is transmitted unimpeded along the path between the sun and the Earth; 2) diffuse radiation, which results from atmospheric scattering from any sky direction; and 3) reflected radiation, which consists of direct and diffuse radiation that is reflected off surrounding terrain features. Insolation is calculated by integrating direct, diffuse, and reflected radiation components over a specified time interval. Also called insolation.

indirect site factor (ISF)

The proportion of diffuse solar radiation reaching a given location, relative to a location with no sky obstructions. Values range from 0 to 1, with 0 being no diffuse radiation (complete sky obstruction) and 1 being the diffuse radiation for an open location (no sky obstruction). See also direct site factor (DSF) and global site factor (GSF).

insolation

Equivalent to incoming solar radiation.

leaf angle distribution

The distribution of inclination and azimuth angles for leaves. The inclination angle is measured between the perpendicular to the leaf surface and the zenith. The azimuth angle is measured between a horizontal projection of the leaf perpendicular and true North.

leaf area index (LAI)

For broad leaf vegetation, the surface area of leaves per unit ground area. For broad leaf vegetation only the upper (or only the lower) surface area is counted. For conifers (with round or square cross-sections), or other non-flat leaves, LAI is calculated as the total leaf surface area (all sides of leaves) divided by two, all per unit ground area. LAI is widely used in models that examine productivity and transpiration, since both are generally proportional to the leaf area.

photosynthetic photon flux density (PPFD)

Incident photon flux density of PAR: the number of photons (400-700 nm wavelength) incident per unit time on a unit surface. The SI unit is $\text{mol m}^{-2} \text{s}^{-1}$. Usually the units of $\mu\text{mol m}^{-2} \text{s}^{-1}$ or $\mu\text{Einsteins m}^{-2} \text{s}^{-1}$, (not part of the SI system) are used.

photosynthetically active radiation (PAR)

Solar radiation in the 400-700 nm waveband. These wavelengths can be used by green plants in photosynthesis.

PPFD

Photosynthetic Photon Flux Density: Incident photon flux density of PAR: the number of photons (400-700 nm wavelength) incident per unit time on a unit surface. The SI unit is $\text{mol m}^{-2} \text{s}^{-1}$. Usually the units of $\mu\text{mol m}^{-2} \text{s}^{-1}$ or $\mu\text{Einsteins m}^{-2} \text{s}^{-1}$, (not part of the SI system) are used.

productivity

The formation of biomass (matter originating from living organisms). Primary productivity refers to the biomass formed in photosynthesis (or chemosynthesis) from solar energy, carbon dioxide, water, and mineral nutrients. Gross productivity refers to the total biomass formed per unit area (or unit volume for aquatic systems), whereas net productivity refers to the biomass formed after losses by respiration are accounted for.

In terms of energy, gross productivity of the entire Earth's biosphere is estimated at 6.53×10^{18} KJ yr⁻¹. This is equivalent to an average gross productivity per unit area of 12.8 MJ m⁻² per year, or 35.0 KJ m⁻² per day (0.405 W m⁻²). Average daily solar radiation intercepted at Earth's surface is 17.0 MJ m⁻² day⁻¹. Hence gross primary productivity of all the ecosystems of the world has an overall efficiency of 0.207%. Net productivity is considerably less than gross productivity, since respiration consumes, on the average, 3.81×10^{18} KJ of the 6.53×10^{18} KJ of gross productivity per year, giving a value of 2.72×10^{18} KJ for net productivity. When divided by the earth's surface area, this is equivalent to 14.7 KJ m⁻² day⁻¹. The percentage of solar radiation which reaches the ground and shows up in net primary productivity is thus about 0.086%.

radians

A unit used to measure angles. There are 2 PI radians in a circle. Radians can be converted to degrees by multiplying by 180/PI. See also degrees.

solar constant

The amount of solar radiation incident above the atmosphere.

solar radiation

The electromagnetic radiation received from the sun at the surface of the Earth. Solar radiation lies almost entirely in the wavelength band of 0.29 - 4 μm, and is often called shortwave radiation. The amount of solar energy beyond 2.5 μm is very small.

standard overcast sky

In an "standard overcast sky distribution" (SOC), diffuse radiation flux varies with zenith angle according to the following relation from Moon and Spencer (1942):

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

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. See also uniform overcast sky.

transmitivity

Transmitivity is the percentage of the solar radiation incident on the atmosphere that is transmitted in the direct beam, through the atmosphere, from the zenith to sea level. That is, the percentage transmitted through a unit atmosphere depth.

transpiration

Transpiration is the process by which water moves by diffusion from the inner leaf surfaces through stomatal pores to the outside air.

uniform overcast sky

In a uniform diffuse distribution, sometimes referred to as a “uniform overcast sky” or UOC, incoming diffuse radiation is the same from all sky directions. In this case the diffuse radiation is proportional to the angular area of a sky sector. See also standard overcast sky.

viewshed

The directions that are visible from a given location.

zenith angle

The angle used to measure sky direction or inclination relative to the zenith. Any sky direction can be represented as a pair of zenith angle, azimuth angle coordinates. See also azimuth angle

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