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Type Package

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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>

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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

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

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

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 possibilities.

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 (θ), it returns the horizon radius (i.e., the radius for θ 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 θ .
5. Before taking the photograph, align the zenith coordinates with the 0 deg θ 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 30° 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:

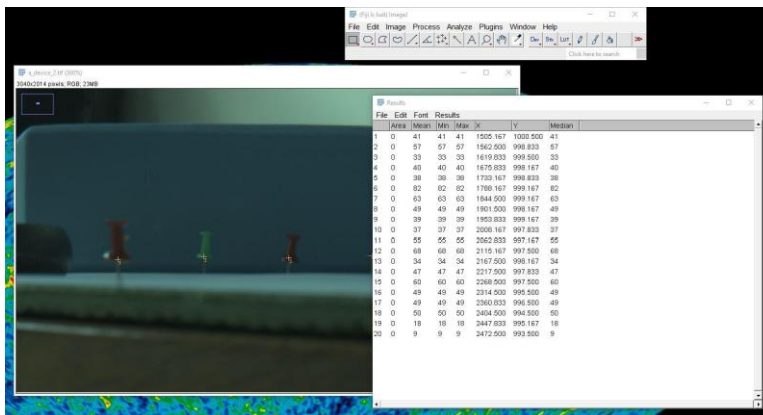
Cut the sheet by the dashed line. Place the yoga mat extended on top of the table. Place the sheet on top of the yoga mat. Align the dashed line with the yoga mat border closest to you. Place push pins on each cross. If you are gentle, the yoga mat will allow you to do that without damaging the table. 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 90° 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 checked 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). 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 hemispherical 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** $f(\chi) = 1 + c \cdot [\exp(d \cdot \chi) - \exp(d \cdot \frac{\pi}{2})] + e \cdot \cos^2 \chi$. Combined, they can predict the relative radiance ρ_R in any sky direction (θ, ϕ) as: $\hat{\rho}_R^\circ(\theta, \phi) = \frac{\Phi(\theta) \cdot f(\chi(\theta, \phi; \theta_\odot, \phi_\odot))}{\Phi(\theta_\odot) \cdot f(\chi(\theta_\odot, \phi_\odot; 0, 0))}$, where θ is the zenith angle, ϕ is the azimuth angle, and θ_\odot, ϕ_\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](https://doi.org/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" = $(R - G + B)/(R + G + B) \cdot \text{logistic}(\text{brightness})$
- "yellow_blue" = $(-R - G + B)/(R + G + B) \cdot \text{logistic}(\text{brightness})$
- "red_cyan" = $(-R + G + B)/(R + G + B) \cdot \text{logistic}(\text{brightness})$

The $\text{logistic}(\text{brightness})$ term is computed as:

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

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

<code>bin</code>	logical <code>terra::SpatRaster</code> with one layer. A binarized hemispherical image. See <code>binarize_with_thr()</code> for details.
<code>z</code>	<code>terra::SpatRaster</code> generated with <code>zenith_image()</code> .
<code>a</code>	<code>terra::SpatRaster</code> generated with <code>azimuth_image()</code> .
<code>m</code>	logical <code>terra::SpatRaster</code> with one layer. A binary mask with TRUE for selected pixels.
<code>angle_width</code>	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 <code>lapply(c(45, 30, 18, 10), function(a) vapply(0:6, function(x) a/2^x, 1))</code> .

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 documenting 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	<i>Correct vignetting effect</i>
--------------------	----------------------------------

Description

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

Usage

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

Arguments

<code>r</code>	terra::SpatRaster of one or more layers (e.g., RGB channels or binary masks) in fisheye projection.
<code>z</code>	terra::SpatRaster generated with zenith_image() .
<code>lens_coef_v</code>	numeric vector. Coefficients of the vignetting function $f_v(\theta) = 1 + a\theta + b\theta^2 + \dots + m\theta^n$, where θ is the zenith angle (in radians) and a, b, \dots, 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("0lloclip"))
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	<i>Display a canopy image</i>
--------------	-------------------------------

Description

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

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_obsured"
)
```

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_obscurd" (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.

Obscurd 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("0lloclip"))
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	<i>Extract digital numbers from sky points</i>
------------	--

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 3×3 local mean around each point; if FALSE, use only the central pixel.

Details

Wraps [terra::extract\(\)](#) to support a 3×3 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

<code>l</code>	list of preprocessed images (<code>terra::SpatRaster</code>) suitable for radiometry sampling. Images must comply with the equidistant projection.
<code>size_px</code>	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 <code>NULL</code> (default), two percent of image width is used (<code>round(terra::ncol(r) * 0.02)</code>).

Value

`data.frame` con dos columnas:

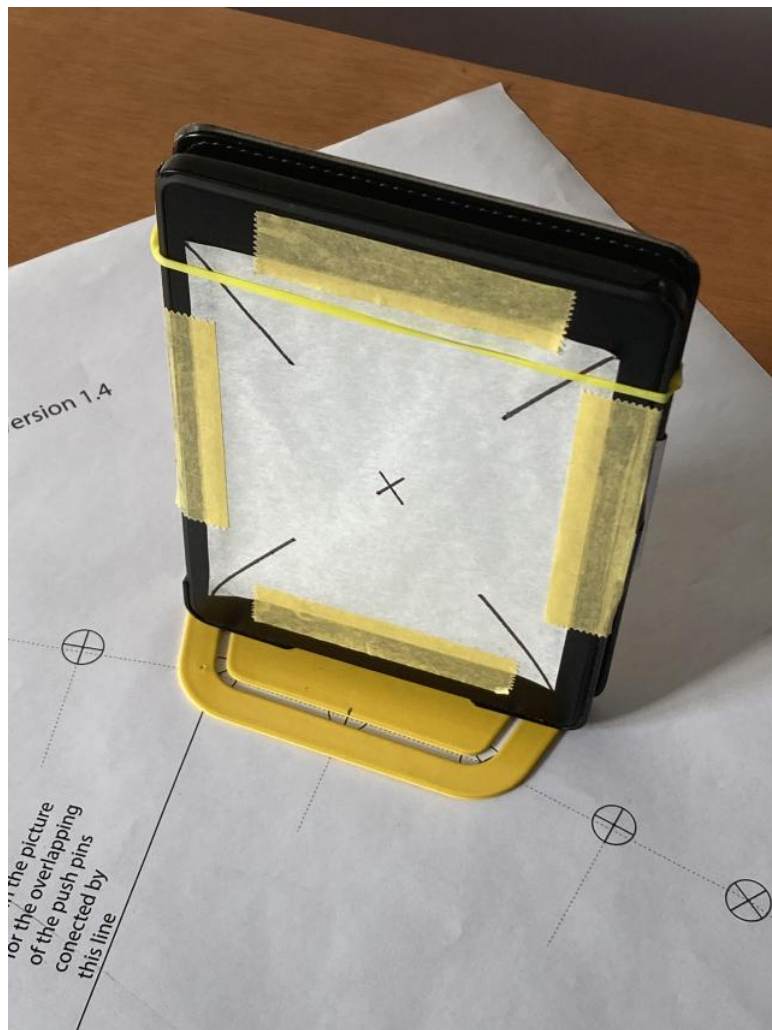
`theta` zenith angle en radianes.

`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]][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]][1])
}
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 hemispherical photography of the forest canopy." *Agricultural and Forest Meteorology*, **352**, 110020. ISSN 0168-1923, [doi:10.1016/j.agrformet.2024.110020](https://doi.org/10.1016/j.agrformet.2024.110020).

extract_rr	<i>Extract digital numbers at sky points and normalize by estimated zenith radiance</i>
------------	---

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 × 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 9×9 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 $\text{ncol}(r) / 2$.

`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	<code>terra::SpatRaster</code> of one or more layers (e.g., RGB channels or binary masks) in fisheye projection.
z	<code>terra::SpatRaster</code> generated with <code>zenith_image()</code> .
a	<code>terra::SpatRaster</code> generated with <code>azimuth_image()</code> .
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 <code>lapply(c(45, 30, 18, 10), function(a) vapply(0:6, function(x) a/2^x, 1))</code> .

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	<i>Fit CIE sky model</i>
---------------	--------------------------

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: zenith_dn numeric vector of length one. 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 a 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. Go 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, Möttus 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 <code>extract_rr()</code> . If it is generated by other means, it must have columns row, col, z, a, and rr.
method	character. Model type to fit: "zenith_only" Quadratic polynomial in zenith angle. "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 <code>extract_rr()</code> or <code>extract_dn()</code> .
r	numeric <code>terra::SpatRaster</code> 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 `tr1s` 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 <i>About HSP software</i> .
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 <code>extract_rr()</code> or <code>extract_dn()</code> .
r	numeric <code>terra::SpatRaster</code> 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 <code>lidR::knnidw()</code> : 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 <i>Details</i> .
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 hemispherical photography of the forest canopy.” *Agricultural and Forest Meteorology*, **352**, 110020. ISSN 0168-1923, [doi:10.1016/j.agrformet.2024.110020](https://doi.org/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](https://doi.org/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](https://doi.org/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

<code>r</code>	numeric terra::SpatRaster or numeric vector. Input data.
<code>mn</code>	numeric vector of length one or NULL. Minimum expected value. If NULL (default), uses the minimum of <code>r</code> .
<code>mx</code>	numeric vector of length one or NULL. Maximum expected value. If NULL (default), uses the maximum of <code>r</code> .
<code>clip</code>	logical vector of length one. If TRUE, clip the output to [0, 1] after rescaling. If FALSE, values greater than <code>mx</code> are scaled proportionally to values above 1, and values less than <code>mn</code> 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	<i>Out-of-the-box reliable binarized image</i>
----------	--

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 3×3 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

$$\text{BRI} = \frac{B - R}{B + R}$$

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 $\theta_z \leq 88^\circ$).

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	<i>Out-of-the-box above-canopy sky</i>
----------------	--

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 <code>extract_rr()</code> . 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	<code>terra::SpatRaster</code> generated with <code>zenith_image()</code> .
a	<code>terra::SpatRaster</code> generated with <code>azimuth_image()</code> .

sky_cie	list. Output of <code>ootb_sky_cie()</code> .
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 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 <i>Examples</i> 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$model_validation$sobs)
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)

```

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

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

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	<i>Optimize sun angular coordinates</i>
------------------	---

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, maxSplittings = 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 <code>black_level_per_channel</code> metadata obtained with <code>rawpy</code> .

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 hemispherical photography of the forest canopy.” *Agricultural and Forest Meteorology*, **352**, 110020. ISSN 0168-1923, [doi:10.1016/j.agrformet.2024.110020](https://doi.org/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 <code>terra::SpatRaster</code> or NULL. Optional ranking raster used to prioritize retention (higher values kept first).
z	<code>terra::SpatRaster</code> generated with <code>zenith_image()</code> .
a	<code>terra::SpatRaster</code> generated with <code>azimuth_image()</code> .
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 3×3 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 3×3 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](https://doi.org/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 length 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 $\text{sectorID} * 1000 + \text{ringID}$. 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 $180 / \text{radians_denom_i}$, 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	<i>Test lens projection function</i>
----------------	--------------------------------------

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	<i>Compute IsoData threshold</i>
-------------	----------------------------------

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	<i>Compute model-based thresholds</i>
----------	---------------------------------------

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, Möttus 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	<i>Compute two-corner thresholds</i>
---------------	--------------------------------------

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 $[\emptyset, 255]$.
2. Smooth the histogram with a discrete Gaussian kernel of standard deviation σ (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 $\min(\text{prom}_{\text{left}}, \text{prom}_{\text{right}})$.
 - 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.

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	<i>Validate CIE sky models</i>
--------------------	--------------------------------

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

<code>model</code>	list. Output of <code>fit_cie_model()</code> .
<code>k</code>	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 $[\emptyset, ncol] \times [\emptyset, nrow]$ 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 <code>read_sky_cie()</code> when refitting).
z	terra::SpatRaster generated with <code>zenith_image()</code> .
a	terra::SpatRaster generated with <code>azimuth_image()</code> .
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 coordinates. Must have equal length.
 zenith, azimuth numeric vectors. Angles in degrees. Must have equal length.

Details

zenith, azimuth \rightarrow 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 \rightarrow 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)
```

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