# Package 'rcaiman'

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**Type** Package

**Title** CAnopy IMage ANalysis

**Version** 2.0.1

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**Description** Tools for preprocessing and processing canopy photographs with support for raw data reading. Provides methods to address variability in sky brightness and to mitigate errors from image acquisition in non-diffuse light. Works with all types of fish-eye lenses, and some methods also apply to conventional lenses.

**License** GPL-3

**BugReports** https://github.com/GastonMauroDiaz/rcaiman/issues

**Encoding** UTF-8

**LazyData** true

**RoxygenNote** 7.3.2

**Depends** filenamer, magrittr, R (>= 3.5), terra

**Imports** methods, testthat, pracma, stats, utils, Rdpack, spatial, lidR, tcltk, foreach, doParallel

**Suggests** autothresholdr, EBImage, imager, reticulate, hemispheR

**RdMacros** Rdpack

**NeedsCompilation** no

**Author** Gastón Mauro Díaz [aut, cre] (ORCID: <https://orcid.org/0000-0002-0362-8616>)

**Maintainer** Gastón Mauro Díaz <gastonmaurodiaz@gmail.com>

**Repository** CRAN

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# Contents

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`apply_by_direction` *Apply a method by direction using a constant field of view*

---

## Description

Applies a method to each set of pixels defined by a direction and a constant field of view (FOV). By default, several built-in methods are available (see `method`), but a custom function can also be provided via the `fun` argument.

## Usage

```
apply_by_direction(
  r,
  z,
  a,
  m,
  spacing = 10,
  laxity = 2.5,
  fov = c(30, 40, 50),
  method = c("thr_isodata", "detect_bg_dn", "fit_coneshaped_model",
    "fit_trend_surface_np1", "fit_trend_surface_np6"),
  fun = NULL,
  parallel = FALSE
)
```

## Arguments

| | |
|---|---|
| r | terra::SpatRaster of one or more layers (e.g., RGB channels or binary masks) in fisheye projection. |
| z | terra::SpatRaster generated with zenith_image(). |
| a | terra::SpatRaster generated with azimuth_image(). |
| m | logical terra::SpatRaster with one layer. A binary mask with TRUE for selected pixels. |
| spacing | numeric vector of length one. Angular spacing (in degrees) between directions to process. |
| laxity | numeric vector of length one. |
| fov | numeric vector. Field of view in degrees. If more than one value is provided, they are tried in order when a method fails. |
| method | character vector of length one. Built-in method to apply. Available options are "thr_isodata", "detect_bg_dn", "fit_coneshaped_model", "fit_trend_surface_np1", and "fit_trend_surface_np6". Ignored if fun is provided. |
| fun | NULL (default) or a function accepting r, z, a, and m as input and returning a single-layer terra::SpatRaster object with the same number of rows and columns as its first input, r. |
| parallel | logical vector of length one. If TRUE, operations are executed in parallel. |

## Value

terra::SpatRaster object with two layers: "dn" for digital number values and "n" for the number of valid pixels used in each directional estimate.

## Note

This function is part of a manuscript currently under preparation.

## References

There are no references for Rd macro \insertAllCites on this help page.

## Examples

```
## Not run:
caim <- read_caim()
r <- caim$Blue
z <- zenith_image(ncol(caim), lens())
a <- azimuth_image(z)
m <- !is.na(z)

# Automatic sky brightness estimation
sky <- apply_by_direction(r, z, a, m, spacing = 10, fov = c(30, 60),
                          method = "detect_bg_dn", parallel = TRUE)
plot(sky$dn)
plot(r / sky$dn)
```

```
# Using cone-shaped model
sky_cs <- apply_by_direction(caim, z, a, m, spacing = 15, fov = 60,
                             method = "fit_coneshaped_model", parallel = TRUE)
plot(sky_cs$dn)

# Using trend surface model
sky_s <- apply_by_direction(caim, z, a, m, spacing = 15, fov = 60,
                            method = "fit_trend_surface_np1", parallel = TRUE)
plot(sky_s$dn)

# Using a custom thresholding function
thr <- apply_by_direction(r, z, a, m, 15, fov = c(30, 40, 50),
  fun = function(r, z, a, m) {
    thr <- tryCatch(thr_twocorner(r[m])$tm, error = function(e) NA)
    r[] <- thr
    r
  },
  parallel = TRUE
)
plot(thr$dn)
plot(binarize_with_thr(r, thr$dn))

## End(Not run)
```

---

`azimuth_image` *Build azimuth image*

---

## Description

Creates a single-layer raster in which pixel values represent azimuth angles, assuming an upwards-looking hemispherical photograph with the optical axis vertically aligned.

## Usage

```
azimuth_image(z, orientation = 0)
```

## Arguments

| | |
|---|---|
| `z` | terra::SpatRaster generated with `zenith_image()`. |
| `orientation` | numeric vector of length one. Azimuth angle (in degrees) corresponding to the direction at which the top of the image was pointing when the picture was taken. This design follows the common field protocol of recording the angle at which the top of the camera points. |

## Value

terra::SpatRaster with the same dimensions as the input zenith image. Each pixel contains the azimuth angle in degrees, with zero representing North and angles increasing counter-clockwise. The object carries attributes `orientation` and `lens_coef`.

## Note

If `orientation = 0`, North (0 deg) is located at the top of the image, as in conventional maps, but East (90 deg) and West (270 deg) appear flipped relative to maps. To understand this, take two flash-card-sized pieces of paper. Place one on a table in front of you and draw a compass rose on it. Hold the other above your head, with the side facing down toward you, and draw another compass rose following the directions from the one on the table. This mimics the situation of taking an upwards-looking photo with a smartphone while viewing the screen, and it will result in a mirrored arrangement. Compare both drawings to see the inversion.

## Examples

```
z <- zenith_image(600, lens("Nikon_FCE9"))
a <- azimuth_image(z)
plot(a)
## Not run:
a <- azimuth_image(z, 45)
plot(a)

## End(Not run)
```

---

# binarize_by_region *Regional thresholding of greyscale images*

---

## Description

Perform thresholding of greyscale images by applying a method regionally, using a segmentation map.

## Usage

```
binarize_by_region(r, segmentation, method)
```

## Arguments

| | |
|---|---|
| `r` | numeric terra::SpatRaster of one layer. Typically the blue channel of a canopy photograph. |
| `segmentation` | numeric terra::SpatRaster of one layer. A labeled segmentation map defining the regions over which to apply the thresholding method. Ring segmentation (see `ring_segmentation()`) is often preferred for fisheye images (Leblanc et al. 2005). |
| `method` | character vector of length one. Name of the thresholding method to apply. See *Details*. |

## Details

This function supports several thresholding methods applied within the regions defined by `segmentation`:

**Methods from the `autothresholdr` package:** Any method supported by `autothresholdr::auto_thresh()` can be used by specifying its name. For example, `"IsoData"` applies the classic iterative intermeans algorithm Ridler and Calvard (1978), which is among the most recommended for canopy photography (Jonckheere et al. 2005).

**In-package implementation of IsoData:** Use `"thr_isodata"` to apply `thr_isodata()`, a native implementation of the same algorithm

**Two-corner method:** Use `"thr_twocorner"` to apply `thr_twocorner()`, which implements a geometric thresholding strategy based on identifying inflection points in the histogram, first introduced to canopy photography by Macfarlane (2011). Since this method tend to fail, the fallback is `thr_isodata`

## Value

Logical terra::SpatRaster (`TRUE` for sky, `FALSE` for non-sky) of the same dimensions as `r`.

## Note

When methods from the `autothresholdr` package are used, `r` values should be constrained to the range $[0, 1]$. See `normalize_minmax()`.

## References

Jonckheere I, Nackaerts K, Muys B, Coppin P (2005). "Assessment of automatic gap fraction estimation of forests from digital hemispherical photography." *Agricultural and Forest Meteorology*, **132**(1-2), 96–114. doi:10.1016/j.agrformet.2005.06.003.

Leblanc SG, Chen JM, Fernandes R, Deering DW, Conley A (2005). "Methodology comparison for canopy structure parameters extraction from digital hemispherical photography in boreal forests." *Agricultural and Forest Meteorology*, **129**(3–4), 187–207. ISSN 0168-1923, doi:10.1016/j.agrformet.2004.09.006.

Macfarlane C (2011). "Classification method of mixed pixels does not affect canopy metrics from digital images of forest overstorey." *Agricultural and Forest Meteorology*, **151**(7), 833–840. doi:10.1016/j.agrformet.2011.01.019.

Ridler TW, Calvard S (1978). "Picture thresholding using an iterative selection method." *IEEE Transactions on Systems, Man, and Cybernetics*, **8**(8), 630–632. doi:10.1109/tsmc.1978.4310039.

## Examples

```
## Not run:
path <- system.file("external/DSCN4500.JPG", package = "rcaiman")
zenith_colrow <- c(1276, 980)
diameter <- 756*2
caim <- read_caim(path, zenith_colrow - diameter/2, diameter, diameter)
z <- zenith_image(ncol(caim), lens("Nikon_FCE9"))
```

```
r <- invert_gamma_correction(caim$Blue)
r <- correct_vignetting(r, z, c(0.0638, -0.101)) %>% normalize_minmax()
rings <- ring_segmentation(z, 15)
bin <- binarize_by_region(r, rings, "thr_isodata")
plot(bin)

## End(Not run)
```

---

`binarize_with_thr` *Binarize with known thresholds*

---

## Description

Apply a threshold or a raster of thresholds to a grayscale image, producing a binary image.

## Usage

```
binarize_with_thr(r, thr)
```

## Arguments

| | |
|---|---|
| `r` | numeric terra::SpatRaster with one layer. |
| `thr` | either a numeric vector of length one (for global thresholding) or a numeric terra::SpatRaster with one layer (for local thresholding). |

## Details

This function supports both global and pixel-wise thresholding. It is a wrapper around the > operator from the `terra` package. If a single numeric threshold is provided via `thr`, it is applied globally to all pixels in `r`. If instead a terra::SpatRaster object is provided, local thresholding is performed, where each pixel is compared to its corresponding threshold value.

This is useful after estimating thresholds using `thr_twocorner()`, `thr_isodata()`, or `apply_by_direction(method = "thr_isodata")`, among other posibilities.

## Value

Logical terra::SpatRaster (`TRUE` for sky, `FALSE` for non-sky) with the same dimensions as `r`.

## Note

For global thresholding, `thr` must be greater than or equal to the minimum value of `r` and lower than its maximum value.

## Examples

```
r <- read_caim()
bin <- binarize_with_thr(r$Blue, thr_isodata(r$Blue[]))
plot(bin)

## Not run:
# This function is also compatible with thresholds estimated using
# the 'autothresholdr' package:
require(autothresholdr)
r <- r$Blue
r <- normalize_minmax(r) %>% multiply_by(255) %>% round()
thr <- auto_thresh(r[], "IsoData")[1]
bin <- binarize_with_thr(r, thr)
plot(bin)

## End(Not run)
```

---

`calc_diameter` *Calculate diameter*

---

## Description

Calculate the diameter in pixels of a 180 deg fisheye image.

## Usage

```
calc_diameter(lens_coef, radius, angle)
```

## Arguments

| | |
|---|---|
| `lens_coef` | numeric vector. Polynomial coefficients of the lens projection function. See `lens()`. |
| `radius` | numeric vector. Distance in pixels from the zenith. |
| `angle` | numeric vector. Zenith angle in degrees. |

## Details

This function is useful when the recording device has a field of view smaller than 180 deg. Given a lens projection function and data points consisting of radii (pixels) and their corresponding zenith angles ($\theta$), it returns the horizon radius (i.e., the radius for $\theta$ equal to 90 deg).

When working with non-circular hemispherical photography, this function helps determine the diameter that a circular image would have if the equipment recorded the whole hemisphere, required to build the correct zenith image to use as input for `expand_noncircular()`.

The required data (radius–angle pairs) can be obtained following the instructions in the user manual of Hemisfer software. A slightly simpler alternative is:

1. Find a vertical wall and a leveled floor, both well-constructed.

2. Draw a triangle of $5 \times 4 \times 3$ meters on the floor, with the 4-meter side along the wall.
3. Place the camera over the vertex 3 meters away from the wall, at a chosen height (e.g., 1.3 m).
4. Make a mark on the wall at the chosen height over the wall-vertex nearest to the camera vertex. Make four more marks at 1 m intervals along a horizontal line. This creates marks for 0, 18, 34, 45, and 54 deg $\theta$.
5. Before taking the photograph, align the zenith coordinates with the 0 deg $\theta$ mark and ensure the optical axis is level.

The line selection tool of ImageJ can be used to measure the distance in pixels between points on the image. Draw a line and use the menu Analyze > Measure to obtain its length.

For obtaining the projection of a new lens, see `calibrate_lens()`.

## Value

Numeric vector of length one. Estimated diameter in pixels, rounded to the nearest even integer (see `zenith_image()` for details).

## Examples

```
# Nikon D50 and Fisheye Nikkor 10.5mm lens
calc_diameter(lens("Nikkor_10.5mm"), 1202, 54)
```

---

# calc_relative_radius *Calculate relative radius*

---

## Description

Convert zenith angles (degrees) to normalized radial distance using the lens projection model.

## Usage

```
calc_relative_radius(angle, lens_coef)
```

## Arguments

| | |
|---|---|
| `angle` | numeric vector. Zenith angles in degrees. |
| `lens_coef` | numeric vector. Polynomial coefficients of the lens projection function. See `lens()`. |

## Details

This helper maps zenith angle(s) to a relative radius in [0, 1] given the lens projection coefficients.

## Value

Numeric vector of the same length as `angle`, constrained to [0, 1].

## Examples

```
calc_relative_radius(45, lens())
```

---

`calc_spherical_distance` *Calculate spherical distance*

---

## Description

Computes the angular distance, in radians, between directions defined by zenith and azimuth angles on the unit sphere.

## Usage

```
calc_spherical_distance(z1, a1, z2, a2)
```

## Arguments

| | |
|---|---|
| `z1` | numeric vector. Zenithal angle in radians. |
| `a1` | numeric vector. Azimuthal angle in radians. |
| `z2` | numeric vector of length one. Zenithal angle in radians. |
| `a2` | numeric vector of length one. Azimuthal angle in radians. |

## Details

This function calculates the angle between two directions originating from the center of a unit sphere, using spherical trigonometry. The result is commonly referred to as *spherical distance* or *angular distance*. These terms are interchangeable when the sphere has radius one, as is standard in many applications, including celestial coordinate systems and, by extension, canopy hemispherical photography.

Spherical distance corresponds to the arc length of the shortest path between two points on the surface of a sphere. When the radius is one, this arc length equals the angle itself, expressed in radians.

## Value

Numeric vector of the same length as `z1` and `a1`, containing the spherical distance (in radians) from each (`z1`, `a1`) point to the reference direction (`z2`, `a2`).

## Examples

```
set.seed(1)
z1 <- rnorm(10, 45, 20) * pi/180
a1 <- rnorm(10, 180, 90) * pi/180
calc_spherical_distance(z1, a1, 0, 0)
```

`calc_zenith_colrow` *Calculate zenith raster coordinates*

## Description

Calculate zenith raster coordinates from points digitized with the open-source software package 'ImageJ'.

## Usage

```
calc_zenith_colrow(path_to_csv)
```

## Arguments

| | |
|---|---|
| `path_to_csv` | character vector of length one. Path to CSV file created with the ImageJ point selection tool. |

## Details

In this context, "zenith" denotes the location in the image that corresponds to the projection of the vertical direction when the optical axis is aligned vertically.

The technique described under the headline 'Optical center characterization' of the user manual of the software Can-Eye can be used to acquire the data for determining the zenith coordinates. This technique was used by Pekin and Macfarlane (2009), among others. Briefly, it consists in drilling a small hole in the cap of the fisheye lens (away from the center), and taking about ten photographs without removing the cap. The cap must be rotated about 30º before taking each photograph.

The point selection tool of 'ImageJ' software should be used to manually digitize the white dots and create a CSV file to feed this function. After digitizing the points on the image, use the dropdown menu Analyze>Measure to open the Results window. To obtain the CSV file, use File>Save As...

Another method (only valid when enough of the circle perimeter is depicted in the image) is taking a very bright picture (e.g., of a white-painted corner of a room) with the lens uncovered (do not use any mount). Then, digitize points over the circle perimeter. This was the method used for producing the example file (see Examples). It is worth noting that the perimeter of the circle depicted in a circular hemispherical photograph is not necessarily the horizon.

## Value

Numeric vector of length two. Raster coordinates of the zenith. These coordinates follow image (raster) convention: the origin is in the upper-left, and the vertical axis increases downward, like a spreadsheet. This contrasts with Cartesian coordinates, where the vertical axis increases upward.

## Note

This function assumes that all data points belong to the same circle, meaning that it does not support multiple holes when the Can-Eye procedure of drilling the lens cap is applied. The circle is fitted using the method presented by Kasa (1976).

## References

Kasa I (1976). "A circle fitting procedure and its error analysis." *IEEE Transactions on Instrumentation and Measurement*, **IM–25**(1), 8–14. ISSN 1557-9662, doi:10.1109/tim.1976.6312298.

Pekin B, Macfarlane C (2009). "Measurement of crown cover and leaf area index using digital cover photography and its application to remote sensing." *Remote Sensing*, **1**(4), 1298–1320. doi:10.3390/rs1041298.

## Examples

```
## Not run:
path <- system.file("external/points_over_perimeter.csv",
                    package = "rcaiman")
calc_zenith_colrow(path)

## End(Not run)
```

---

`calibrate_lens` *Calibrate lens*

---

## Description

Calibrate a fisheye lens to derive the mathematical relationship between image-space radial distances from the zenith and zenith angles in hemispherical space (assuming upward-looking hemispherical photography with the optical axis vertically aligned).

## Usage

```
calibrate_lens(path_to_csv, degree = 3)
```

## Arguments

| | |
|---|---|
| `path_to_csv` | character vector. Path(s) to CSV file(s) created with the ImageJ point selection tool. See *Note*. |
| `degree` | numeric vector of length one. Polynomial model degree. |

## Details

Fisheye lenses have a wide field of view and radial symmetry with respect to distortion. This property allows precise fitting of a polynomial model to relate pixel distances to zenith angles. The method implemented here, known as the "simple method", is described in detail by Díaz et al. (2024).

## Value

List with named elements:

`ds` Data frame used to fit the model.

`model` `lm` object fitted to pixel distance vs. zenith angle.

`horizon_radius` Radius at 90 deg.

`lens_coef` Numeric vector of polynomial model coefficients for predicting relative radius.

`zenith_colrow` Raster coordinates of the zenith push pin.

`max_theta` Maximum zenith angle (deg).

`max_theta_px` Distance in pixels between the zenith and the maximum zenith angle.

## Step-by-step guide for producing a CSV file to feed this function

### Materials:

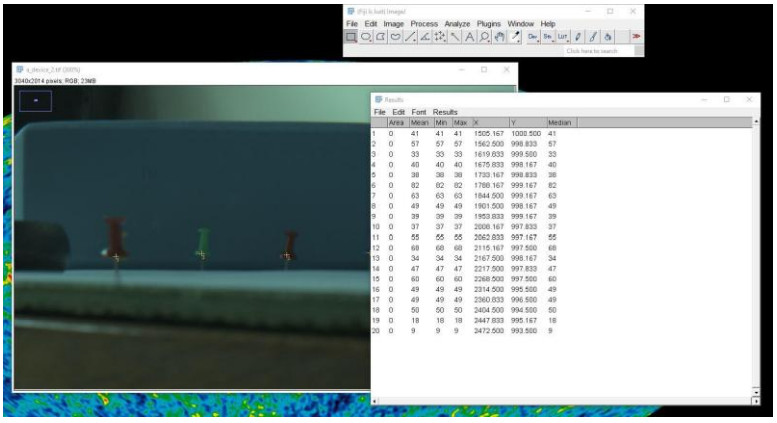
- this package and ImageJ
- camera and lens
- tripod
- standard yoga mat
- table at least as wide as the yoga mat width
- twenty two push pins of different colors
- one print of this sheet (A1 size, almost like a research poster).
- scissors
- some patience

### Instructions:

Cut the sheet by the dashed line. Place the yoga mat extended on top of the table. Place the sheet on top of the yoga mat. Align the dashed line with the yoga mat border closest to you. Place push pins on each cross. If you are gentle, the yoga mat will allow you to do that without damaging the table. Of course, other materials could be used to obtain the same result, such as cardboard, foam, nails, etc.

Place the camera on the tripod. Align its optical axis with the table while looking for getting an image showing the overlapping of the three pairs of push pins, as instructed in the print. In order to take care of the line of pins at 90º relative to the optical axis, it may be of help to use the naked eye to align the entrance pupil of the lens with the pins. The alignment of the push pins only guarantees the position of the lens entrance pupil, the leveling should be cheeked with an instrument, and the alignment between the optical axis and the radius of the zenith push pin should be taken into account. In practice, the latter is achieved by aligning the camera body with the orthogonal frame made by the quarter circle.

Take a photo and transfer it to the computer, open it with ImageJ, and use the point selection tool to digitize the push pins, starting from the zenith push pin and not skipping any shown push pin. End with an additional point where the image meets the surrounding black (or the last pixel in case there is not blackness because it is not a circular hemispherical image. There is no need to follow the line formed by the push pins). Then, use the dropdown menu Analyze>Measure to open the window Results. To obtain the CSV, use File>Save As...



## Note

To calibrate different directions, think of the fisheye image as an analog clock. To calibrate 3 o'clock, attach the camera to the tripod in landscape mode while leaving the quarter-circle at the lens's right side. To calibrate 9 o'clock, rotate the camera to put the quarter-circle at the lens's left side. To calibrate 12 and 6 o'clock, do the same but with the camera in portrait mode.

## References

Díaz GM, Lang M, Kaha M (2024). "Simple calibration of fisheye lenses for hemipherical photography of the forest canopy." *Agricultural and Forest Meteorology*, **352**, 110020. ISSN 0168-1923, doi:10.1016/j.agrformet.2024.110020.

## See Also

`test_lens_coef()`, `crosscalibrate_lens()`, `extract_radiometry()`

## Examples

```
path <- system.file("external/Results_calibration.csv", package = "rcaiman")
calibration <- calibrate_lens(path)
coefficients(calibration$model)
calibration$lens_coef %>% signif(3)
calibration$horizon_radius

## Not run:
test_lens_coef(calibration$lens_coef) #MacOS and Windows tend to differ here
test_lens_coef(c(0.628, 0.0399, -0.0217))

## End(Not run)

.fp <- function(theta, lens_coef) {
  x <- lens_coef[1:5]
  x[is.na(x)] <- 0
  for (i in 1:5) assign(letters[i], x[i])
  a * theta + b * theta^2 + c * theta^3 + d * theta^4 + e * theta^5
}

plot(calibration$ds)
theta <- seq(0, pi/2, pi/180)
lines(theta, .fp(theta, coefficients(calibration$model)))
```

---

# chessboard *Perform chessboard segmentation*

---

## Description

Segment a raster into square regions of equal size arranged in a chessboard-like pattern.

### Usage

```
chessboard(r, size)
```

### Arguments

| | |
|---|---|
| r | numeric terra::SpatRaster. One or more layers used to drive heterogeneity. |
| size | Numeric vector of length one. Size (in pixels) of each square segment. Must be a positive integer. |

### Details

This function divides the extent of a terra::SpatRaster into non-overlapping square segments of the given size, producing a segmentation map where each segment has a unique integer label. It can be an alternative to `sky_grid_segmentation()` in special cases.

### Value

terra::SpatRaster with one layer and integer values, where each unique value corresponds to a square-segment ID.

### Examples

```
caim <- read_caim()
seg <- chessboard(caim, 20)
plot(caim$Blue)
plot(extract_feature(caim$Blue, seg))
```

---

## cie_image *CIE sky image*

---

### Description

Generate an image of relative radiance or luminance based on the CIE General Sky model.

### Usage

```
cie_image(z, a, sun_angles, sky_coef)
```

### Arguments

| | |
|---|---|
| z | terra::SpatRaster generated with `zenith_image()`. |
| a | terra::SpatRaster generated with `azimuth_image()`. |
| sun_angles | named numeric vector of length two, with components `z` and `a` in degrees, e.g., `c(z = 49.3, a = 123.1)`. See `estimate_sun_angles()` for details. |
| sky_coef | numeric vector of length five. Parameters of the CIE sky model. |

## Value

terra::SpatRaster with one layer whose pixel values represent relative luminance or radiance across the sky hemisphere, depending on whether the data used to obtain `sky_coef` was luminance or radiance.

## Note

Coefficient sets and formulation are available in cie_table.

## Examples

```
z <- zenith_image(50, lens())
a <- azimuth_image(z)
sky_coef <- cie_table[4,1:5] %>% as.numeric()
sun_angles <- c(z = 45, a = 0)
plot(cie_image(z, a, sun_angles, sky_coef))
```

---

# `cie_table` *Set of 15 CIE Standard Skies*

---

## Description

The Commission Internationale de l'Éclairage (CIE; International Commission on Illumination) standard (CIE 2004) defines 15 pre-calibrated sky luminance distributions, each described by a pair of analytical functions, the **gradation function** $\Phi(\theta) = 1 + a \cdot \exp\left(\frac{b}{\cos\theta}\right)$, and the **indicatrix function** $f(\chi) = 1 + c \cdot \left[\exp(d \cdot \chi) - \exp\left(d \cdot \frac{\pi}{2}\right)\right] + e \cdot \cos^2\chi$. Combined, they can predict the relative radiance $\rho_R$ in any sky direction $(\theta, \phi)$ as: $\hat{\rho_R}^{\circ}(\theta,\phi) = \frac{\Phi(\theta)\cdot f(\chi(\theta,\phi;\theta_\odot,\phi_\odot))}{\Phi(0)\cdot f(\chi(\theta,\phi;0,0))}$, where $\theta$ is the zenith angle, $\phi$ is the azimuth angle, and $\theta_\odot, \phi_\odot$ are the zenith and azimuth of the sun disk.

## Usage

```
cie_table
```

## Format

`data.frame` with 15 rows and 8 columns:

`a` gradation function parameter.

`b` gradation function parameter.

`c` indicatrix function parameter.

`d` indicatrix function parameter.

`e` indicatrix function parameter.

`indicatrix_group` factor with six categories and numerical tags.

`general_sky_type` factor with three categories: `"Overcast"`, `"Clear"`, and `"Partly cloudy"`.

`description` user-friendly description of the sky type.

## Source

Li et al. (2016)

## References

CIE (2004). "ISO 15469:2004(E) / CIE S 011/E:2003 - Spatial distribution of daylight — CIE standard general sky." https://www.iso.org/standard/38608.html. International Standard.

Li DHW, Lou S, Lam JC, Wu RHT (2016). "Determining solar irradiance on inclined planes from classified CIE (International Commission on Illumination) standard skies." *Energy*, **101**, 462–470. doi:10.1016/j.energy.2016.02.054.

---

`complementary_gradients`

*Calculate complementary gradients*

---

## Description

Compute three color-opponent gradients to enhance the visual separation between sky and canopy in hemispherical photographs, particularly under diffuse light or complex cloud patterns.

## Usage

```
complementary_gradients(caim)
```

## Arguments

| | |
|---|---|
| `caim` | numeric terra::SpatRaster with three layers named `"Red"`, `"Green"`, and `"Blue"`. Digital numbers should be linearly related to radiance. See `read_caim_raw()` for details. |

## Details

The method exploits chromatic differences between the red, green, and blue bands, following a simplified opponent-color logic. Each gradient is normalized by total brightness and modulated by a logistic contrast function to reduce the influence of underexposed regions:

- `"green_magenta"` = $(R - G + B)/(R + G + B) \cdot$ logistic(brightness)
- `"yellow_blue"` = $(-R - G + B)/(R + G + B) \cdot$ logistic(brightness)
- `"red_cyan"` = $(-R + G + B)/(R + G + B) \cdot$ logistic(brightness)

The `logistic(brightness)` term is computed as:

$$\text{logistic}(x) = \frac{1}{1 + \exp\left(-\frac{x - q_{0.1}}{\text{IQR}}\right)}$$

where $q_{0.1}$ is the 10th percentile of brightness values ($x = R+G+B$), and $IQR$ is their interquartile range.

This weighting suppresses gradients in poorly exposed regions to reduce spurious values caused by low signal-to-noise ratios.

## Value

Numeric terra::SpatRaster with three layers and the same geometry as `caim`. The layers (`"green_magenta"`, `"yellow_blue"`, `"red_cyan"`) are chromatic gradients modulated by brightness.

## Note

This function is part of a paper under preparation.

## References

There are no references for Rd macro `\insertAllCites` on this help page.

## Examples

```
## Not run:
caim <- read_caim()
com <- complementary_gradients(caim)
plot(com)

## End(Not run)
```

---

# compute_canopy_openness

*Calculate canopy openness*

---

## Description

Calculate canopy openness from a binarized hemispherical image with angular coordinates.

## Usage

```
compute_canopy_openness(bin, z, a, m = NULL, angle_width = 10)
```

## Arguments

| | |
|---|---|
| `bin` | logical terra::SpatRaster with one layer. A binarized hemispherical image. See `binarize_with_thr()` for details. |
| `z` | terra::SpatRaster generated with `zenith_image()`. |
| `a` | terra::SpatRaster generated with `azimuth_image()`. |
| `m` | logical terra::SpatRaster with one layer. A binary mask with `TRUE` for selected pixels. |
| `angle_width` | numeric vector of length one. Angle in deg that must divide both 0–360 and 0–90 into an integer number of segments. Retrieve a set of valid values by running `lapply(c(45, 30, 18, 10), function(a) vapply(0:6, function(x) a/2^x, 1))`. |

## Details

Canopy openness is computed following the equation from Gonsamo et al. (2011):

$$CO = \sum_{i=1}^{N} GF(\phi_i, \theta_i) \cdot \frac{\cos(\theta_{1,i}) - \cos(\theta_{2,i})}{n_i}$$

where $GF(\phi_i, \theta_i)$ is the gap fraction in cell $i$, $\theta_{1,i}$ and $\theta_{2,i}$ are the lower and upper zenith angles of the cell, $n_i$ is the number of cells in the corresponding zenith ring, and $N$ is the total number of cells.

When a mask is provided via the `m` argument, the equation is adjusted to compensate for the reduced area of the sky vault:

$$CO = \frac{\sum_{i=1}^{N} GF(\phi_i, \theta_i) \cdot w_i}{\sum_{i=1}^{N} w_i} \quad \text{with} \quad w_i = \frac{\cos(\theta_{1,i}) - \cos(\theta_{2,i})}{n_i}$$

The denominator ensures that the resulting openness value remains scale-independent. Without this normalization, masking would lead to underestimation, as the numerator alone assumes full hemispherical coverage.

## Value

Numeric vector of length one, constrained to the range $[0, 1]$.

## References

Gonsamo A, Walter JN, Pellikka P (2011). "CIMES: A package of programs for determining canopy geometry and solar radiation regimes through hemispherical photographs." *Computers and Electronics in Agriculture*, **79**(2), 207–215. doi:10.1016/j.compag.2011.10.001.

## Examples

```
caim <- read_caim()
z <- zenith_image(ncol(caim), lens())
a <- azimuth_image(z)
m <- select_sky_region(z, 0, 70)
bin <- binarize_with_thr(caim$Blue, thr_isodata(caim$Blue[m]))
plot(bin)
compute_canopy_openness(bin, z, a, m, 10)
```

conventional_lens_image *Generate conventional-lens-like image*

## Description

Create an RGB image that resembles a photo taken with a conventional lens, using a small patch from the example hemispherical image.

## Usage

```
conventional_lens_image()
```

## Details

This is a fixed crop and reorientation of `read_caim()`. It does not perform any re-projection. Intended for documentating functions.

The following code was used to define the region:

```
caim <- read_caim()
r <- caim$Blue
z <- zenith_image(ncol(caim), lens())
a <- azimuth_image(z)

m <- rast(z)
m[] <- calc_spherical_distance(
  z[] * pi / 180,
  a[] * pi / 180,
  1,# hinge-angle
  90 * pi / 180
)
m <- !binarize_with_thr(m, 30 * pi / 180)
m[is.na(z)] <- 0
m

x11()
plot(m * caim$Blue)
za <- click(c(z, a))
za
row_col <- row_col_from_zenith_azimuth(z, a, za[,1], za[,2])
plot(caim$Blue)
points(row_col$col, nrow(caim) - row_col$row, col = 2, pch = 10)
mn_y <- min(nrow(caim) -row_col$row)
mx_y <- max(nrow(caim) -row_col$row)
mn_x <- min(row_col$col)
mx_x <- max(row_col$col)
r <- terra::crop(caim$Blue, terra::ext(mn_x, mx_x, mn_y, mx_y))
plot(r)
```

## Value

Three-layer terra::SpatRaster with bands in RGB order.

## See Also

`read_caim()`

## Examples

```
conventional_lens_image()
```

---

`correct_vignetting` *Correct vignetting effect*

---

## Description

Apply a vignetting correction to an image using a polynomial model.

## Usage

```
correct_vignetting(r, z, lens_coef_v)
```

## Arguments

| | |
|---|---|
| `r` | terra::SpatRaster of one or more layers (e.g., RGB channels or binary masks) in fisheye projection. |
| `z` | terra::SpatRaster generated with `zenith_image()`. |
| `lens_coef_v` | numeric vector. Coefficients of the vignetting function $f_v(\theta) = 1 + a\theta + b\theta^2 + \cdots + m\theta^n$, where $\theta$ is the zenith angle (in radians) and $a, b, \ldots, m$ are the polynomial coefficients. Degrees up to 6 are supported. See `extract_radiometry()` for guidance on estimating these coefficients. |

## Details

Vignetting is the gradual reduction of image brightness toward the periphery. This function corrects it by applying a device-specific correction as a function of the zenith angle at each pixel.

## Value

terra::SpatRaster with the same content as `r` but with pixel values adjusted to correct for vignetting, preserving all other properties (layers, names, extent, and CRS).

## Examples

```
## Not run:
path <- system.file("external/APC_0836.jpg", package = "rcaiman")
caim <- read_caim(path)
z <- zenith_image(2132, lens("Olloclip"))
a <- azimuth_image(z)
zenith_colrow <- c(1063, 771)

caim <- expand_noncircular(caim, z, zenith_colrow)
m <- !is.na(caim$Red) & !is.na(z)
caim[!m] <- 0

bin <- binarize_with_thr(caim$Blue, thr_isodata(caim$Blue[m]))
display_caim(caim$Blue, bin)

caim <- invert_gamma_correction(caim, 2.2)
caim <- correct_vignetting(caim, z, c(-0.0546, -0.561, 0.22)) %>%
        normalize_minmax()

## End(Not run)
```

---

`crop_caim` *Crop a canopy image*

---

## Description

Extracts a rectangular region of interest (ROI) from a canopy image. This function complements `read_caim()` and `read_caim_raw()`.

## Usage

```
crop_caim(r, upper_left = NULL, width = NULL, height = NULL)
```

## Arguments

| | |
|---|---|
| `r` | terra::SpatRaster. |
| `upper_left` | numeric vector of length two. Pixel coordinates of the upper-left corner of the ROI, in the format `c(column, row)`. |
| `width, height` | numeric vector of length one. Size (in pixels) of the rectangular ROI to read. |

## Value

terra::SpatRaster object containing the same layers and values as `r` but restricted to the selected ROI, preserving all other properties.

## Note

`rcaiman` uses terra without geographic semantics: rasters are kept with unit resolution (cell size = 1) and a standardized extent `ext(0, ncol, 0, nrow)` with CRS EPSG:7589.

## Examples

```
caim <- read_caim()
ncell(caim)
caim <- crop_caim(caim, c(231,334), 15, 10)
ncell(caim)
```

---

`crosscalibrate_lens` *Cross-calibrate lens*

---

## Description

Given two photographs taken from the same point (matching entrance pupils and aligned optical axes), with calibrated and uncalibrated cameras, derives a polynomial projection for the uncalibrated device. Intended for cases where a camera calibrated with a method of higher accuracy than `calibrate_lens()` is available, or when there is a main camera to which all other devices should be adjusted.

Points must be digitized in tandem with ImageJ and saved as CSV files. See `calibrate_lens()` for background and general concepts.

## Usage

```
crosscalibrate_lens(
  path_to_csv_uncal,
  path_to_csv_cal,
  zenith_colrow_uncal,
  zenith_colrow_cal,
  diameter_cal,
  lens_coef,
  degree = 3
)
```

## Arguments

`path_to_csv_uncal`, `path_to_csv_cal`
: character vectors of length one. Paths to CSV files created with ImageJ's point selection tool (uncalibrated and calibrated images, respectively).

`zenith_colrow_uncal`, `zenith_colrow_cal`
: numeric vectors of length two. Raster coordinates of the zenith for the uncalibrated and calibrated images; see `calc_zenith_colrow()`.

`diameter_cal`
: numeric vector of length one. Image diameter (pixels) of the calibrated camera.

`lens_coef`
: numeric vector. Lens projection coefficients of the calibrated camera.

`degree`
: numeric vector of length one. Polynomial degree for the uncalibrated model fit (default 3).

## Details

Estimate a lens projection for an uncalibrated camera by referencing a calibrated camera photographed from the exact same location.

## Value

List with components:

`ds` `data.frame` with zenith angle (`theta`, radians) and pixel radius (`px`) from the uncalibrated camera.

`model` `lm` object: polynomial fit of `px ~ theta`.

`horizon_radius` numeric vector of length one. Pixel radius at 90 deg.

`lens_coef` numeric vector. Distortion coefficients normalized by `horizon_radius`.

## See Also

`calibrate_lens()`, `calc_zenith_colrow()`

---

# `defuzzify` *Defuzzify a fuzzy classification*

---

## Description

Converts fuzzy membership values into a binary classification using a regional approach that preserves aggregation consistency between the fuzzy and binary representations.

## Usage

```
defuzzify(mem, segmentation)
```

## Arguments

| | |
|---|---|
| `mem` | numeric terra::SpatRaster of one layer. Degree of membership in a fuzzy classification. |
| `segmentation` | single-layer terra::SpatRaster with integer values. |

## Details

The conversion is applied within segments defined by `segmentation`, ensuring that, in each segment, the aggregated Boolean result matches the aggregated fuzzy value. This approach is well suited for converting subpixel estimates, such as gap fraction, into binary outputs.

## Value

Logical terra::SpatRaster of the same dimensions as `mem`, where each pixel value represents the binary version of `mem` after applying the regional defuzzification procedure.

### Note

This method is also available in the HSP software package. See `hsp_compat()`.

### Examples

```
## Not run:
caim <- read_caim()
r <- caim$Blue
z <- zenith_image(ncol(caim), lens())
a <- azimuth_image(z)

path <- system.file("external/example.txt", package = "rcaiman")
sky_cie <- read_sky_cie(gsub(".txt", "", path), z, a)

sky_above <- ootb_sky_above(sky_cie$model$rr$sky_points, z, a, sky_cie)

ratio <- r / sky_above$dn_raster
ratio <- normalize_minmax(ratio, 0, 1, TRUE)
plot(ratio)
g <- sky_grid_segmentation(z, a, 10)
bin2 <- defuzzify(ratio, g)
plot(bin2) # unsatisfactory results due to light conditions

## End(Not run)
```

---

## `display_caim` *Display a canopy image*

---

### Description

Wrapper for `EBImage::display()` that streamlines the visualization of canopy images, optionally overlaying binary masks and segmentation borders. It is intended for quick inspection of processed or intermediate results in a graphical viewer.

### Usage

```
display_caim(caim = NULL, bin = NULL, g = NULL)
```

### Arguments

| | |
|---|---|
| `caim` | terra::SpatRaster. Typically the output of `read_caim()`. Can be multi- or single-layer. |
| `bin` | logical terra::SpatRaster with one layer. A binarized hemispherical image. See `binarize_with_thr()` for details. |
| `g` | single-layer terra::SpatRaster with integer values. Sky segmentation map produced by `sky_grid_segmentation()`. |

## Value

Invisible NULL. Called for side effects (image viewer popup).

## Examples

```
## Not run:
caim <- read_caim()
z <- zenith_image(ncol(caim), lens())
r <- normalize_minmax(caim$Blue)
g <- ring_segmentation(z, 30)
bin <- binarize_by_region(r, g, method = "thr_isodata")
display_caim(caim$Blue, bin, g)

## End(Not run)
```

---

# estimate_sun_angles *Estimate sun angular coordinates*

---

## Description

Estimates the sun's zenith and azimuth angles (deg) from a canopy hemispherical photograph, using either direct detection of the solar disk or indirect cues from the circumsolar region.

## Usage

```
estimate_sun_angles(
  r,
  z,
  a,
  bin,
  g,
  angular_radius_sun = 30,
  method = "assume_obscured"
)
```

## Arguments

| | |
|---|---|
| r | numeric terra::SpatRaster of one layer. Typically the blue band of a canopy image. |
| z | terra::SpatRaster generated with zenith_image(). |
| a | terra::SpatRaster generated with azimuth_image(). |
| bin | logical terra::SpatRaster of one layer. Binary image where TRUE marks candidate sky pixels. Typically the output of binarize_with_thr(). |
| g | single-layer terra::SpatRaster with integer values. Sky segmentation map produced by sky_grid_segmentation(). |

`angular_radius_sun`
: numeric vector of length one. Maximum angular radius (in degrees) used to define the circumsolar region.

`method`
: character vector of length one. Estimation mode: `"assume_obscured"` (default) or `"assume_veiled"`.

## Details

This function can operate under two alternative assumptions for estimating the sun position:

**Veiled sun** The solar disk is visible or partially obscured; the position is inferred from localized brightness peaks.

**Obscured sun** The solar disk is not visible; the position is inferred from radiometric and spatial cues aggregated over the circumsolar region.

When `method = "assume_veiled"`, `g` and `angular_radius_sun` are ignored. Estimates refer to positions above the horizon; therefore, estimated angles may require further manipulation if the photograph was acquired under crepuscular light.

## Value

Named numeric vector of length two, with names `z` and `a`, representing the sun's zenith and azimuth angles (in degrees).

## Note

A scientific article presenting and validating this method is currently under preparation.

## Examples

```
## Not run:
caim <- read_caim()
z <- zenith_image(ncol(caim), lens())
a <- azimuth_image(z)
m <- !is.na(z)
r <- caim$Blue

bin <- binarize_by_region(r, ring_segmentation(z, 15), "thr_isodata") &
  select_sky_region(z, 0, 88)

g <- sky_grid_segmentation(z, a, 10)
sun_angles <- estimate_sun_angles(r, z, a, bin, g,
                                  angular_radius_sun = 30)
row_col <- row_col_from_zenith_azimuth(z, a,
                                       sun_angles["z"],
                                       sun_angles["a"])
plot(caim$Blue)
points(row_col[1,2], nrow(caim) - row_col[1,1], col = "yellow",
       pch = 8, cex = 3)

## End(Not run)
```

expand_noncircular *Expand non-circular*

## Description

Add NA margins to a hemispherical photograph to align radiance at the zenith with the image center. In this context, "zenith" denotes the location in the image that corresponds to the projection of the vertical direction when the optical axis is aligned vertically. Intended for non-circular images.

## Usage

```
expand_noncircular(caim, z, zenith_colrow)
```

## Arguments

| | |
|---|---|
| caim | terra::SpatRaster. Typically the output of read_caim(). |
| z | terra::SpatRaster generated with zenith_image(). |
| zenith_colrow | numeric vector of length two. Raster coordinates of the zenith (column, row). See calc_zenith_colrow(). Coordinates follow the raster convention (column, row), not matrix order. |

## Value

terra::SpatRaster with the same layers and pixel values as caim, but with NA margins added to center the zenith.

## Note

rcaiman uses terra without geographic semantics: rasters are kept with unit resolution (cell size = 1) and a standardized extent ext(0, ncol, 0, nrow) with CRS EPSG:7589.

## Examples

```
## Not run:
# Non-circular fisheye images from a smartphone with an auxiliary Lens
# (also applicable to non-circular fisheye images from DSLR cameras)
path <- system.file("external/APC_0836.jpg", package = "rcaiman")
caim <- read_caim(path)
z <- zenith_image(2132/2,  lens("Olloclip"))
a <- azimuth_image(z)
zenith_colrow <- c(1063, 771)/2
caim <- expand_noncircular(caim, z, zenith_colrow)
plot(caim$Blue, col = seq(0, 1, 1/255) %>% grey())
m <- !is.na(caim$Red) & !is.na(z)
plot(m, add = TRUE, alpha = 0.3, legend = FALSE)

## End(Not run)
```

`extract_dn` *Extract digital numbers from sky points*

## Description

Obtain digital numbers from a raster at positions defined by sky points, with optional local averaging.

## Usage

```
extract_dn(r, sky_points, use_window = TRUE)
```

## Arguments

| | |
|---|---|
| `r` | terra::SpatRaster. Image from which `sky_points` were sampled (or any raster with identical dimensions). |
| `sky_points` | `data.frame` with columns `row` and `col` (raster coordinates). |
| `use_window` | logical of length one. If `TRUE` (default), use a $3 \times 3$ local mean around each point; if `FALSE`, use only the central pixel. |

## Details

Wraps `terra::extract()` to support a $3 \times 3$ window centered on each target pixel (local mean). When it is disabled, only the central pixel value is retrieved.

## Value

`data.frame` containing the original `sky_points` plus one column per layer in `r` (named after the layers).

## Note

For instructions on manually digitizing sky points, see the "Digitizing sky points with ImageJ" and "Digitizing sky points with QGIS" sections in `fit_cie_model()`.

## See Also

`extract_sky_points()`

## Examples

```
## Not run:
caim <- read_caim()
r <- caim$Blue
z <- zenith_image(ncol(caim), lens())
a <- azimuth_image(z)

# See fit_cie_model() for details on below file
```

```
path <- system.file("external/sky_points.csv",
                    package = "rcaiman")
sky_points <- read.csv(path)
sky_points <- sky_points[c("Y", "X")]
colnames(sky_points) <- c("row", "col")
head(sky_points)
plot(caim$Blue)
points(sky_points$col, nrow(caim) - sky_points$row, col = 2, pch = 10)

sky_points <- extract_dn(caim, sky_points)
head(sky_points)

# To aggregate DNs across points (excluding 'row' and 'col'):
apply(sky_points[, -(1:2)], 2, mean, na.rm = TRUE)

## End(Not run)
```

---

`extract_feature` *Extract feature*

---

## Description

Extract a numeric or logical summary from segmented raster regions using a user-defined reducer, returning one value per segment as a raster map or a named vector.

## Usage

```
extract_feature(
  r,
  segmentation,
  fun = mean,
  return = "raster",
  ignore_label_0 = TRUE
)
```

## Arguments

| | |
|---|---|
| `r` | numeric terra::SpatRaster with one layer. |
| `segmentation` | single-layer terra::SpatRaster. Segmentation map of r, typically created with functions such as `sky_grid_segmentation()`, `ring_segmentation()` or `sector_segmentation()`, but any raster with integer segment labels is accepted. |
| `fun` | function taking a numeric/logical vector and returning a single numeric or logical value (default `mean`). |
| `return` | character of length one. Either `"raster"` (default) or `"vector"`, controlling whether to return a map with per-segment values or a named vector (one value per segment). |
| `ignore_label_0` | logical of length one. If `TRUE`, the segment labeled `0` is ignored. |

### Details

Segments labeled `0` can be ignored via `ignore_label_0 = TRUE`. The function in `fun` must return a single numeric or logical value for any input vector (e.g., `mean`, `median`, or a custom reducer).

### Value

If `return = "raster"`, a terra::SpatRaster where each pixel holds its segment's feature value. If `return = "vector"`, a named numeric (or logical) vector with one value per segment.

### Examples

```
r <- read_caim()
z <- zenith_image(ncol(r),lens())
a <- azimuth_image(z)
g <- sky_grid_segmentation(z, a, 10)
print(extract_feature(r$Blue, g, return = "vector"))
# plot(extract_feature(r$Blue, g, return = "raster"))
```

---

## `extract_radiometry` *Extract radiometry data for calibration*

---

### Description

Buid a datasets for vignetting modeling by sistematically extracting radiometry from images taken with the aid of a portable light source and the calibration board detailed in `calibrate_lens()`.

### Usage

```
extract_radiometry(l, size_px = NULL)
```

### Arguments

| | |
|---|---|
| `l` | list of preprocessed images (terra::SpatRaster) suitable for radiometry sampling. Images must comply with the equidistant projection. |
| `size_px` | numeric vector of length one. Diameter (pixels) of the circular sampling area at the image center; off-center, the sampled region becomes an ellipse under the equidistant projection. If `NULL` (default), two percent of image width is used (`round(terra::ncol(r) * 0.02)`). |

### Value

`data.frame` con dos columnas:

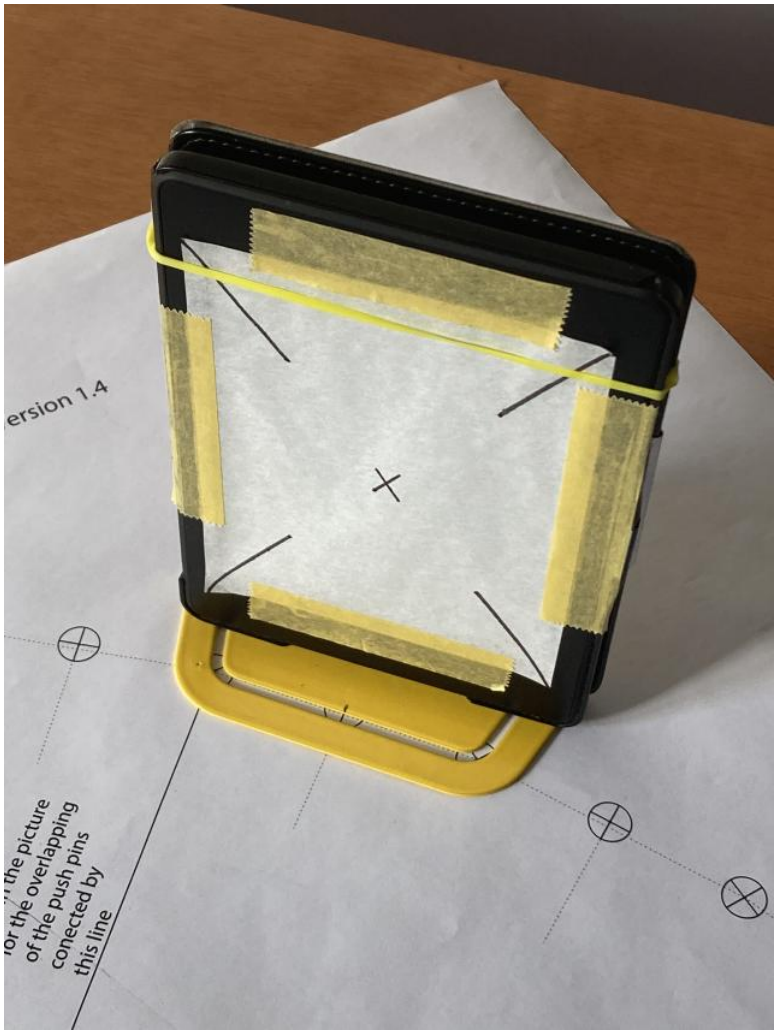
`theta` zenith angle en radianes.

`radiometry` digital number normalizado.

## Guidance

Lenses have the inconvenient property of increasingly attenuating light along the direction orthogonal to the optical axis. This phenomenon is known as the vignetting effect and varies with lens model and aperture setting. The method outlined here, known as the simple method, is explained in details in Díaz et al. (2024). Next explanation might serve mostly as a quick recap of it.

The development of the simple method was done with a Kindle Paperwhite eBooks reader of 6" with built-in light. However, an iPhone 6 plus was also tested in the early stages of development and no substantial differences were observed. A metal bookends desk book holder was used to fasten the eBook reader upright and a semi-transparent paper to favor a Lambertian light distribution. In addition, the latter was used to draw on in order to guide pixel sampling. The book holder also facilitated the alignment of the screen with the dotted lines of the printed quarter-circle.




As a general guideline, a wide variety of mobile devices could be used as light sources, but if scattered data points are obtained with it, then other light sources should be tested in order to double check that the light quality is not the reason for points scattering.

With the room only illuminated by the portable light source, nine photographs should be taken with

the light source located in the equivalent to 0, 10, 20, 30, 40, 50, 60, 70, and 80 degrees of zenith angle, respectively. Camera configuration should be in manual mode and set with the aperture (f/number) for which a vignetting function is required. The shutter speed should be regulated to obtain light-source pixels with middle grey values. The nine photographs should be taken **without changing the camera configuration and the light conditions**.

This code exemplifies how to use the function to obtain data and base R functions to obtain the vignetting function ($f_v$).

```
zenith_colrow <- c(1500, 997)
diameter <- 947*2
z <- zenith_image(diameter, c(0.689, 0.0131, -0.0295))
a <- azimuth_image(z)

.read_raw <- function(path_to_raw_file) {
  r <- read_caim_raw(path_to_raw_file, only_blue = TRUE)
  r <- crop_caim(r, zenith_colrow - diameter/2, diameter, diameter)
  r <- fisheye_to_equidistant(r, z, a, m, radius = diameter/2,
```

```
                                k = 1, p = 1, rmax = 100)
}

l <- Map(.read_raw, dir("raw/up/", full.names = TRUE))
up_data <- extract_radiometry(l)
l <- Map(.read_raw, dir("raw/down/", full.names = TRUE))
down_data <- extract_radiometry(l)
l <- Map(.read_raw, dir("raw/right/", full.names = TRUE))
right_data <- extract_radiometry(l)
l <- Map(.read_raw, dir("raw/left/", full.names = TRUE))
left_data <- extract_radiometry(l)

ds <- rbind(up_data, down_data, right_data, left_data)

plot(ds, xlim = c(0, pi/2), ylim= c(0.5,1.05),
      col = c(rep(1,9),rep(2,9),rep(3,9),rep(4,9)))
legend("bottomleft", legend = c("up", "down", "right", "left"),
       col = 1:4, pch = 1)

fit <- lm((1 - ds$radiometry) ~ poly(ds$theta, 3, raw = TRUE) - 1)
summary(fit)
coef <- -fit$coefficients #did you notice the minus sign?
.fv <- function(x) 1 + coef[1] * x + coef[2] * x^2 + coef[3] * x^3
curve(.fv, add = TRUE, col = 2)
coef
```

Once one of the aperture settings is calibrated, it can be used to calibrate all the rest. To do so, the equipment should be used to take photographs in all desired exposition and without moving the camera, including the aperture already calibrated and preferably under an open sky in stable diffuse light conditions. Below code can be used as a template.

```
zenith_colrow <- c(1500, 997)
diameter <- 947*2
z <- zenith_image(diameter, c(0.689, 0.0131, -0.0295))
a <- azimuth_image(z)

files <- dir("raw/", full.names = TRUE)
l <- list()
for (i in seq_along(files)) {
  if (i == 1) {
    # because the first aperture was the one already calibrated
    .read_raw <- function(path_to_raw_file) {
        r <- read_caim_raw(path_to_raw_file, only_blue = TRUE)
        r <- crop_caim(r, zenith_colrow - diameter/2, diameter, diameter)
        r <- correct_vignetting(r, z, c(0.0302, -0.320, 0.0908))
        r <- fisheye_to_equidistant(r, z, a, m, radius = diameter/2,
                                    k = 1, p = 1, rmax = 100)
      }
  } else {
```

```
      .read_raw <- function(path_to_raw_file) {
          r <- read_caim_raw(path_to_raw_file, only_blue = TRUE)
          r <- crop_caim(r, zenith_colrow - diameter/2, diameter, diameter)
          r <- fisheye_to_equidistant(r, z, a, m, radius = diameter/2,
                                      k = 1, p = 1, rmax = 100)
        }
  }
  l[[i]] <- .read_raw(files[i])
}

ref <- l[[1]]
rings <- ring_segmentation(zenith_image(ncol(ref), lens()), 3)
theta <- seq(1.5, 90 - 1.5, 3) * pi/180

.fun <- function(r) {
  r <- extract_feature(r, rings, return = "vector")
  r/r[1]
}

l <- Map(.fun, l)

.fun <- function(x) {
  x / l[[1]][] # because the first is the one already calibrated
}
radiometry <- Map(.fun, l)

l <- list()
for (i in 2:length(radiometry)) {
  l[[i-1]] <- data.frame(theta = theta, radiometry = radiometry[[i]][])
}
ds <- l[[1]]
head(ds)
```

The result is one dataset (ds) for each file. This is all what it is needed before using base R functions to fit a vignetting function

## Note

This function does not fit the vignetting function itself. The output is a dataset to be used in subsequent modeling steps. See above sections for guidance.

## References

Díaz GM, Lang M, Kaha M (2024). "Simple calibration of fisheye lenses for hemipherical photography of the forest canopy." *Agricultural and Forest Meteorology*, **352**, 110020. ISSN 0168-1923, doi:10.1016/j.agrformet.2024.110020.

`extract_rr` *Extract digital numbers at sky points and normalize by estimated zenith radiance*

## Description

Compute relative radiance at selected sky points by dividing their digital numbers (DN) by an estimated zenith DN.

## Usage

```
extract_rr(r, z, a, sky_points, no_of_points = 3, use_window = TRUE)
```

## Arguments

| | |
|---|---|
| `r` | terra::SpatRaster. Raster supplying the DN values; must share rows and columns with the image used to obtain `sky_points`. DN must be linearly related to radiance. See `read_caim_raw()`. |
| `z` | terra::SpatRaster generated with `zenith_image()`. |
| `a` | terra::SpatRaster generated with `azimuth_image()`. |
| `sky_points` | `data.frame` with columns `row` and `col` (raster coordinates). |
| `no_of_points` | numeric vector of length one or `NULL`. Number of near-zenith points used to estimate the zenith DN using inverse distance weighting (power = 2). If `NULL`, the zenith DN is forced to 1, so `rr` = `dn`. |
| `use_window` | logical of length one. If `TRUE` (default), use a $3 \times 3$ local mean around each point; if `FALSE`, use only the central pixel. |

## Value

List with named elements:

`zenith_dn` numeric. Estimated DN at the zenith.

`sky_points` `data.frame` with columns `row`, `col`, `a`, `z`, `dn`, and `rr` (pixel location, angular coordinates, extracted DN, and relative radiance). If `no_of_points` is `NULL`, `zenith_dn` = 1 and `dn` = `rr`.

## Examples

```
## Not run:
caim <- read_caim()
z <- zenith_image(ncol(caim), lens())
a <- azimuth_image(z)

# See fit_cie_model() for details on the CSV file
path <- system.file("external/sky_points.csv",
                    package = "rcaiman")
sky_points <- read.csv(path)
```

```
sky_points <- sky_points[c("Y", "X")]
colnames(sky_points) <- c("row", "col")
head(sky_points)

plot(caim$Blue)
points(sky_points$col, nrow(caim) - sky_points$row, col = 2, pch = 10)
rr <- extract_rr(caim$Blue, z, a, sky_points, 1)
points(rr$sky_points$col, nrow(caim) - rr$sky_points$row, col = 3, pch = 0)

## End(Not run)
```

---

`extract_sky_points` *Extract sky points*

---

## Description

Sample representative sky pixels for use in model fitting or interpolation.

## Usage

```
extract_sky_points(r, bin, g, dist_to_black = 3, method = "grid")
```

## Arguments

| | |
|---|---|
| `r` | numeric terra::SpatRaster of one layer. Typically the blue band of a canopy image. |
| `bin` | logical terra::SpatRaster of one layer. Binary image where `TRUE` marks candidate sky pixels. Typically the output of `binarize_with_thr()`. |
| `g` | numeric terra::SpatRaster of one layer. Segmentation grid, usually built with `sky_grid_segmentation()` or `chessboard()`. Ignored when `method = "local_max"`. |
| `dist_to_black` | numeric vector of length one or `NULL`. Minimum distance (pixels) to the nearest black pixel for a candidate sky pixel to be valid. If `NULL`, no distance constraint is applied. |
| `method` | character vector of length one. Sampling method; either `"grid"` (default) or `"local_max"`. |

## Details

Two sampling strategies are provided:

`"grid"` select one sky point per cell of a segmentation grid (`g`) as the brightest pixel marked `TRUE` in `bin`, provided the cell's white pixel count exceeds one fourth of the mean across valid cells.

`"local_max"` detect local maxima within a fixed $9 \times 9$ window, restricted to pixels marked `TRUE` in `bin`, after removing patches of connected `TRUE` pixels that are implausible based on fixed area/size thresholds. Each detected maximum is taken as a sky point.

Use `"grid"` to promote an even, representative spatial distribution (good for model fitting), and `"local_max"` to be exhaustive for interpolation.

## Value

`data.frame` with columns `row` and `col`.

## Examples

```
## Not run:
caim <- read_caim()
z <- zenith_image(ncol(caim), lens())
a <- azimuth_image(z)
m <- !is.na(z)
r <- caim$Blue

bin <- binarize_by_region(r, ring_segmentation(z, 15), "thr_isodata") &
  select_sky_region(z, 0, 88)

g <- sky_grid_segmentation(z, a, 10)
sky_points <- extract_sky_points(r, bin, g,
                                 dist_to_black = 3)
plot(bin)
points(sky_points$col, nrow(caim) - sky_points$row, col = 2, pch = 10)

## End(Not run)
```

---

`fisheye_to_equidistant` *Fisheye to equidistant*

---

## Description

Reproject a hemispherical image from fisheye to equidistant projection (also known as polar projection) to standardize its geometry for subsequent analysis and comparison between images.

## Usage

```
fisheye_to_equidistant(r, z, a, m, radius = NULL, k = 1, p = 1, rmax = 100)
```

## Arguments

| | |
|---|---|
| `r` | terra::SpatRaster of one or more layers (e.g., RGB channels or binary masks) in fisheye projection. |
| `z` | terra::SpatRaster generated with `zenith_image()`. |
| `a` | terra::SpatRaster generated with `azimuth_image()`. |
| `m` | logical terra::SpatRaster with one layer. A binary mask with `TRUE` for selected pixels. |
| `radius` | numeric vector of length one. Radius (in pixels) of the reprojected hemispherical image. Must be an integer value (no decimal part). If `NULL` (default), it is set to `ncol(r) / 2`. |

k, p, rmax — numeric vector of length one. Parameters passed to lidR::knnidw(): number of neighbors (k), inverse distance weighting exponent (p), and maximum search radius (rmax) in units of the output resolution.

## Details

Pixel values and coordinates are treated as 3D points and reprojected using Cartesian interpolation. Internally, this function uses lidR::knnidw() as interpolation engine, so arguments k, p, and rmax are passed to it without modification.

## Value

terra::SpatRaster with the same number of layers as r, reprojected to equidistant projection with circular shape and radius given by 'radius

## Examples

```
## Not run:
path <- system.file("external/APC_0836.jpg", package = "rcaiman")
caim <- read_caim(path)
calc_diameter(c(0.801, 0.178, -0.179), 1052, 86.2)
z <- zenith_image(2216,  c(0.801, 0.178, -0.179))
a <- azimuth_image(z)
zenith_colrow <- c(1063, 771)

caim <- expand_noncircular(caim, z, zenith_colrow)
m <- !is.na(caim$Red) & select_sky_region(z, 0, 86.2)
caim[!m] <- 0
m2 <- fisheye_to_equidistant(m, z, a, !is.na(z), radius = 600)
m2 <- binarize_with_thr(m2, 0.5) #to turn it logical
caim2[!m2] <- 0

plot(caim)

## End(Not run)
```

---

# fisheye_to_pano *Fisheye to panoramic*

---

## Description

Reprojects a fisheye (hemispherical) image into a panoramic view using a cylindrical projection. The output is standardized so that rows correspond to zenith angle bands and columns to azimuthal sectors.

## Usage

```
fisheye_to_pano(r, z, a, fun = mean, angle_width = 1)
```

## Arguments

| | |
|---|---|
| r | terra::SpatRaster of one or more layers (e.g., RGB channels or binary masks) in fisheye projection. |
| z | terra::SpatRaster generated with zenith_image(). |
| a | terra::SpatRaster generated with azimuth_image(). |
| fun | function taking a numeric/logical vector and returning a single numeric or logical value (default mean). |
| angle_width | numeric vector of length one. Angle in deg that must divide both 0–360 and 0–90 into an integer number of segments. Retrieve a set of valid values by running lapply(c(45, 30, 18, 10), function(a) vapply(0:6, function(x) a/2^x, 1)). |

## Details

This function computes a cylindrical projection by aggregating pixel values according to their zenith and azimuth angles. Internally, it creates a segmentation grid with sky_grid_segmentation() and applies extract_feature() to compute a summary statistic (e.g., mean) of pixel values within each cell.

## Value

terra::SpatRaster with rows representing zenith angle bands and columns representing azimuthal sectors. The number of layers and names matches that of the input r.

## Note

An early version of this function was used in Díaz et al. (2021).

## References

Díaz GM, Negri PA, Lencinas JD (2021). "Toward making canopy hemispherical photography independent of illumination conditions: A deep-learning-based approach." *Agricultural and Forest Meteorology*, **296**, 108234. doi:10.1016/j.agrformet.2020.108234.

## Examples

```
## Not run:
caim <- read_caim()
z <- zenith_image(ncol(caim), lens())
a <- azimuth_image(z)
pano <- fisheye_to_pano(caim, z, a)
plotRGB(pano %>% normalize_minmax() %>% multiply_by(255))

## End(Not run)
```

fit_cie_model *Fit CIE sky model*

## Description

Fit the CIE sky model to data sampled from a canopy photograph using general-purpose optimization.

## Usage

```
fit_cie_model(
  rr,
  sun_angles,
  custom_sky_coef = NULL,
  std_sky_no = NULL,
  general_sky_type = NULL,
  method = c("Nelder-Mead", "BFGS", "CG", "SANN")
)
```

## Arguments

| | |
|---|---|
| rr | list, typically the output of `extract_rr()`. If generated by other means, it must contain:<br>`zenith_dn` numeric vector of length one.<br>`sky_points` `data.frame` with columns `a` (azimuth, deg), `z` (zenith, deg), and `rr` (relative radiance). |
| sun_angles | named numeric vector of length two, with components `z` and `a` in degrees, e.g., `c(z = 49.3, a = 123.1)`. See `estimate_sun_angles()` for details. |
| custom_sky_coef | numeric vector of length five, or numeric matrix with five columns. Custom starting coefficients for optimization. If not provided, coefficients are initialized from standard skies. |
| std_sky_no | numeric vector. Standard sky numbers as in cie_table. If not provided, all are used. |
| general_sky_type | character vector of length one. Must be `"Overcast"`, `"Clear"`, or `"Partly cloudy"`. See column `general_sky_type` in cie_table for details. If not provided, all sky types are used. |
| method | character vector. Optimization methods passed to `stats::optim()`. See that function for supported names. |

## Details

The method is based on Lang et al. (2010). For best results, the input data should show a linear relation between digital numbers and the amount of light reaching the sensor. See `extract_radiometry()` and `read_caim_raw()` for details. As a compromise solution, `invert_gamma_correction()` can be used.

## Value

List with the following components:

`rr` The input `rr` with an added `pred` column in `sky_points`, containing predicted values.

`opt_result` List returned by `stats::optim()`.

`coef` Numeric vector of length five. CIE model coefficients.

`sun_angles` Numeric vector of length two. Sun zenith and azimuth (degrees).

`method` Character string. Optimization method used.

`start` Numeric vector of length five. Starting parameters.

`metric` Numeric value. Mean squared deviation as in Gauch et al. (2003).

## Background

This function is based on Lang et al. (2010). In theory, the best result would be obtained with data showing a linear relation between digital numbers and the amount of light reaching the sensor. See `extract_radiometry()` and `read_caim_raw()` for further details. As a compromise solution, `invert_gamma_correction()` can be used.

## Digitizing sky points with ImageJ

The point selection tool of 'ImageJ' software can be used to manually digitize points and create a CSV file from which to read coordinates (see *Examples*). After digitizing the points on the image, this is a recommended workflow: 1. Use the dropdown menu *Analyze* > *Measure* to open the Results window. 2. Use *File* > *Save As...* to obtain the CSV file.

Use this code to create the input `sky_points` from ImageJ data:

```
sky_points <- read.csv(path)
sky_points <- sky_points[c("Y", "X")]
colnames(sky_points) <- c("row", "col")
```

## Digitizing sky points with QGIS

To use the QGIS software to manually digitize points, drag and drop the image in an empty project, create an new vector layer, digitize points manually, save the editions, and close the project.

To create the new vector layer, this is a recommended workflow:

1. Fo to the dropdown menu *Layer* > *Create Layer* > *New Geopackage Layer...*
2. Choose "point" in the Geometry type dropdown list
3. Make sure the CRS is EPSG:7589.
4. Click on the *Toogle Editing* icon
5. Click on the *Add Points Feature* icon.

Use this code to create the input `sky_points` from QGIS data:

```
sky_points <- terra::vect(path)
sky_points <- terra::extract(caim, sky_points, cells = TRUE)
sky_points <- terra::rowColFromCell(caim, sky_points$cell) %>% as.data.frame()
colnames(sky_points) <- c("row", "col")
```

## References

Gauch HG, Hwang JTG, Fick GW (2003). "Model evaluation by comparison of model-based predictions and measured values." *Agronomy Journal*, **95**(6), 1442–1446. ISSN 1435-0645, doi:10.2134/agronj2003.1442.

Lang M, Kuusk A, Mõttus M, Rautiainen M, Nilson T (2010). "Canopy gap fraction estimation from digital hemispherical images using sky radiance models and a linear conversion method." *Agricultural and Forest Meteorology*, **150**(1), 20–29. doi:10.1016/j.agrformet.2009.08.001.

## Examples

```
## Not run:
caim <- read_caim()
z <- zenith_image(ncol(caim), lens())
a <- azimuth_image(z)

# Manual method following Lang et al. (2010)
path <- system.file("external/sky_points.csv",
                    package = "rcaiman")
sky_points <- read.csv(path)
sky_points <- sky_points[c("Y", "X")]
colnames(sky_points) <- c("row", "col")
head(sky_points)
plot(caim$Blue)
points(sky_points$col, nrow(caim) - sky_points$row, col = 2, pch = 10)

# x11()
# plot(caim$Blue)
# sun_angles <- click(c(z, a), 1) %>% as.numeric()
sun_angles <- c(z = 49.5, a = 27.4) #taken with above lines then hardcoded

sun_row_col <- row_col_from_zenith_azimuth(z, a,
                                           sun_angles["z"],
                                           sun_angles["a"])
points(sun_row_col[2], nrow(caim) - sun_row_col[1],
       col = "yellow", pch = 8, cex = 3)

rr <- extract_rr(caim$Blue, z, a, sky_points)

set.seed(7)
model <- fit_cie_model(rr, sun_angles,
                           general_sky_type = "Clear")

plot(model$rr$sky_points$rr, model$rr$sky_points$pred)
abline(0,1)
lm(model$rr$sky_points$pred~model$rr$sky_points$rr) %>% summary()

sky <- cie_image(z, a, model$sun_angles, model$coef) * model$rr$zenith_dn

plot(sky)
ratio <- caim$Blue/sky
```

```
plot(ratio)
plot(ratio > 1.05)
plot(ratio > 1.15)

## End(Not run)
```

---

`fit_coneshaped_model` *Fit cone-shaped model*

---

## Description

Fit a polynomial model to predict relative radiance from spherical coordinates using data sampled from a canopy photograph.

## Usage

```
fit_coneshaped_model(sky_points, method = "zenith_n_azimuth")
```

## Arguments

| | |
|---|---|
| `sky_points` | `data.frame` returned by `extract_rr()`. If it is generated by other means, it must have columns `row`, `col`, `z`, `a`, and `rr`. |
| `method` | character. Model type to fit:<br>`"zenith_only"` Quadratic polynomial in zenith angle.<br>`"zenith_n_azimuth"` Quadratic polynomial in zenith plus sinusoidal terms in azimuth. |

## Details

This model requires only `sky_points`, making it useful in workflows where sun position cannot be reliably estimated, such as in `apply_by_direction()`. Otherwise, `fit_cie_model()` is a better choice.

Depending on `method`, it can fit:

***A zenith-only quadratic model***

$$sDN = a + b\theta + c\theta^2$$

***A zenith-plus-azimuth model, adding sinusoidal terms***

$$sDN = a + b\theta + c\theta^2 + d\sin(\phi) + e\cos(\phi)$$

See Díaz and Lencinas (2018) for details on the full model.

## Value

List with the following components:

`fun` Function taking `zenith` and `azimuth` (degrees) and returning predicted relative radiance.

`model` `lm` object fitted by `stats::lm()`.

Returns `NULL` (with a warning) if the number of input points is fewer than 20.

## References

Díaz GM, Lencinas JD (2018). "Model-based local thresholding for canopy hemispherical photography." *Canadian Journal of Forest Research*, **48**(10), 1204–1216. doi:10.1139/cjfr20180006.

## Examples

```
## Not run:
caim <- read_caim()
z <- zenith_image(ncol(caim), lens())
a <- azimuth_image(z)
m <- !is.na(z)
r <- caim$Blue

bin <- binarize_by_region(r, ring_segmentation(z, 15), "thr_isodata") &
  select_sky_region(z, 0, 88)

g <- sky_grid_segmentation(z, a, 10, first_ring_different = TRUE)
sky_points <- extract_sky_points(r, bin, g, dist_to_black = 3)
plot(bin)
points(sky_points$col, nrow(caim) - sky_points$row, col = 2, pch = 10)
rr <- extract_rr(r, z, a, sky_points)

model <- fit_coneshaped_model(rr$sky_points)
summary(model$model)
sky_cs <- model$fun(z, a) * rr$zenith_dn
plot(sky_cs)

z_mini <- zenith_image(50, lens())
sky_cs <- model$fun(z_mini, azimuth_image(z_mini))
persp(sky_cs, theta = 90, phi = 20)


## End(Not run)
```

---

`fit_trend_surface` *Fit a trend surface to sky digital numbers*

---

## Description

Fits a trend surface to sky digital numbers using `spatial::surf.ls()` as the computational workhorse.

## Usage

```
fit_trend_surface(sky_points, r, np = 6, col_id = "dn", extrapolate = FALSE)
```

## Arguments

| | |
|---|---|
| sky_points | data.frame with columns row, col, and one additional numeric column with values to interpolate. Typically returned by extract_rr() or extract_dn(). |
| r | numeric terra::SpatRaster with one layer. Image from which sky_points were derived, or another raster with the same number of rows and columns. Used only as geometric template; cell values are ignored. |
| np | degree of polynomial surface |
| col_id | numeric or character vector of length one. The name or position of the column in sky_points containing the values to interpolate. |
| extrapolate | logical vector of length one. If TRUE, predictions are extrapolated to the entire extent of r; otherwise, predictions are limited to the convex hull of the input sky points. |

## Details

This function models the variation in digital numbers across the sky dome by fitting a polynomial surface in Cartesian space. It is intended to capture smooth large-scale gradients and is more effective when called via apply_by_direction().

## Value

List with named elements:

raster terra::SpatRaster containing the fitted surface.

model object of class trls returned by spatial::surf.ls().

r2 numeric value giving the coefficient of determination ($R^2$) of the fit.

## References

There are no references for Rd macro \insertAllCites on this help page.

## Examples

```
## Not run:
caim <- read_caim()
z <- zenith_image(ncol(caim), lens())
a <- azimuth_image(z)
m <- !is.na(z)
r <- caim$Blue

bin <- binarize_by_region(r, ring_segmentation(z, 15), "thr_isodata") &
  select_sky_region(z, 0, 88)

g <- sky_grid_segmentation(z, a, 10, first_ring_different = TRUE)
sky_points <- extract_sky_points(r, bin, g, dist_to_black = 3)
plot(bin)
points(sky_points$col, nrow(caim) - sky_points$row, col = 2, pch = 10)
sky_points <- extract_dn(r, sky_points, use_window = TRUE)
```

```
sky_s <- fit_trend_surface(sky_points, r, np = 4, col_id = 3,
                           extrapolate = TRUE)
plot(sky_s$raster)
binarize_with_thr(r/sky_s$raster, 0.5) %>% plot()

sky_s <- fit_trend_surface(sky_points, r, np = 6, col_id = 3,
                           extrapolate = FALSE)
plot(sky_s$raster)
binarize_with_thr(r/sky_s$raster, 0.5) %>% plot()

## End(Not run)
```

---

`grow_black` *Grow black regions in a binary mask*

---

## Description

Grow black pixels in a binary mask using a kernel of user-defined size. Useful to reduce errors associated with inter-class borders.

## Usage

```
grow_black(bin, dist_to_black)
```

## Arguments

| | |
|---|---|
| `bin` | logical terra::SpatRaster with one layer. A binarized hemispherical image. See `binarize_with_thr()` for details. |
| `dist_to_black` | numeric vector of length one. Buffer distance (pixels) used to expand black regions. |

## Details

Expands the regions with value `FALSE` (typically rendered as black) in a binary image by applying a square-shaped buffer. Any white pixels (value `TRUE`) within a distance equal to or less than `dist_to_black` from a black pixel will be turned black.

## Value

Logical terra::SpatRaster with the same dimensions as `bin`. Compared to the input `bin`, black regions (`FALSE`) have been expanded by the specified buffer distance.

## Examples

```
## Not run:
r <- read_caim()
bin <- binarize_with_thr(r$Blue, thr_isodata(r$Blue[]))
plot(bin)
bin <- grow_black(bin, 11)
```

```
plot(bin)

## End(Not run)
```

---

`hsp_compat` *HSP compatibility functions*

---

## Description

Read and write legacy files from HSP (HemiSPherical Project Manager) projects to interoperate with existing workflows. Intended for legacy support; not required when working fully within `rcaiman`.

## Usage

```
hsp_read_manual_input(path_to_HSP_project, img_name)

hsp_read_opt_sky_coef(path_to_HSP_project, img_name)

hsp_write_sky_points(sky_points, path_to_HSP_project, img_name)

hsp_write_sun_coord(sun_row_col, path_to_HSP_project, img_name)
```

## Arguments

| | |
|---|---|
| `path_to_HSP_project` | character vector of length one. Path to the HSP project folder (e.g., `"C:/Users/johndoe/Documents/HSP` |
| `img_name` | character vector of length one (e.g., `"DSCN6342.pgm"` or `"DSCN6342"`). See *About HSP software*. |
| `sky_points` | `data.frame` with columns `row` and `col`. |
| `sun_row_col` | numeric vector of length two. Raster coordinates (row, column) of the solar disk. |

## Value

See *Functions*

## About HSP software

HSP (introduced in (Lang et al. 2013), based on the method in (Lang et al. 2010)) runs exclusively on Windows. HSP stores pre-processed images as PGM files in the `manipulate` subfolder of each project (itself inside the `projects` folder).

## Functions

`hsp_read_manual_input()` read sky marks and sun position defined manually within an HSP project; returns a named list with components `weight`, `max_points`, `angle`, `point_radius`, `sun_row_col`, `sky_points`, and `zenith_dn`.

`hsp_read_opt_sky_coef()` read optimized CIE sky coefficients from an HSP project; returns a numeric vector of length five.

`hsp_write_sky_points()` write a file with sky point coordinates compatible with HSP; creates a file on disk.

`hsp_write_sun_coord()` write a file with solar disk coordinates compatible with HSP; creates a file on disk.

## References

Lang M, Kodar A, Arumäe T (2013). "Restoration of above canopy reference hemispherical image from below canopy measurements for plant area index estimation in forests." *Forestry Studies*, **59**(1), 13–27. doi:10.2478/fsmu20130008.

Lang M, Kuusk A, Mõttus M, Rautiainen M, Nilson T (2010). "Canopy gap fraction estimation from digital hemispherical images using sky radiance models and a linear conversion method." *Agricultural and Forest Meteorology*, **150**(1), 20–29. doi:10.1016/j.agrformet.2009.08.001.

## Examples

```
## Not run:
# NOTE: assumes the working directory is the HSP project folder (e.g., an RStudio project).

# From HSP to R in order to compare ---------------------------------------
r <- read_caim("manipulate/IMG_1013.pgm")
z <- zenith_image(ncol(r), lens())
a <- azimuth_image(z)
manual_input <- read_manual_input(".", "IMG_1013")
sun_row_col <- manual_input$sun_row_col
sun_angles <- zenith_azimuth_from_row_col(
  z, a,
  sun_row_col[1],
  sun_row_col[2]
)
sun_angles <- as.vector(sun_angles)

sky_points <- manual_input$sky_points
rr <- extract_rr(r, z, a, sky_points)
model <- fit_cie_model(rr, sun_angles)
sky <- cie_image(
  z, a,
  model$sun_angles,
  model$coef
) * model$rr$zenith_dn
plot(r / sky)

r <- read_caim("manipulate/IMG_1013.pgm")
```

```
sky_coef <- read_opt_sky_coef(".", "IMG_1013")
sky_m <- cie_image(z, a, sun_angles, sky_coef)
sky_m <- cie_sky_manual * manual_input$zenith_dn
plot(r / sky_m)

# From R to HSP  ------------------------------------------------------------
r <- read_caim("manipulate/IMG_1014.pgm")
z <- zenith_image(ncol(r), lens())
a <- azimuth_image(z)
m <- !is.na(z)
g <- sky_grid_segmentation(z, a, 10)
bin <- binarize_with_thr(caim$Blue, thr_isodata(caim$Blue[m]))
bin <- select_sky_region(z, 0, 85) & bin

sun_angles <- estimate_sun_angles(r, z, a, bin, g)
sun_row_col <- row_col_from_zenith_azimuth(
  z, a,
  sun_angles["z"],
  sun_angles["a"]
) %>% as.numeric()
write_sun_coord(sun_row_col, ".", "IMG_1014")

sky_points <- extract_sky_points(r, bin, g)
write_sky_points(sky_points, ".", "IMG_1014")

## End(Not run)
```

---

`interpolate_planar` *Interpolate in planar space*

---

## Description

Interpolate values from canopy photographs using inverse distance weighting (IDW) with k-nearest neighbors in image (planar) coordinates. A radius limits neighbor search.

## Usage

```
interpolate_planar(sky_points, r, k = 3, p = 2, rmax = 200, col_id = "dn")
```

## Arguments

| | |
|---|---|
| `sky_points` | `data.frame` with columns `row`, `col`, and one additional numeric column with values to interpolate. Typically returned by `extract_rr()` or `extract_dn()`. |
| `r` | numeric terra::SpatRaster with one layer. Image from which `sky_points` were derived, or another raster with the same number of rows and columns. Used only as geometric template; cell values are ignored. |
| `k, p, rmax` | numeric vector of length one. Parameters passed to `lidR::knnidw()`: number of neighbors (`k`), inverse distance weighting exponent (`p`), and maximum search radius (`rmax`) in units of the output resolution. |

`col_id` numeric or character vector of length one. The name or position of the column in `sky_points` containing the values to interpolate.

## Details

Delegates interpolation to `lidR::knnidw()`, passing `k`, `p`, and `rmax` unchanged. Defaults follow Lang et al. (2013). Note that `rmax` is given in pixels but intended to approximate 15–20 deg in angular terms. Therefore, this value needs fine-tuning based on image resolution and lens projection. For best results, the interpolated quantity should be linearly related to scene radiance; see `extract_radiometry()` and `read_caim_raw()`. For JPEG images, consider `invert_gamma_correction()` to reverse gamma encoding.

## Value

Numeric terra::SpatRaster with one layer and the same geometry as `r`.

## Note

No consistency checks are performed to ensure that `sky_points` and `r` are geometrically compatible. Incorrect combinations may lead to invalid outputs.

## References

Lang M, Kodar A, Arumäe T (2013). "Restoration of above canopy reference hemispherical image from below canopy measurements for plant area index estimation in forests." *Forestry Studies*, **59**(1), 13–27. doi:10.2478/fsmu20130008.

## Examples

```
## Not run:
caim <- read_caim()
z <- zenith_image(ncol(caim), lens())
a <- azimuth_image(z)
m <- !is.na(z)
r <- caim$Blue

bin <- binarize_by_region(r, ring_segmentation(z, 15), "thr_isodata") &
  select_sky_region(z, 0, 88)

g <- sky_grid_segmentation(z, a, 10)
sky_points <- extract_sky_points(r, bin, g, dist_to_black = 3)
plot(bin)
points(sky_points$col, nrow(caim) - sky_points$row, col = 2, pch = 10)
sky_points <- extract_dn(r, sky_points)

sky <- interpolate_planar(sky_points, r, col_id = 3)
plot(sky)
plot(r/sky)

## End(Not run)
```

`interpolate_spherical` *Interpolate in spherical space*

## Description

Interpolate values from canopy photographs using inverse distance weighting (IDW) with k-nearest neighbors, computing distances in spherical coordinates that map the sky vault. Optionally blend with a model surface to fill voids.

## Usage

```
interpolate_spherical(
  sky_points,
  z,
  a,
  filling_source = NULL,
  w = 1,
  k = 3,
  p = 2,
  angular_radius = 20,
  rule = "any",
  size = 50
)
```

## Arguments

| | |
|---|---|
| `sky_points` | `data.frame` returned by `extract_rr()`. If generated by other means, it must contain columns `row`, `col`, `z`, `a`, and `rr`, where the first four define geometry (degrees) and `rr` is the value to interpolate. |
| `z` | terra::SpatRaster generated with `zenith_image()`. |
| `a` | terra::SpatRaster generated with `azimuth_image()`. |
| `filling_source` | optional numeric terra::SpatRaster with one layer. Surface used to complement `rr` when neighbors are insufficient (e.g., output of `fit_cie_model()`). If `NULL` (default), no filling is applied. |
| `w` | numeric vector of length one. Weight assigned to `filling_source` in the blend with local estimates (see Eq. 6 in Lang et al. (2010)). |
| `k` | numeric vector of length one. Number of neighbors. |
| `p` | numeric vector of length one. Inverse distance weighting exponent. |
| `angular_radius` | numeric vector of length one. The maximum radius for searching k-nearest neighbors (KNN) in degrees. |
| `rule` | character vector of length one. Either `"any"` or `"all"`. With `"any"`, pixels within `angular_radius` of at least one sample are interpolated. With `"all"`, pixels are interpolated only if the `k` nearest neighbors lie within `angular_radius`. If `k = 1`, both are equivalent. |
| `size` | numeric vector of length one. Number of rows and columns of the low-resolution grid used before resampling to full resolution. |

## Details

Distances are great-circle distances on the sky vault. When `filling_source` is provided, local IDW estimates are blended with that surface following Eq. 6 in Lang et al. (2010). For efficiency, interpolation runs on a temporary low-resolution grid of size `size`.

## Value

Numeric terra::SpatRaster with one layer of interpolated values and the geometry of `z`.

## Note

This function assumes that `sky_points` and the terra::SpatRaster inputs are spatially aligned and share the same geometry. No checks are performed to enforce this.

## References

Lang M, Kuusk A, Mõttus M, Rautiainen M, Nilson T (2010). "Canopy gap fraction estimation from digital hemispherical images using sky radiance models and a linear conversion method." *Agricultural and Forest Meteorology*, **150**(1), 20–29. doi:10.1016/j.agrformet.2009.08.001.

## Examples

```
## Not run:
caim <- read_caim()
z <- zenith_image(ncol(caim), lens())
a <- azimuth_image(z)

# Manual method following Lang et al. (2010)
path <- system.file("external/sky_points.csv",
                    package = "rcaiman")
sky_points <- read.csv(path)
sky_points <- sky_points[c("Y", "X")]
colnames(sky_points) <- c("row", "col")
head(sky_points)
plot(caim$Blue)
points(sky_points$col, nrow(caim) - sky_points$row, col = 2, pch = 10)

# x11()
# plot(caim$Blue)
# sun_angles <- click(c(z, a), 1) %>% as.numeric()
sun_angles <- c(z = 49.5, a = 27.4) #taken with above lines then hardcoded

sun_row_col <- row_col_from_zenith_azimuth(z, a,
                                           sun_angles["z"],
                                           sun_angles["a"])
points(sun_row_col[2], nrow(caim) - sun_row_col[1],
       col = "yellow", pch = 8, cex = 3)

rr <- extract_rr(caim$Blue, z, a, sky_points)

set.seed(7)
```

```
model <- fit_cie_model(rr, sun_angles,
                       general_sky_type = "Clear")

sky_cie <- cie_image(z, a, model$sun_angles, model$coef)

sky_rr <- interpolate_spherical(rr$sky_points, z, a,
                                filling_source = sky_cie,
                                w = 1,
                                k = 10,
                                p = 2,
                                angular_radius = 20,
                                rule = "any",
                                size = 50)
plot(r/sky_rr/rr$zenith_dn)

## End(Not run)
```

---

`invert_gamma_correction` *Gamma back correction of JPEG images*

---

## Description

Approximates the inversion of the gamma encoding applied to JPEG images.

## Usage

```
invert_gamma_correction(dn, gamma = 2.2)
```

## Arguments

| | |
|---|---|
| dn | numeric vector or terra::SpatRaster. Digital numbers from a JPEG file (range 0–255, as per standard 8-bit encoding). |
| gamma | numeric vector of length one. Exponent applied in the inverse gamma correction (typically 2.2 for sRGB). |

## Details

Digital cameras typically encode images using the sRGB color space, which applies a non-linear transformation—commonly referred to as gamma correction—to the sensor's linear luminance response. This function applies a power transformation to approximate the inverse of that encoding, restoring a response closer to linear.

## Value

Same properties as dn, with values adjusted by inverse gamma correction and rescaled to the range $[0, 1]$.

## References

There are no references for Rd macro \insertAllCites on this help page.

## Examples

```
## Not run:
path <- system.file("external/APC_0836.jpg", package = "rcaiman")
caim <- read_caim(path)
z <- zenith_image(2132,  lens("Olloclip"))
a <- azimuth_image(z)
zenith_colrow <- c(1063, 771)

caim <- expand_noncircular(caim, z, zenith_colrow)
m <- !is.na(caim$Red) & !is.na(z)
caim[!m] <- 0

bin <- binarize_with_thr(caim$Blue, thr_isodata(caim$Blue[m]))

display_caim(caim$Blue, bin)

caim <- invert_gamma_correction(caim, 2.2)

## End(Not run)
```

---

# lens *Access the lens database*

---

## Description

Retrieve projection coefficients and field-of-view (FOV, deg) for known lenses. Coefficients expect zenith angle in radians and return relative radius.

## Usage

```
lens(type = "equidistant", return = "coef")
```

## Arguments

| | |
|---|---|
| type | Character vector of length one. Lens identifier. See *Details*. |
| return | Character vector of length one. Either "coef"(default) or "fov". Controls whether to return projection coefficients or maximum FOV. |

## Details

In upward-looking leveled hemispherical photography, the zenith corresponds to the center of a circular image whose perimeter represents the horizon, assuming a lens with a 180° field of view. The relative radius is the radial distance to a given point, expressed as a fraction of the maximum radius (i.e., the horizon). The equidistant projection model, also called polar projection, is the

standard reference model, characterized by a linear relationship between zenith angle and relative radius.

Real lenses deviate from ideal projections. Following Hemisfer software, this package models deviations with polynomial functions. All angular values are in radians.

Currently available lenses:

**"equidistant"** Ideal equidistant projection (Schneider et al. 2009).

**"Nikkor_10.5mm"** AF DX Fisheye Nikkor 10.5mm f/2.8G ED (Pekin and Macfarlane 2009).

**"Nikon_FCE9"** Nikon FC-E9 converter (Díaz et al. 2024).

**"Olloclip"** Auxiliary lens for mobile devices manufactured by Olloclip (Díaz et al. 2024).

**"Nikkor_8mm"** AF–S Fisheye Nikkor 8–15mm f/3.5–4.5E ED (Díaz et al. 2024).

See `calibrate_lens()` for fitting new projection functions.

## Value

Numeric vector. Depends on `return`:

**"coef"** Polynomial coefficients of the projection function (relative radius as a function of `theta`, radians).

**"fov"** numeric vector of length one. Maximum field of view (deg).

## References

Díaz GM, Lang M, Kaha M (2024). "Simple calibration of fisheye lenses for hemipherical photography of the forest canopy." *Agricultural and Forest Meteorology*, **352**, 110020. ISSN 0168-1923, doi:10.1016/j.agrformet.2024.110020.

Pekin B, Macfarlane C (2009). "Measurement of crown cover and leaf area index using digital cover photography and its application to remote sensing." *Remote Sensing*, **1**(4), 1298–1320. doi:10.3390/rs1041298.

Schneider D, Schwalbe E, Maas H (2009). "Validation of geometric models for fisheye lenses." *ISPRS Journal of Photogrammetry and Remote Sensing*, **64**(3), 259–266. doi:10.1016/j.isprsjprs.2009.01.001.

## Examples

```
lens("Nikon_FCE9")
lens("Nikon_FCE9", return = "fov")

.fp <- function(theta, lens_coef) {
  x <- lens_coef[1:5]
  x[is.na(x)] <- 0
  for (i in 1:5) assign(letters[i], x[i])
  a * theta + b * theta^2 + c * theta^3 + d * theta^4 + e * theta^5
}

theta <- seq(0, pi/2, pi/180)
plot(theta, .fp(theta, lens()), type = "l", lty = 2,
```

```
      ylab = "relative radius")
lines(theta, .fp(theta, lens("Nikon_FCE9")))
```

---

`normalize_minmax` *Normalize data using min-max rescaling*

---

## Description

Rescale numeric or raster data from an expected range to the range $[0, 1]$.

## Usage

```
normalize_minmax(r, mn = NULL, mx = NULL, clip = FALSE)
```

## Arguments

| | |
|---|---|
| `r` | numeric terra::SpatRaster or numeric vector. Input data. |
| `mn` | numeric vector of length one or `NULL`. Minimum expected value. If `NULL` (default), uses the minimum of `r`. |
| `mx` | numeric vector of length one or `NULL`. Maximum expected value. If `NULL` (default), uses the maximum of `r`. |
| `clip` | logical vector of length one. If `TRUE`, clip the output to $[0, 1]$ after rescaling. If `FALSE`, values greater than `mx` are scaled proportionally to values above `1`, and values less than `mn` to values below `0`. |

## Value

Same properties as `r`, with values rescaled to the range $[0, 1]$ if `mn` and `mx` match the range of `r` or extend beyond it. If `clip = TRUE`, values will be within $[0, 1]$ even if this implies data loss.

## Examples

```
normalize_minmax(read_caim())
```

`ootb_bin` *Out-of-the-box reliable binarized image*

## Description

Robust binarization without parameter tuning.

## Usage

```
ootb_bin(caim, z, a, m, parallel = TRUE)
```

## Arguments

| | |
|---|---|
| `caim` | numeric terra::SpatRaster with three layers named `"Red"`, `"Green"`, and `"Blue"`. Digital numbers should be linearly related to radiance. See `read_caim_raw()` for details. |
| `z` | terra::SpatRaster generated with `zenith_image()`. |
| `a` | terra::SpatRaster generated with `azimuth_image()`. |
| `m` | logical terra::SpatRaster with one layer. A binary mask with `TRUE` for selected pixels. |
| `parallel` | logical vector of length one. If `TRUE`, operations are executed in parallel. |

## Details

Runs a predefined pipeline that incrementally refines a binary sky mask by combining gradient-based enhancement, local thresholding, polar segmentation, and a spectral index sensitive to sunlit canopy.

1. *Enhancement.* Compute complementary gradients with `complementary_gradients()` and build an enhancer that mixes the strongest complementary response with the blue band: `mem <- mean(normalize_minmax(max(yellow_blue, red_cyan)), normalize_minmax(Blue^(1/2.2)))`. Gamma correction (see `invert_gamma_correction()`) is applied to the blue band to reduce sky brightness variability.
2. *Local thresholding.* Apply `apply_by_direction()` on `mem` with `method = "thr_isodata"` to obtain an initial binary mask. Local thresholding is required because background non-uniformity remains in the enhanced image.
3. *Cleanup.* Remove isolated pixels and apply a one-pixel binary dilation. This compensates small artifacts produced by band misalignment resulting from the radiometric-first policy of `read_caim_raw()`.
4. *Polar quadtree segmentation.* Segment this preclassification of sky and non-sky pixels with `polar_qtree()` parameterized to yield circular trapezoids never smaller than $3 \times 3$ degrees and to minimize segments with mixed classes.
5. *Object-based image analysis.* Keep segments that contain between 10 and 90 percent of sky pixels. For each kept segment, estimate a local sky reference as the maximum blue value, use it to normalize per segment (`ratio <- Blue / sky_segment_max`), interpret the normalization as the degree of membership to the sky class, and then defuzzify with a fixed threshold `0.5`.

6. *Blue–Red Index (BRI).* Compute
$$\mathrm{BRI} = \frac{B - R}{B + R}$$
where $B$ and $R$ are blue and red digital numbers. BRI decreases on sunlit canopy because direct sunlight is warmer than diffuse skylight. Use a scene-adaptive threshold given by the median BRI over the current non-sky region to flip misclassified sky pixels to non-sky.
7. *Zenith mask.* Apply the final zenith-angle gate (e.g., keep $\theta_z \leq 88°$).

## Value

Logical terra::SpatRaster (`TRUE` for sky, `FALSE` for non-sky) with the same number of rows and columns as `caim`.

## Note

This function is part of a paper under preparation.

## Examples

```
## Not run:
caim <- read_caim()
r <- caim$Blue
z <- zenith_image(ncol(caim), lens())
a <- azimuth_image(z)
m <- !is.na(z)
bin <- ootb_bin(caim, z, a, m)
plot(bin)

## End(Not run)
```

---

`ootb_sky_above` *Out-of-the-box above-canopy sky*

---

## Description

Generate an above-canopy sky brightness map without manual tuning.

## Usage

```
ootb_sky_above(sky_points, z, a, sky_cie, size = 100)
```

## Arguments

| | |
|---|---|
| `sky_points` | `data.frame` returned by `extract_rr()`. If generated by other means, it must contain columns `row`, `col`, `z`, `a`, and `rr`, where the first four define geometry (degrees) and `rr` is the value to interpolate. |
| `z` | terra::SpatRaster generated with `zenith_image()`. |
| `a` | terra::SpatRaster generated with `azimuth_image()`. |

`sky_cie` list. Output of `ootb_sky_cie()`.

`size` numeric vector of length one. Number of rows and columns of the low-resolution grid used before resampling to full resolution.

## Details

Interpolates sky brightness with IDW and k-nearest neighbors in spherical space via `interpolate_spherical()`, blending observations with a fitted sky model. Blending and IDW parameters are derived from `sky_cie` validation metrics, and the result is scaled by the modeled zenith value to yield digital numbers.

## Value

Named list with:

`dn_raster` numeric terra::SpatRaster with interpolated above-canopy sky brightness in digital numbers.

`w` numeric. Weight assigned to the model-based filling source.

`k` integer. Number of nearest neighbors used by IDW.

`p` numeric. IDW power parameter.

## Note

This function is part of a paper under preparation.

## Examples

```
## Not run:
caim <- read_caim()
z <- zenith_image(ncol(caim), lens())
a <- azimuth_image(z)

path <- system.file("external/example.txt", package = "rcaiman")
sky_cie <- read_sky_cie(gsub(".txt", "", path), caim$Blue, z, a)

sky_points <- sky_cie$model$rr$sky_points
sky_above <- ootb_sky_above(sky_points, z, a, sky_cie)
plot(sky_above$dn_raster)
plot(caim$Blue/sky_above$dn_raster)

## End(Not run)
```

ootb_sky_cie *Out-of-the-box CIE sky model and raster*

## Description

Fit and validate a CIE general sky model from a canopy photograph without manual parameter tuning, and return the predicted raster.

## Usage

```
ootb_sky_cie(
  r,
  z,
  a,
  m,
  bin,
  gs,
  min_spherical_dist = seq(0, 12, 3),
  method = c("Nelder-Mead", "BFGS", "CG", "SANN"),
  custom_sky_coef = NULL,
  parallel = TRUE
)
```

## Arguments

| | |
|---|---|
| r | numeric terra::SpatRaster of one layer. Typically, the blue band of a a canopy photograph. Digital numbers should be linearly related to radiance. See `read_caim_raw()` for details. |
| z | terra::SpatRaster generated with `zenith_image()`. |
| a | terra::SpatRaster generated with `azimuth_image()`. |
| m | logical terra::SpatRaster with one layer. A binary mask with `TRUE` for selected pixels. |
| bin | logical terra::SpatRaster with one layer. A binarized hemispherical image. See `binarize_with_thr()` for details. |
| gs | `list` where each element is the output of `sky_grid_segmentation()`. See *Examples* for guidance. |
| min_spherical_dist | numeric vector. Values passed to `rem_nearby_points()`. |
| method | character vector. Optimization methods for `fit_cie_model()`. |
| custom_sky_coef | optional numeric vector of length five. If `NULL` (default), the 15 standard CIE skies are tested as starting conditions. Use this to avoid recomputing the initial step (depending only on `method`) when testing other inputs. |
| parallel | logical vector of length one. If `TRUE`, operations are executed in parallel. |

## Details

Runs a full pipeline to fit a CIE sky model to radiance from a canopy image:

1. a preliminary estimate of sky digital numbers is attempted using the two-corner method aiming to start with a comprehensive sampling of the sky vault (see `method = "detect_bg_dn"` of `apply_by_direction()`).
2. sky point extraction is performed with `extract_sky_points()`, using information from a binary mask (`bin`) and post-filtering with `rem_nearby_points()` and `rem_outliers()`.
3. relative radiance is computed with `extract_rr()` and fitted to CIE sky models using `fit_cie_model()`, selecting the best among different initial conditions and optimization methods.
4. model validation is performed via `validate_cie_model()`.
5. raster prediction with `cie_image()`.

## Value

List with:

`rr_raster` numeric terra::SpatRaster. Predicted relative radiance.

`model` list returned by `fit_cie_model()`. The optimal fit.

`model_validation` list returned by `validate_cie_model()`.

`dist_to_black` Value of `dist_to_black` used in `extract_sky_points()` for the optimal fit.

`use_window` `logical`. Whether a window was used in `extract_rr()` for the optimal fit.

`min_spherical_dist` Value of `min_dist` used in `rem_nearby_points(space = "spherical")` for the optimal fit.

`sky_points` `data.frame` with columns `row` and `col`. Locations of sky points.

`sun_row_col` `data.frame` with the estimated sun-disk position in image coordinates.

`g` Sky grid used for the optimal fit (as returned by `sky_grid_segmentation()`).

`tested_grids` character vector describing the tested grid configurations.

`tested_distances` character vector of tested `min_dist` values in `rem_nearby_points(space = "spherical")`.

`tested_methods` character vector of optimization methods tested in `fit_cie_model()`.

`optimal_start` starting parameters selected after testing the 15 CIE skies.

`model_up` model fitted to relative radiance detected with the two-corner method, if that step succeeded; otherwise `NULL`.

## Note

This function is part of a paper under preparation.

## Examples

```
## Not run:
caim <- read_caim()
r <- caim$Blue
z <- zenith_image(ncol(caim), lens())
a <- azimuth_image(z)
m <- !is.na(z)

bin <- ootb_bin(caim, z, a, m, TRUE)

set.seed(7)
gs <- list(
  #high res
  sky_grid_segmentation(z, a, 2.25, first_ring_different = TRUE),
  sky_grid_segmentation(z, a, 2.8125, first_ring_different = TRUE),
  #medium res
  sky_grid_segmentation(z, a, 9, first_ring_different = TRUE),
  sky_grid_segmentation(z, a, 10, first_ring_different = TRUE),
  #low res
  sky_grid_segmentation(z, a, 15, first_ring_different = FALSE),
  sky_grid_segmentation(z, a, 18, first_ring_different = FALSE)
)

sky_cie <- ootb_sky_cie(r, z, a, m, bin, gs,
                        method = c("Nelder-Mead", "BFGS", "CG", "SANN"),
                        min_spherical_dist = seq(0, 12, 3),
                        parallel = TRUE)

sky_cie$rr_raster
plot(sky_cie$rr_raster)
sky_cie$model_validation$rmse
plot(sky_cie$model_validation$pred, sky_cie$model_validation$obs)
abline(0,1)

ratio <- r/sky_cie$rr_raster/sky_cie$model$rr$zenith_dn
plot(ratio)
plot(select_sky_region(ratio, 0.95, 1.05))
plot(select_sky_region(ratio, 1.15, max(ratio[], na.rm = TRUE)))

plot(bin)
points(sky_cie$sky_points$col,
       nrow(caim) - sky_cie$sky_points$row, col = 2, pch = 10)


## End(Not run)
```

---

# optim_dist_to_black *Optimize minimum distance to black pixels*

---

## Description

Estimate an optimal buffer (dist_to_black) to keep sampled sky points away from candidate canopy pixels (black pixels).

## Usage

```
optim_dist_to_black(r, z, a, m, bin, g)
```

## Arguments

| | |
|---|---|
| r | numeric terra::SpatRaster of one layer. Typically the blue band of a canopy image. |
| z | terra::SpatRaster generated with zenith_image(). |
| a | terra::SpatRaster generated with azimuth_image(). |
| m | logical terra::SpatRaster with one layer. A binary mask with TRUE for selected pixels. |
| bin | logical terra::SpatRaster of one layer. Binary image where TRUE marks candidate sky pixels. Typically the output of binarize_with_thr(). |
| g | numeric terra::SpatRaster of one layer. Segmentation grid, usually built with sky_grid_segmentation() or chessboard(). Ignored when method = "local_max". |

## Details

The heuristic seeks the largest buffer that still yields uniform angular coverage. It iteratively decreases dist_to_black while monitoring the percentage of 30 deg sky-grid cells covered by sampled points. If coverage is low, the buffer is relaxed (and may be removed). This balances border avoidance with representativeness across the sky vault.

## Value

numeric vector of length one to be passed as dist_to_black to extract_sky_points(), or NULL if no buffer is advised.

## Examples

```
## Not run:
caim <- read_caim()
z <- zenith_image(ncol(caim), lens())
a <- azimuth_image(z)
m <- !is.na(z)
r <- caim$Blue

bin <- binarize_by_region(r, ring_segmentation(z, 15), "thr_isodata") &
  select_sky_region(z, 0, 88)
g <- sky_grid_segmentation(z, a, 10, first_ring_different = TRUE)

dist_to_black <- optim_dist_to_black(r, z, a, m, bin, g)
dist_to_black
```

```
bin <- grow_black(bin, 11)
plot(bin)
dist_to_black <- optim_dist_to_black(r, z, a, m, bin, g)
dist_to_black

## End(Not run)
```

---

`optim_sun_angles` *Optimize sun angular coordinates*

---

## Description

Refine the solar position in a fitted CIE sky model by optimizing zenith and azimuth to best match observed relative radiance.

## Usage

```
optim_sun_angles(model, method = c("Nelder-Mead", "BFGS", "CG", "SANN"))
```

## Arguments

| | |
|---|---|
| `model` | list returned by `fit_cie_model()`. |
| `method` | character vector. One or more optimization methods supported by `stats::optim()`. Each is applied independently. |

## Details

Evaluates one or more methods from `stats::optim()` starting at `model$sun_angles`. After each optimization the model is re-fitted and the process repeats until the change in solar position is < 1 deg. The best result across methods is kept.

## Value

List like `model`, potentially with updated `sun_angles` and `metric`, and a new `method_sun` indicating the best optimization method. If no improvement is found, `method_sun` is `NULL`.

## Note

The objective function penalizes solutions that move the sun position by more than 10 deg from the initial estimate to discourage unrealistic shifts.

## Examples

```
## Not run:
caim <- read_caim()
z <- zenith_image(ncol(caim), lens())
a <- azimuth_image(z)

# See fit_cie_model() for details on below file
```

```
path <- system.file("external/sky_points.csv",
                    package = "rcaiman")
sky_points <- read.csv(path)
sky_points <- sky_points[c("Y", "X")]
colnames(sky_points) <- c("row", "col")
sun_angles <- c(z = 39.5, a = 17.4)

rr <- extract_rr(caim$Blue, z, a, sky_points)

set.seed(7)
model <- fit_cie_model(rr, sun_angles, general_sky_type = "Clear")

print(model$sun_angles)
print(model$metric)

plot(model$rr$sky_points$rr, model$rr$sky_points$pred)
abline(0,1)
lm(model$rr$sky_points$pred~model$rr$sky_points$rr) %>% summary()

model <- optim_sun_angles(model)
print(model$sun_angles)
print(model$metric)
model$method_sun

## End(Not run)
```

---

`paint_with_mask` *Paint with mask*

---

## Description

Paint image pixels inside or outside a logical mask with a solid color.

## Usage

```
paint_with_mask(r, m, color = "red", where = "outside")
```

## Arguments

| | |
|---|---|
| `r` | terra::SpatRaster. The image. Values should be normalized, see `normalize_minmax()`. Only images with one or three layers are supported. |
| `m` | logical terra::SpatRaster with one layer. A binary mask with `TRUE` for selected pixels. |
| `color` | character vector of length one or numeric vector of length three. Fill color. If character, it is converted to RGB automatically. If numeric, values must be in range $[0, 1]$. |
| `where` | character vector of length one Region to paint relative to `m`. Either `"outside"` (default) or `"inside"`. |

## Value

numeric terra::SpatRaster with three layers and the geometry of `r`. Equal to `r`, but with pixels in the selected region painted with `color`. Single-layer inputs are replicated to allow color painting.

## Examples

```
## Not run:
r <- read_caim()
z <- zenith_image(ncol(r), lens())
a <- azimuth_image(z)
m <- select_sky_region(z, 20, 70) & select_sky_region(a, 90, 180)

masked_caim <-  paint_with_mask(normalize_minmax(r), m)
plotRGB(masked_caim * 255)

masked_bin <- paint_with_mask(binarize_with_thr(r$Blue, 125), m)
plotRGB(masked_bin * 255)

r <- normalize_minmax(r)
paint_with_mask(r, m, color = c(0.2, 0.2, 0.2))  # vector
paint_with_mask(r, m, color = "blue")     # name
paint_with_mask(r, m, color = "#00FF00")  # hexadecimal

## End(Not run)
```

---

# polar_qtree *Generate polar quadtree segmentation*

---

## Description

Segment a hemispherical image into large circular trapezoids and recursively split them into four trapezoids of equal angular size whenever brightness heterogeneity exceeds a predefined threshold.

## Usage

```
polar_qtree(r, z, a, scale_parameter, angle_width = 30, max_splittings = 6)
```

## Arguments

| | |
|---|---|
| `r` | numeric terra::SpatRaster. One or more layers used to drive heterogeneity. |
| `z` | terra::SpatRaster generated with `zenith_image()`. |
| `a` | terra::SpatRaster generated with `azimuth_image()`. |
| `scale_parameter` | numeric vector of length one. Threshold on `delta` controlling splits (see *Details*). |

| | |
|---|---|
| angle_width | numeric vector of length one. Angle in deg that must divide both 0–360 and 0–90 into an integer number of segments. Retrieve a set of valid values by running `lapply(c(45, 30, 18, 10), function(a) vapply(0:6, function(x) a/2^x, 1))`. |
| max_splittings | numeric vector of length one. Maximum recursion depth. |

## Details

A circular trapezoid, hereafter referred to as a cell, is the intersection of a ring (zenith-angle band) and a sector (azimuth-angle band). Heterogeneity within a cell is measured as the standard deviation of pixel values (a first-order texture metric). The change in heterogeneity due to splitting is `delta`, defined as the sum of the standard deviations of the four subcells minus the standard deviation of the parent cell. A split is kept where `delta > scale_parameter`. For multi-layer `r`, `delta` is computed per layer and averaged to decide splits. Angular resolution at level `i` is `angle_width / 2^i`.

## Value

Single-layer terra::SpatRaster with integer values and the same number of rows and columns as `r`.

## Examples

```
## Not run:
# Find large patches of white ------------------------------------------------
caim <- read_caim()
r <- caim$Blue
z <- zenith_image(ncol(caim), lens())
a <- azimuth_image(z)

bin <- binarize_with_thr(r, thr_isodata(r[]))
plot(bin)

seg <- polar_qtree(bin, z, a, 0, 30, 3)
plot(extract_feature(bin, seg) == 1)

## End(Not run)
```

---

# read_bin *Write and read binarized images*

---

## Description

Wrapper functions around `terra::rast()` to read and write binary masks.

## Usage

```
read_bin(path)

write_bin(bin, path)
```

### Arguments

| | |
|---|---|
| path | character vector of length one. File path to read or write. See examples. |
| bin | logical terra::SpatRaster with a single layer. |

### Details

`write_bin()` multiplies the input logical raster by 255 and writes the result as a GeoTIFF (`GTiff`) with datatype `INT1U`. Both `write_bin()` and `read_bin()` set the raster extent to `terra::ext(0, ncol(r), 0, nrow(r))` and the CRS to EPSG:7589.

### Value

See *Functions*

### Functions

`write_bin` Write a one-layer logical terra::SpatRaster to disk as a GeoTIFF (`GTiff`, `INT1U`). No return value.

`read_bin` Read a file with values `255` and/or `0`, such as the one produced by `write_bin` (see *Details*), and return a logical terra::SpatRaster (`TRUE` for `255`, `FALSE` for `0`).

### See Also

`read_caim()`, `write_caim()`.

### Examples

```
## Not run:
z <- zenith_image(1000, lens())
m <- !is.na(z)
my_file <- file.path(tempdir(), "mask.tif")
write_bin(m, my_file)
m_from_disk <- read_bin(my_file)
plot(m - m_from_disk)

## End(Not run)
```

---

## `read_caim` *Read a canopy image from a file*

---

### Description

Reads a born-digital image (typically RGB-JPEG or RGB-TIFF) using `terra::rast()` and returns a terra::SpatRaster object. Optionally, it can extract a rectangular region of interest (ROI) specified by the user.

## Usage

```
read_caim(path = NULL, upper_left = NULL, width = NULL, height = NULL)
```

## Arguments

| | |
|---|---|
| `path` | character vector of length one. Path to an image file, including extension. If `NULL`, an example image is returned. |
| `upper_left` | numeric vector of length two. Pixel coordinates of the upper-left corner of the ROI, in the format `c(column, row)`. |
| `width, height` | numeric vector of length one. Size (in pixels) of the rectangular ROI to read. |

## Details

This function is intended for importing color hemispherical photographs, such as those obtained with digital cameras equipped with fisheye lenses. For raw image files (e.g., NEF, CR2), see `read_caim_raw()`.

Internally, this is a wrapper around `terra::rast()`, so support for image formats depends on the capabilities of the `terra` package.

If no arguments are provided, a sample image will be returned.

## Value

Numeric terra::SpatRaster, typically with layers named `"Red"`, `"Green"`, and `"Blue"`. If the file format or metadata prevents automatic layer naming, names will be inferred and a warning may be issued.

## Selecting a Region of Interest

To load a specific subregion from the image, use the arguments `upper_left`, `width`, and `height`. These are expressed in raster coordinates, similar to a spreadsheet layout: **columns first, then rows**. In other words, specify coordinates as `c(column, row)`, **not** `c(row, column)`, which is typical in `data.frame` objects.

While any image editor can be used to obtain these values, this function was tested with ImageJ, particularly the Fiji distribution. A recommended workflow:

1. Open the image in Fiji.
2. Draw a rectangular selection.
3. Go to *Edit* > *Selection* > *Specify...* to read `upper_left`, `width`, and `height`.

## Note

The example image was created from a raw photograph taken with a Nikon Coolpix 5700 and a FC-E9 auxiliary lens, processed with the following code:

```
zenith_colrow <- c(1290, 988)/2
diameter <- 756
z <- zenith_image(diameter, lens("Nikon_FCE9"))
```

```
a <- azimuth_image(z)
m <- !is.na(z)
caim <- read_caim_raw("DSCN4606.NEF")
caim <- crop_caim(caim, zenith_colrow - diameter/2, diameter, diameter)
caim <- correct_vignetting(caim, z, c(0.0638, -0.101))
caim <- c(mean(caim$Y, caim$M), caim$G, caim$C)
caim <- fisheye_to_equidistant(caim, z, a, m, radius = 300, k = 1)
write_caim(caim, "example.tif", 16)
```

## See Also

write_caim()

## Examples

```
path <- system.file("external/DSCN4500.JPG", package = "rcaiman")
zenith_colrow <- c(1276, 980)
diameter <- 756*2
caim <- read_caim(path, zenith_colrow - diameter/2, diameter, diameter)
plot(caim$Blue)
```

---

# read_caim_raw *Read a canopy image from a raw file*

---

## Description

Read unprocessed sensor data from a camera RAW file and split the signal by spectral band according to the in-camera color filter array (CFA). Use this to obtain images with precise radiometry.

## Usage

```
read_caim_raw(path, only_blue = FALSE, offset_value = NULL)
```

## Arguments

| | |
|---|---|
| path | character vector of length one. Path to a file with raw data (including file extension). |
| only_blue | logical vector of length one. If TRUE, return only the blue/cyan band. |
| offset_value | numeric vector of length one. Optional black level offsets to replace black_level_per_channel metadata obtained with rawpy. |

## Details

Uses Python rawpy through reticulate to access sensor data and black-level metadata. Optionally extracts only the blue/cyan band.

## Value

Numeric terra::SpatRaster:

- single-layer if `only_blue = TRUE`.
- multi-layer if `only_blue = FALSE`, with one layer per color per CFA color (e.g., R, G, B).

Layers are named according to metadata in the raw file.

## Check Python Accessibility

To ensure that R can access a Python installation, run the following test:

```
reticulate::py_eval("1+1")
```

If R can access Python successfully, you will see `2` in the console. If not, you will receive instructions on how to install Python.

## Create a Virtual Environment

After passing the Python accessibility test, create a virtual environment using the following command:

```
reticulate::virtualenv_create()
```

## Install `rawpy`

Install the rawpy package within the virtual environment:

```
reticulate::py_install("rawpy")
```

## For RStudio Users

If you are an RStudio user who works with projects, you will need a *.Renviron* file in the root of each project. To create a *.Renviron* file, follow these steps:

- Create a "New Blank File" named ".Renviron" (without an extension) in the project's root directory.
- Run bellow code:

```
path <- file.path(reticulate::virtualenv_root(),
reticulate::virtualenv_list(), "Scripts", "python.exe")
paste("RETICULATE_PYTHON =", path)
```

- Copy/paste the line from the console (the string between the quotes) into the .Renviron file. This is an example `RETICULATE_PYTHON = ~/.virtualenvs/r-reticulate/Scripts/python.exe`

- Do not forget to save the changes

By following these steps, users can easily set up their environment to access raw data efficiently, but it is not the only way of doing it, you might know an easier or better one.

See the help page of `read_caim()` and `fisheye_to_equidistant()` as a complement to this help page. Further details about raw files can be found in Díaz et al. (2024).

## References

Díaz GM, Lang M, Kaha M (2024). "Simple calibration of fisheye lenses for hemipherical photography of the forest canopy." *Agricultural and Forest Meteorology*, **352**, 110020. ISSN 0168-1923, doi:10.1016/j.agrformet.2024.110020.

## See Also

`read_caim()`

## Examples

```
## Not run:
file_name <- tempfile(fileext = ".NEF")
download.file("https://osf.io/s49py/download", file_name, mode = "wb")

# Geometric and radiometric corrections -----------------------------------
zenith_colrow <- c(1290, 988)/2
diameter <- 756
z <- zenith_image(diameter, lens("Nikon_FCE9"))
a <- azimuth_image(z)
m <- !is.na(z)
caim <- read_caim_raw(file_name, only_blue = TRUE)
caim <- crop_caim(caim, zenith_colrow - diameter/2, diameter, diameter)
caim <- correct_vignetting(caim, z, c(0.0638, -0.101))
caim <- fisheye_to_equidistant(caim, z, a, m, radius = 300,
                               k = 1, p = 1, rmax = 100)

## End(Not run)
```

---

# rem_isolated_black_pixels

*Remove isolated black pixels*

---

## Description

Replace single black pixels (`FALSE`) that are fully surrounded by white pixels (`TRUE`) with white. Uses 8-connectivity.

## Usage

```
rem_isolated_black_pixels(bin)
```

### Arguments

| | |
|---|---|
| bin | logical terra::SpatRaster with a single layer. |

### Value

Logical terra::SpatRaster of one layer.

### Examples

```
## Not run:
caim <- read_caim()
r <- caim$Blue
z <- zenith_image(ncol(caim), lens())
a <- azimuth_image(z)

path <- system.file("external/example.txt", package = "rcaiman")
sky <- read_sky_cie(gsub(".txt", "", path), caim$Blue, z, a)
plot(sky$rr_raster)
sky <- sky$rr_raster * sky$model$rr$zenith_dn

bin <- binarize_with_thr(r / sky, 0.9)
plot(bin)
bin2 <- rem_isolated_black_pixels(bin)
plot(bin2)

## End(Not run)
```

---

## rem_nearby_points *Remove nearby sky points*

---

### Description

Select a subset of points so that no retained pair is closer than `min_dist` in planar or spherical space.

### Usage

```
rem_nearby_points(
  sky_points,
  r = NULL,
  z = NULL,
  a = NULL,
  min_dist = 3,
  space = "planar",
  use_window = TRUE
)
```

## Arguments

| | |
|---|---|
| sky_points | data.frame with columns row and col (raster coordinates). |
| r | single-layer terra::SpatRaster or NULL. Optional ranking raster used to prioritize retention (higher values kept first). |
| z | terra::SpatRaster generated with zenith_image(). |
| a | terra::SpatRaster generated with azimuth_image(). |
| min_dist | numeric vector of length one. Minimum allowed distance between retained points. Units: pixels for "planar", deg for "spherical". |
| space | character vector of length one. Coordinate system for distances: "planar" (default) or "spherical". |
| use_window | logical of length one. If TRUE (default), use a $3 \times 3$ local mean around each point; if FALSE, use only the central pixel. |

## Details

When space = "planar", distances are computed in image coordinates and z and a are ignored. When space = "spherical", distances are angular (deg) in hemispherical coordinates. If r is provided, points are ranked by the extracted raster values and retained in descending order.

## Value

A data.frame with columns row and col for retained points.

## Note

It is assumed that sky_points were extracted from an image with the same dimensions as the r, z, and a rasters. No checks are performed.

## Examples

```
## Not run:
caim <- read_caim()
r <- caim$Blue
z <- zenith_image(ncol(caim), lens())
a <- azimuth_image(z)
bin <- binarize_by_region(r, ring_segmentation(z, 30),
                          method = "thr_isodata")
bin <- bin & select_sky_region(z, 0, 80)
g <- sky_grid_segmentation(z, a, 10, first_ring_different = TRUE)
sky_points <- extract_sky_points(r, bin, g, dist_to_black = 3)

# planar
sky_points_p <- rem_nearby_points(sky_points, r, min_dist = 100,
                                        space = "planar")
plot(r)
points(sky_points$col, nrow(caim) - sky_points$row, col = 2, pch = 10)
points(sky_points_p$col, nrow(caim) - sky_points_p$row, col = 3, pch = 0)

# spherical
```

```
sky_points_s <- rem_nearby_points(sky_points, r, z, a, min_dist = 30,
                                        space = "spherical")
plot(r)
points(sky_points$col, nrow(caim) - sky_points$row, col = 2, pch = 10)
points(sky_points_s$col, nrow(caim) - sky_points_s$row, col = 3, pch = 0)

## End(Not run)
```

---

`rem_outliers` *Remove statistical outliers in sky points*

---

## Description

Remove sky points considered outliers relative to their local neighbors in a user-specified variable.

## Usage

```
rem_outliers(
  sky_points,
  r,
  z,
  a,
  k = 20,
  angular_radius = 20,
  laxity = 2,
  cutoff_side = "both",
  use_window = TRUE,
  trend = NULL
)
```

## Arguments

| | |
|---|---|
| `sky_points` | `data.frame` with columns `row` and `col` (raster coordinates). |
| `r` | terra::SpatRaster. Image from which `sky_points` were sampled (or any raster with identical dimensions). |
| `z` | terra::SpatRaster generated with `zenith_image()`. |
| `a` | terra::SpatRaster generated with `azimuth_image()`. |
| `k` | numeric vector of length one. Number of neighbors. |
| `angular_radius` | numeric vector of length one. The maximum radius for searching k-nearest neighbors (KNN) in degrees. |
| `laxity` | numeric vector of length one. |
| `cutoff_side` | character vector of length one. Options are "both" (default), "upper" or "lower". Controls which side(s) of the inequality are evaluated to detect outliers. See Details. |
| `use_window` | logical of length one. If `TRUE` (default), use a $3 \times 3$ local mean around each point; if `FALSE`, use only the central pixel. |

`trend` numeric vector of length one or `NULL`. Zero to three. Specifies the order of the polynomial surface fitted to the neighbors to account for spatial trends. Use NULL (default) to skip detrending.

## Details

Based on the Statistical Outlier Removal (SOR) filter from the PCL library. Distances are computed on a spherical surface. The number of neighbors is controlled by `k`, and `angular_radius` sets the maximum search radius (deg). If fewer than `k` neighbors are found within that radius, the point is retained due to insufficient evidence for removal. The decision criterion follows Leys et al. (2013):

$$M - laxity \times MAD < x_i < M + laxity \times MAD$$

where $x_i$ is the value from `r` at sky point `i`, $M$ and $MAD$ are the median and median absolute deviation, respectively, computed from the the neighbors of $x_i$, and $laxity$ is the user-defined threshold.

`cutoff_side` controls which side(s) of the inequality are evaluated: `"both"` (default), `"left"` (left tail only), or `"right"` (right tail only).

## Value

The retained points represented as a data.frame with columns `row` and `col`, same as `sky_points`.

## Note

This function assumes that `sky_points` and the terra::SpatRaster objects refer to the same image geometry. No checks are performed.

## References

Leys C, Ley C, Klein O, Bernard P, Licata L (2013). "Detecting outliers: Do not use standard deviation around the mean, use absolute deviation around the median." *Journal of Experimental Social Psychology*, **49**(4), 764–766. ISSN 0022-1031, doi:10.1016/j.jesp.2013.03.013.

## Examples

```
## Not run:
caim <- read_caim()
r <- caim$Blue
z <- zenith_image(ncol(caim), lens())
a <- azimuth_image(z)
m <- !is.na(z)
bin <- binarize_by_region(r, ring_segmentation(z, 30),
                          method = "thr_isodata")
bin <- bin & select_sky_region(z, 0, 80)
g <- sky_grid_segmentation(z, a, 5, first_ring_different = TRUE)
sky_points <- extract_sky_points(r, bin, g,
                                 dist_to_black = 3)
plot(r)
points(sky_points$col, nrow(caim) - sky_points$row, col = 2, pch = 10)

sky_points <- rem_outliers(sky_points, r, z, a,
                                 k = 5,
```

```
                                angular_radius = 20,
                                laxity = 2,
                                cutoff_side = "left")
points(sky_points$col, nrow(caim) - sky_points$row, col = 3, pch = 0)

## End(Not run)
```

---

`ring_segmentation` *Assign zenith-ring labels*

---

## Description

Segment a hemispherical view into concentric rings by slicing the zenith angle from `0` to `90` deg at equal steps.

## Usage

```
ring_segmentation(z, angle_width, return = "id")
```

## Arguments

| | |
|---|---|
| `z` | terra::SpatRaster generated with `zenith_image()`. |
| `angle_width` | numeric vector of length one. Ring width in degrees. Must divide the 0-90 deg range into an integer number of segments. |
| `return` | character vector of length one. Output mode: "id" (default) or "angle". |

## Value

Single-layer terra::SpatRaster: ring IDs if `return = "id"`, or mean zenith angle (deg) if `return = "angle"`.

## Examples

```
z <- zenith_image(600, lens())
rings <- ring_segmentation(z, 15)
plot(rings == 1)
```

## sector_segmentation *Assign azimuth-sector labels*

### Description

Segment a hemispherical view into equal azimuth sectors by slicing the azimuth angle from `0` to `360` deg at fixed steps.

### Usage

```
sector_segmentation(a, angle_width)
```

### Arguments

| | |
|---|---|
| `a` | terra::SpatRaster generated with `azimuth_image()`. |
| `angle_width` | numeric vector of lenght one. Sector width in degrees. Must divide the 0–360 deg range into an integer number of sectors. |

### Value

Single-layer terra::SpatRaster with integer values. Segments will resemble pizza slices.

### Examples

```
z <- zenith_image(600, lens())
a <- azimuth_image(z)
sectors <- sector_segmentation(a, 15)
plot(sectors == 1)
```

## select_sky_region *Select sky region*

### Description

Select pixels from a single-layer image based on value limits.

### Usage

```
select_sky_region(r, from, to)
```

### Arguments

| | |
|---|---|
| `r` | single-layer terra::SpatRaster, typically from `zenith_image()` or `azimuth_image()`. |
| `from, to` | numeric vectors of length one. Angles in deg, inclusive limits. |

## Details

Works with any numeric terra::SpatRaster of one layer, but is especially well-suited for images from `zenith_image()` or `azimuth_image()`. For azimuth ranges that wrap around 0 deg, combine two masks with logical OR.

## Value

Logical terra::SpatRaster (`TRUE` for the selected region) of the same dimensions as `r`.

## See Also

`paint_with_mask()`

## Examples

```
## Not run:
z <- zenith_image(1000, lens())
a <- azimuth_image(z)
m1 <- select_sky_region(z, 20, 70)
plot(m1)
m2 <- select_sky_region(a, 330, 360)
plot(m2)
plot(m1 & m2)
plot(m1 | m2)

# 15 deg on each side of 0
m1 <- select_sky_region(a, 0, 15)
m2 <- select_sky_region(a, 345, 360)
plot(m1 | m2)

# You can use this
plot(!is.na(z))
# instead of this
plot(select_sky_region(z, 0, 90))

## End(Not run)
```

---

# `sky_grid_centers` *Map sky-grid centers to raster coordinates*

---

## Description

Return image row and column indices for the center point of each cell in a sky grid composed of circular trapezoids of equal angular resolution defined by `angle_width`.

## Usage

```
sky_grid_centers(z, a, angle_width)
```

### Arguments

| | |
|---|---|
| z | terra::SpatRaster generated with zenith_image(). |
| a | terra::SpatRaster generated with azimuth_image(). |
| angle_width | numeric vector of length one. Angle in deg that must divide both 0–360 and 0–90 into an integer number of segments. Retrieve a set of valid values by running lapply(c(45, 30, 18, 10), function(a) vapply(0:6, function(x) a/2^x, 1)). |

### Value

data.frame with integer columns row and col, one per grid cell.

### See Also

sky_grid_segmentation()

### Examples

```
z <- zenith_image(100, lens())
a <- azimuth_image(z)
sky_grid_centers(z, a, 45)
```

---

## sky_grid_segmentation *Assign sky-grid labels*

---

### Description

Segment a hemispherical view into equal-angle bins in zenith and azimuth, assigning each pixel a grid-cell ID.

### Usage

```
sky_grid_segmentation(z, a, angle_width, first_ring_different = FALSE)
```

### Arguments

| | |
|---|---|
| z | terra::SpatRaster generated with zenith_image(). |
| a | terra::SpatRaster generated with azimuth_image(). |
| angle_width | numeric vector of length one. Angle in deg that must divide both 0–360 and 0–90 into an integer number of segments. Retrieve a set of valid values by running lapply(c(45, 30, 18, 10), function(a) vapply(0:6, function(x) a/2^x, 1)). |
| first_ring_different | logical vector of length one. If TRUE, do not subdivide the first ring. |

## Details

The intersection of zenith rings and azimuth sectors forms a grid whose cells are circular trapezoids. By default, IDs encode both components as `sectorID * 1000 + ringID`. If `first_ring_different = TRUE`, the zenith ring is not subdivided.

The code below outputs a comprehensive list of valid values for `angle_width`. For convenience, the column `radians_denom` can be used to provide `angle_width` as `180 / radians_denom_i`, where `radians_denom_i` is a value taken from `radians_denom`.

```
df <- data.frame(degrees = 90 / 1:180)

deg_to_pi_expr <- function(deg) {
  frac <- MASS::fractions(deg / 180)
  strsplit(as.character(frac), "/")[[1]][2] %>% as.numeric()
}

df$radians_denom <- sapply(df$degrees, function(deg) deg_to_pi_expr(deg))

z <- zenith_image(10, lens())
a <- azimuth_image(z)
u <- c()
for (i in 1:nrow(df)) {
  u <- c(u, tryCatch(is((sky_grid_segmentation(z, a,
                              180/df$radians_denom[i])), "SpatRaster"),
                     error = function(e) FALSE))
}
df <- df[u, ]
df
```

## Value

Single-layer terra::SpatRaster with integer labels. The object carries attributes `angle_width` and `first_ring_different`.

## See Also

`sky_grid_centers()`, `ring_segmentation()`, `sector_segmentation()`

## Examples

```
caim <- read_caim()
z <- zenith_image(ncol(caim), lens())
a <- azimuth_image(z)
g <- sky_grid_segmentation(z, a, 15)
plot(g == 24005)
## Not run:
display_caim(g = g)

## End(Not run)
```

`test_lens_coef` *Test lens projection function*

## Description

Verify that a lens projection maps zenith 0 deg to 0 and 90 to 1.

## Usage

```
test_lens_coef(lens_coef)
```

## Arguments

| | |
|---|---|
| `lens_coef` | numeric vector. Polynomial coefficients of the lens projection function. See `lens()`. |

## Details

The package tolerate a number very close to 1 at 90 deg but not exactly 1 as long as it is greater than 1. See `testthat::expect_equal()` for tolerance details.

When the test fails at *"Test that lens projection function does not predict values barely below one"*, the best practice is to manually edit the last coefficient (e.g., change -0.0296 to -0.0295).

If the check *"works within the 0–1 range"* fails, new calibration data may be required.

## Value

Invisibly returns `TRUE` if all checks pass; otherwise an error is thrown.

## See Also

`calc_relative_radius()`

## Examples

```
test_lens_coef(lens("Nikon_FCE9"))
test_lens_coef(2/pi)
```

`thr_isodata` *Compute IsoData threshold*

## Description

Compute a threshold using the IsoData algorithm Ridler and Calvard (1978), recommended by Jonckheere et al. (2005).

## Usage

```
thr_isodata(x)
```

## Arguments

| | |
|---|---|
| `x` | numeric vector or a single-column `matrix` or `data.frame` able to be coerced to numeric. |

## Details

Implementation follows the IsoData method by Gabriel Landini, as implemented in `autothresholdr::auto_thresh()`. Unlike that version, this function accepts numeric data over an arbitrary range. `NA` values are ignored.

## Value

Numeric vector of length one.

## References

Jonckheere I, Nackaerts K, Muys B, Coppin P (2005). "Assessment of automatic gap fraction estimation of forests from digital hemispherical photography." *Agricultural and Forest Meteorology*, **132**(1-2), 96–114. doi:10.1016/j.agrformet.2005.06.003.

Ridler TW, Calvard S (1978). "Picture thresholding using an iterative selection method." *IEEE Transactions on Systems, Man, and Cybernetics*, **8**(8), 630–632. doi:10.1109/tsmc.1978.4310039.

## Examples

```
caim <- read_caim()
thr_isodata(caim$Blue[])
```

`thr_mblt` *Compute model-based thresholds*

## Description

Compute threshold values from background digital numbers (DN) using Equation 1 in Díaz and Lencinas (2018), a linear function whose slope can be weighted.

## Usage

```
thr_mblt(dn, intercept, slope)
```

## Arguments

| | |
|---|---|
| `dn` | numeric vector or terra::SpatRaster. Background digital number. Values must be normalized; if taken from JPEG, apply gamma back correction. |
| `intercept`, `slope` | numeric vectors of length one. Linear coefficients. |

## Details

The model was derived from canopy targets (perforated, rigid, dark surfaces) backlit under homogeneous illumination, photographed with a Nikon Coolpix 5700 in JPEG mode. Images were gamma-back-corrected with a default gamma of 2.2 (see `invert_gamma_correction()`). Results showed that the optimal threshold is linearly related to the background DN (see Figures 1 and 7 in Díaz and Lencinas (2018)). This shifted the goal from estimating an optimal threshold Song et al. (2014) to estimating the background DN as if the canopy were absent, as proposed by Lang et al. (2010).

To apply the weighting parameter (w) from Equation 1, supply `slope` as $slope \times w$.

Equation 1 was developed with 8-bit images. New coefficients should be calibrated in the 0–255 domain, which is what `thr_mblt()` expects, even though the `dn` argument must be normalized. This design choice harmonizes behavior across the package.

## Value

An object of the same class and dimensions as `dn`.

## Note

Users are encouraged to acquire raw files (see `read_caim_raw()`).

## References

Díaz GM, Lencinas JD (2018). "Model-based local thresholding for canopy hemispherical photography." *Canadian Journal of Forest Research*, **48**(10), 1204–1216. doi:10.1139/cjfr20180006.

Lang M, Kuusk A, Mõttus M, Rautiainen M, Nilson T (2010). "Canopy gap fraction estimation

from digital hemispherical images using sky radiance models and a linear conversion method." *Agricultural and Forest Meteorology*, **150**(1), 20–29. doi:10.1016/j.agrformet.2009.08.001.

Song GM, Doley D, Yates D, Chao K, Hsieh C (2014). "Improving accuracy of canopy hemispherical photography by a constant threshold value derived from an unobscured overcast sky." *Canadian Journal of Forest Research*, **44**(1), 17–27. doi:10.1139/cjfr20130082.

## See Also

`normalize_minmax()`, `invert_gamma_correction()`

## Examples

```
thr_mblt(invert_gamma_correction(125), -7.8, 0.95 * 0.5)
```

---

# thr_twocorner *Compute two-corner thresholds*

---

## Description

Apply Rosin's geometric corner detector for unimodal histograms Rosin (2001) to both sides of a bimodal canopy histogram as in Macfarlane's two-corner approach Macfarlane (2011). Optional slope-reduction as in Macfarlane is supported. Peak detection can use a prominence-based method or Macfarlane's original windowed maxima.

## Usage

```
thr_twocorner(
  x,
  sigma = 2,
  slope_reduction = TRUE,
  method = "prominence",
  diagnose = FALSE,
  adjust_par = TRUE
)
```

## Arguments

| | |
|---|---|
| `x` | numeric vector or a single-column `matrix` or `data.frame` able to be coerced to numeric. |
| `sigma` | numeric vector of length one. Standard deviation (DN) of the Gaussian kernel used to smooth the histogram prior to peak detection and Rosin's construction. |
| `slope_reduction` | logical vector of length one. If `TRUE`, apply Macfarlane's slope-reduction before Rosin's construction on each side. |
| `method` | character vector of length one. Peak detection strategy. One of `"prominence"` (default) or `"macfarlane"`. |

`diagnose` logical vector of length one. If `TRUE`, plot the geometric construction.

`adjust_par` logical vector of length one. If `TRUE` and `diagnose = TRUE`, temporarily adjust and then restore graphical parameters.

## Details

Runs the following pipeline:

1. Build an 8-bit histogram of `x` after min–max normalization to `[0,255]`.
2. Smooth the histogram with a discrete Gaussian kernel of standard deviation `sigma` (in DN), using reflective padding to mitigate edge bias.
3. Detect the two mode peaks according to `method`:
   - `method = "prominence"`: find local maxima via discrete derivatives with plateau handling; find nearest left/right minima; compute peak prominence as $\min(y[p]-y[L],\, y[p]-y[R])$; filter by minimum prominence and minimum peak separation; select the pair that maximizes $\min(\mathrm{prom}_{\mathrm{left}},\, \mathrm{prom}_{\mathrm{right}})$.
   - `method = "macfarlane"`: search peaks within fixed DN windows as in Macfarlane (2011). Peak search is performed on the **unsmoothed** histogram, as originally proposed.
4. Apply Rosin's corner construction on each mode. The line end at the "first empty bin after the last filled bin" is determined on the **unsmoothed** histogram Rosin (2001). If `slope_reduction = TRUE` and the peak height exceeds the mean of the smoothed histogram, the peak height is reduced to that mean before the geometric construction (Macfarlane's variant).
5. Derive thresholds:

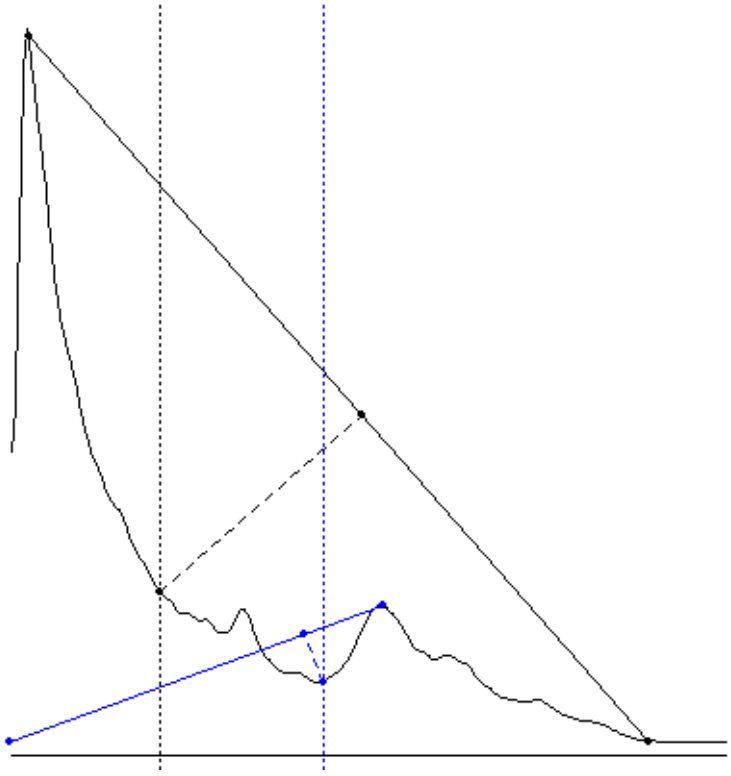
$$T_l = DN_{lc} + (DN_{uc} - DN_{lc}) \times 0.25$$

$$T_m = DN_{lc} + (DN_{uc} - DN_{lc}) \times 0.50$$

$$T_h = DN_{lc} + (DN_{uc} - DN_{lc}) \times 0.75$$

where $DN_{lc}$ and $DN_{uc}$ are the lower and upper corners.

When `diagnose = TRUE`, a geometric construction like the one shown below is sent to the active graphics device.



When `diagnose = TRUE` and `adjust_par = TRUE`, the function temporarily adjusts margins to draw the geometric construction in a large square format and restores the previous settings on exit. If `adjust_par = FALSE`, no parameters are changed and the plot respects the current device/layout.

## Value

A list with:

**lp** Lower peak DN.

**lc** Lower corner DN (Rosin on the left mode).

**tl** Low threshold derived from `lc` and `uc`.

**tm** Mid threshold derived from `lc` and `uc`.

**th** High threshold derived from `lc` and `uc`.

**uc** Upper corner DN (Rosin on the right mode).

**up** Upper peak DN.

## References

Macfarlane C (2011). "Classification method of mixed pixels does not affect canopy metrics from digital images of forest overstorey." *Agricultural and Forest Meteorology*, **151**(7), 833–840. doi:10.1016/j.agrformet.2011.01.019.

Rosin PL (2001). "Unimodal thresholding." *Pattern Recognition*, **34**(11), 2083–2096. ISSN 0031-3203, doi:10.1016/s00313203(00)001369.

## Examples

```
caim <- conventional_lens_image()
# Prominence-based peak detection, Gaussian smoothing with sigma = 2 DN
thr <- thr_twocorner(caim$Blue[], sigma = 2, slope_reduction = FALSE,
                     method = "prominence")
# Original Macfarlane peak search (for comparison)
thr2 <- thr_twocorner(caim$Blue[], sigma = 2, slope_reduction = TRUE,
                      method = "macfarlane")
data.frame(unlist(thr), unlist(thr2))
```

---

# validate_cie_model *Validate CIE sky models*

---

## Description

Validate CIE sky models fitted with `fit_cie_model()` (or `ootb_sky_cie()`) using k-fold cross-validation on relative radiance.

## Usage

```
validate_cie_model(model, k = 10)
```

## Arguments

| | |
|---|---|
| `model` | list. Output of `fit_cie_model()`. |
| `k` | numeric vector of length one. Number of folds. |

## Details

Validation uses k-fold cross-validation with `k = 10` by default (Kohavi 1995). For each fold, predictions are compared against observed relative radiance and a simple linear regression of predicted vs. observed is fitted, following Piñeiro et al. (2008). Outliers are detected with a median–MAD rule (see `rem_outliers()`) using a threshold of 3 and removed before fitting the regression.

## Value

A list with:

**lm** An object of class `lm` (see `stats::lm()`) for predicted vs. observed.

**pred** Numeric vector of predicted relative radiance used in `lm`.

**obs** Numeric vector of observed relative radiance used in `lm`.

**r_squared** Coefficient of determination ($R^2$).

**rmse** Root mean squared error (RMSE).

**mae** Median absolute error (MAE).

**is_outlier** Logical vector marking outliers (MAD > 3) in the original sky-point set.

**metric** Numeric value. Mean squared deviation as in Gauch et al. (2003).

## References

Gauch HG, Hwang JTG, Fick GW (2003). "Model evaluation by comparison of model-based predictions and measured values." *Agronomy Journal*, **95**(6), 1442–1446. ISSN 1435-0645, doi:10.2134/agronj2003.1442.

Kohavi R (1995). "A study of cross-validation and bootstrap for accuracy estimation and model selection." In *Proceedings of the 14th International Joint Conference on Artificial Intelligence - Volume 2*, IJCAI'95, 1137–1143. ISBN 1558603638.

Piñeiro G, Perelman S, Guerschman JP, Paruelo JM (2008). "How to evaluate models: Observed vs. predicted or predicted vs. observed?" *Ecological Modelling*, **216**(3-4), 316–322. doi:10.1016/j.ecolmodel.2008.05.006.

## Examples

```
## Not run:
caim <- read_caim()
z <- zenith_image(ncol(caim), lens())
a <- azimuth_image(z)
path <- system.file("external/sky_points.csv", package = "rcaiman")
sky_points <- read.csv(path)[c("Y", "X")]
names(sky_points) <- c("row", "col")
rr <- extract_rr(caim$Blue, z, a, sky_points)

set.seed(7)
model <- fit_cie_model(rr, sun_angles = c(z = 49.5, a = 27.4),
                       general_sky_type = "Clear", method = "CG")
val <- validate_cie_model(model, k = 10)
val$r_squared
val$rmse

## End(Not run)
```

---

`write_caim` *Write canopy image*

---

## Description

Wrapper around `terra::writeRaster()` that writes a canopy image as GeoTIFF with 8- or 16-bit unsigned integers, setting CRS and extent.

## Usage

```
write_caim(caim, path, bit_depth)
```

### Arguments

| | |
|---|---|
| caim | terra::SpatRaster. |
| path | character vector of length one. Destination file path (extension .tif will be enforced). |
| bit_depth | numeric vector of length one. Either 8 or 16. |

### Details

Adds the .tif extension to path if missing. The CRS is set to EPSG:7589 and the extent to [0, ncol] × [0, nrow] in pixel units. Data are written as INT1U when bit_depth = 8 and INT2U when bit_depth = 16.

### Value

No return value. Called for side effects.

### Examples

```
## Not run:
caim <- read_caim() %>% normalize_minmax(0, 255)
write_caim(caim * (2^8 - 1),  file.path(tempdir(), "test_8bit"),  8)
write_caim(caim * (2^16 - 1), file.path(tempdir(), "test_16bit"), 16)
# Note: values are scaled by (2^bit_depth - 1) to avoid the maximum bin,
# which read_caim() might turn NA.

## End(Not run)
```

---

## write_sky_cie *Write and read out-of-the-box CIE sky model and raster*

---

### Description

Persist and restore the out-of-the-box CIE sky model, its diagnostics, and related rasters/points. The writer produces a human-readable .txt manifest plus CSV and GeoPackage sidecar files. The reader reconstructs a list object compatible with the out-of-the-box pipeline.

### Usage

```
write_sky_cie(sky_cie, name)

read_sky_cie(name, r, z, a, refit_allowed = FALSE)
```

## Arguments

| | |
|---|---|
| sky_cie | list. Object holding the fitted CIE model, diagnostics, and derived rasters, as produced by the out-of-the-box workflow. |
| name | character vector of length one. File base name without extension. A path can be included, e.g., "C:/Users/Doe/Documents/DSCN4500". |
| r | numeric terra::SpatRaster of one layer. The canopy image used in the out-of-the-box workflow (used by read_sky_cie() when refitting). |
| z | terra::SpatRaster generated with zenith_image(). |
| a | terra::SpatRaster generated with azimuth_image(). |
| refit_allowed | logical vector of length one. If TRUE, allow automatic re-fit when manual edits are detected. |

## Details

Encoding is UTF-8. Decimal point is .. Unknown keys are ignored with a warning. Missing required keys trigger an error. The manifest begins with format_version: which is checked for basic compatibility.

When read_sky_cie() detects manual edits (moved sun disk or changed sky points) and refit_allowed = TRUE, it re-fits the CIE model using the current r, z, and a, then revalidates.

## Value

See *Functions*.

## Functions

write_sky_cie No return value. Writes six files to disk with the prefix name (see below).

read_sky_cie Returns a list similar to the output of ootb_sky_cie() and suitable as input to ootb_sky_above().

## Files written by write_sky_cie

- Plain text manifest: name.txt
- CSV with sky radiance samples: name_rr.csv
- CSV with sky radiance samples for the upward pass: name_rr_up.csv (optional)
- GeoPackage with sky sample points: name_sky_points.gpkg
- GeoPackage with the sun disk location: name_sun_disk.gpkg
- CSV with validation pairs: name_val.csv

## Text file keys

format_version: Semantic version of the manifest.

sun_theta: Solar zenith (deg).

sun_phi: Solar azimuth (deg).

`method_sun`: Method used to optimize sun coordinates.

`zenith_dn`: Reference DN at zenith.

`start_a:...start_e`: Initial CIE coefficients.

`is_from_detected_sky_dn`: Enables `_rr_up.csv` if `TRUE`.

`fit_a:...fit_e`: Fitted CIE coefficients.

`method`: Method used to fit CIE coefficients.

`dist_to_black`: Argument passed to `extract_sky_points()`.

`grid`: Sky grid parameters (`angle_width`, `first_ring_different`).

`min_spherical_dist`: Sampling buffer distance (deg).

`sky_points_no`: Number of sky points.

`outliers_no`: Number of sky points that were detected as outliers.

`rmse`: Validation metrics. Root mean squared error.

`r_squared`: Validation metric. Coefficient of determination.

`mae`: Validation metrics. Mean absolute error.

`[Tested: . . . ]` Enumerates tested methods/grids/distances.

## Examples

```
## Not run:
caim <- read_caim()
z <- zenith_image(ncol(caim), lens())
a <- azimuth_image(z)

# Read a previously written model
path <- system.file("external/example.txt", package = "rcaiman")
sky_cie <- read_sky_cie(gsub(".txt", "", path), r = caim$Blue, z = z, a = a,
                        refit_allowed = TRUE)

## End(Not run)
```

---

`zenith_azimuth_from_row_col` *Map between zenith–azimuth angles and raster coordinates*

---

## Description

Bidirectional helpers to convert between angular coordinates on the hemispherical image (`zenith`, `azimuth`) and raster coordinates (`row`, `col`).

## Usage

```
zenith_azimuth_from_row_col(z, a, row, col)

row_col_from_zenith_azimuth(z, a, zenith, azimuth)
```

### Arguments

| | |
|---|---|
| z | terra::SpatRaster generated with zenith_image(). |
| a | terra::SpatRaster generated with azimuth_image(). |
| row, col | numeric vectors. raster coodinates. Must have equal length. |
| zenith, azimuth | numeric vectors. Angles in degrees. Must have equal length. |

### Details

**zenith, azimuth → row, col.** A sparse set of valid sky points is sampled over the image and enriched with their angular coordinates. Two local least-squares surfaces (spatial::surf.ls, np = 6) are fitted to predict row and col as smooth functions of (azimuth, zenith). Predictions are rounded to the nearest integer index. Out-of-bounds indices are not produced under normal conditions; clamp externally if needed.

**row, col → zenith, azimuth.** Angles are obtained by direct lookup on z and a using terra::cellFromRowCol. If any queried cell is NA (e.g., outside the calibrated lens footprint), a synthetic z is reconstructed from the lens model attached to z (attribute lens_coef), and a is rebuilt with azimuth_image() using the stored orientation attribute in a. This yields robust angle retrieval near borders.

### Value

See *Functions*

### Functions

| | |
|---|---|
| row_col_from_zenith_azimuth | Return image indices for given angles. |
| zenith_azimuth_from_row_col | Return angles in degrees for given image indices. |

### Examples

```
z <- zenith_image(1000, lens())
a <- azimuth_image(z)

rc <- row_col_from_zenith_azimuth(z, a, zenith = c(30, 60), azimuth = c(90, 270))
rc

ang <- zenith_azimuth_from_row_col(z, a, row = rc$row, col = rc$col)
ang
```

---

## zenith_image *Build Zenith image*

---

### Description

Build a single-layer image with zenith angle values, assuming upwards-looking hemispherical photography with the optical axis vertically aligned.

## Usage

```
zenith_image(diameter, lens_coef)
```

## Arguments

| | |
|---|---|
| diameter | numeric vector of length one. Diameter in pixels expressed as an even integer. This places the zenith point between pixels. Snapping the zenith point between pixels does not affect accuracy because half-pixel is less than the uncertainty in localizing the circle within the picture. |
| lens_coef | numeric vector. Polynomial coefficients of the lens projection function. See lens(). |

## Value

terra::SpatRaster with zenith angles in degrees, showing a complete hemispherical view with the zenith at the center. The object carries attributes lens_coef.

## Examples

```
z <- zenith_image(600, lens("Nikon_FCE9"))
plot(z)
```

# Index