Package ‘marsrad’

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Title Mars Solar Radiation

Version 1.0.1

Description A set of functions to calculate solar irradiance and insolation on Mars horizontal and inclined surfaces. Based on NASA Technical Memoranda 102299, 103623, 105216, 106321, and 106700, i.e. the canonical Mars solar radiation papers.

License GPL-3

URL https://georges.fyi/marsrad/,
https://github.com/georgeslabreche/marsrad

BugReports https://github.com/georgeslabreche/marsrad/issues

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`marsrad-package` *marsrad: Mars Solar Radiation*

Description

A set of functions to calculate solar irradiance and insolation on Mars horizontal and inclined surfaces. Based on NASA Technical Memoranda 102299, 103623, 105216, 106321, and 106700, i.e. the canonical Mars solar radiation papers.

Details

The package provides three types of solar radiation calculations:

- Instantaneous irradiance (G_* functions) — Power per unit area at a specific moment
- Daily insolation (H_* functions) — Energy per unit area over one Martian sol
- Period insolation (I_* functions) — Energy per unit area over multiple sols

All calculations support both horizontal and inclined surfaces. The package includes functions for optimal tilt angle calculation, sunrise/sunset times, and atmospheric optical depth modeling.

Package Information

Version 1.0.0

License GPL-3

Website https://georges.fyi/marsrad/

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Depends R (>= 2.10)

Citation

If you use this package in your research or publication, please cite the paper it was developed for:

Labrèche, G., & Cordes, F. (2020). Using a Rover's Active Suspension System as a 2-Axis Solar Tracker Mechanism. *15th International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS '20)*. https://www.hou.usra.edu/meetings/isairas2020fullpapers/pdf/5035.pdf

Links

Package website https://georges.fyi/marsrad/

Package GitHub repository https://github.com/georgeslabreche/marsrad

Author LinkedIn https://www.linkedin.com/in/georgeslabreche/

Author website https://georges.fyi

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References

Appelbaum, J., & Flood, D. J. (1989). Solar Radiation on Mars. NASA Technical Memorandum 102299. https://ntrs.nasa.gov/citations/19890018252

Appelbaum, J., & Flood, D. J. (1990). Solar radiation on Mars: Update 1990. NASA Technical Memorandum 103623. https://ntrs.nasa.gov/citations/19910005804

Appelbaum, J., & Flood, D. J. (1991). Solar radiation on Mars: Update 1991. NASA Technical Memorandum 105216. https://ntrs.nasa.gov/citations/19910023732

Appelbaum, J., Sherman, I., & Landis, G. A. (1993). Solar radiation on Mars: Stationary photovoltaic array. NASA Technical Memorandum 106321. https://ntrs.nasa.gov/citations/19940010257

Appelbaum, J., Flood, D. J., & Norambuena, M. (1994). Solar radiation on Mars: Tracking photovoltaic array. NASA Technical Memorandum 106700. https://ntrs.nasa.gov/citations/19950004977

See Also

Labrèche, G. (2020). Exploiting the SherpaTT Rover Active Suspension System to Enable Optimal Solar Array Inclination and Orientation for Long Traverses in a Martian Environment. *Master's Thesis, Luleå University of Technology*. https://www.diva-portal.org/smash/record.jsf?pid=diva2:1413245

Examples

```
# Calculate horizontal irradiance at Viking 1 landing site on Ls 90 (northern summer solstice)
G_h(Ls = 90, phi = 22.48, longitude = -48, Ts = 12, tau = 0.5)

# Find optimal panel tilt angle for the same location and season
optimal_angle(Ls = 90, phi = 22.48)

# Calculate daily insolation on a horizontal surface
H_h(Ls = 90, phi = 22.48, longitude = -48, tau = 0.5)

# Calculate insolation over a 24-hour period on an inclined surface
I_i(Ls = 90, phi = 22.48, longitude = -48, tau = 0.5, Ts_start = 0,
    Ts_end = 24, beta = 25, gamma_c = 0)
```

---

albedo *The albedo function.*

Description

Calculate the albedo value given geographical location and tau factor. Source: Appelbaum, Joseph & Landis, Geoffrey & Sherman, I. (1991). Solar radiation on Mars — Update 1991.

Usage

```
albedo(latitude, longitude, tau, coordinates_rounding = TRUE)
```

Arguments

`latitude`	Planetary latitude [deg], from -90° to +90°
`longitude`	Planetary longitude [deg], from -180° to 180°
`tau`	Atmospheric optical depth (dimensionless)
`coordinates_rounding`	Logical, whether to round coordinates to nearest grid point

Value

Surface albedo value (dimensionless, 0-1)

`declination` *Solar declination angle on Mars*

Description

Calculates the angular position of the Sun at solar noon with respect to the plane of the Martian equator. For Mars: -24.936° <= delta <= 24.936°. The declination is 0° at vernal (Ls=0°) and autumnal equinoxes (Ls=180°), +24.936° at summer solstice (Ls=90°), and -24.936° at winter solstice (Ls=270°). Implements Equation 7 from Appelbaum & Flood (1990).

Usage

```
declination(Ls, unit = 1)
```

Arguments

`Ls`	Areocentric longitude [deg]
`unit`	Output unit: 1 for radians, 2 for degrees (default: 1)

Value

Declination angle [rad] or [deg] depending on unit parameter

`f` *Normalized net flux function*

Description

Calculates the normalized net solar flux on the Martian surface accounting for multiple wavelength and multiple scattering in the atmosphere. Based on Pollack's calculations presented in Appelbaum & Flood (1990). Can use polynomial expression or lookup tables.

Usage

```
f(z, tau, al = 0.1)
```

Arguments

`z`	Sun zenith angle [deg]
`tau`	Atmospheric optical depth (dimensionless)
`al`	Surface albedo (dimensionless, ranges from 0.1 to 0.4)

Value

Normalized net flux (dimensionless)

Environment Variables

The function behavior can be configured via environment variables:

NET_FLUX_FUNCTION_TYPE: Controls which implementation to use:

- `"polynomial"` (default) - Analytical polynomial expression with ~0.7% mean error. Maximum error ~7% at zenith angles 80-85° and tau > 5.
- `"lookup_v1"` - Lookup table from NASA TM-102299. Albedo fixed at 0.1.
- `"lookup_v2"` - Lookup table from NASA TM-103623. Supports albedo 0.1 and 0.4.

Set with: `Sys.setenv(NET_FLUX_FUNCTION_TYPE = "polynomial")`

NET_FLUX_FUNCTION_SHOW_WARNINGS: Controls warning display (TRUE/FALSE, default: TRUE). Warnings are shown when polynomial calculations may have notable error margin (tau > 5 or z >= 80°).

Set with: `Sys.setenv(NET_FLUX_FUNCTION_SHOW_WARNINGS = TRUE)`

G_ali *Albedo-reflected irradiance on Mars inclined surface*

Description

Calculates the solar irradiance reflected from the Martian surface (ground-reflected radiation) incident on an inclined surface. Accounts for the view factor of the ground from the tilted surface.

Usage

```
G_ali(
  Ls,
  phi,
  longitude,
  Ts,
  z = Z(Ls = Ls, Ts = Ts, phi = phi),
  tau,
  al = albedo(latitude = phi, longitude = longitude, tau = tau),
  beta
)
```

Arguments

Ls	Areocentric longitude [deg]
phi	Planetary latitude [deg]
longitude	Planetary longitude [deg]
Ts	Solar time [h]
z	Sun zenith angle [deg]. If not provided, calculated from Ls, phi, and Ts
tau	Atmospheric optical depth (dimensionless)
al	Surface albedo (dimensionless, 0-1). If not provided, calculated from latitude, longitude, and tau
beta	Surface tilt/slope angle from horizontal [deg]

Value

Albedo-reflected irradiance on inclined surface [W/m²]

G_b — *Direct beam irradiance on Mars surface normal to solar rays*

Description

Calculates the direct beam solar irradiance on the Martian surface normal to the solar rays (i.e., perpendicular to the sun's direction). Uses Beer's law to account for atmospheric attenuation. Implements Equation 14 from Appelbaum & Flood (1990).

Usage

```
G_b(Ls, phi = NULL, Ts = NULL, z = Z(Ls = Ls, phi = phi, Ts = Ts), tau)
```

Arguments

Ls	Areocentric longitude [deg]
phi	Planetary latitude [deg]. Can be NULL if z is provided
Ts	Solar time [h]. Can be NULL if z is provided
z	Sun zenith angle [deg]. If not provided, calculated from Ls, phi, and Ts
tau	Atmospheric optical depth (dimensionless)

Value

Direct beam irradiance normal to sun [W/m²]

G_bh *Direct beam irradiance on Mars horizontal surface*

Description

Calculates the direct beam solar irradiance incident on a horizontal surface on Mars. Accounts for the angle of incidence on the horizontal plane. Implements Equation 18 from Appelbaum & Flood (1990).

Usage

```
G_bh(Ls, phi, Ts, z = Z(Ls = Ls, phi = phi, Ts = Ts), tau)
```

Arguments

Ls	Areocentric longitude [deg]
phi	Planetary latitude [deg]
Ts	Solar time [h]
z	Sun zenith angle [deg]. If not provided, calculated from Ls, phi, and Ts
tau	Atmospheric optical depth (dimensionless)

Value

Direct beam irradiance on horizontal surface [W/m²]

G_bi *Direct beam irradiance on Mars inclined surface*

Description

Calculates the direct beam solar irradiance incident on an inclined surface on Mars. Accounts for the sun's angle of incidence on the tilted and oriented surface. Based on Appelbaum, Flood & Norambuena (1994).

Usage

```
G_bi(Ls, phi, Ts, z = Z(Ls = Ls, phi = phi, Ts = Ts), tau, beta, gamma_c)
```

Arguments

Ls	Areocentric longitude [deg]
phi	Planetary latitude [deg]
Ts	Solar time [h]
z	Sun zenith angle [deg]. If not provided, calculated from Ls, phi, and Ts
tau	Atmospheric optical depth (dimensionless)
beta	Surface tilt/slope angle from horizontal [deg]
gamma_c	Surface azimuth angle [deg]. Zero facing equator, east negative, west positive (-180 to +180)

Value

Direct beam irradiance on inclined surface [W/m²]

G_dh *Diffuse irradiance on Mars horizontal surface*

Description

Calculates the diffuse solar irradiance (scattered by atmospheric dust) incident on a horizontal surface on Mars. Computed as the difference between global and direct beam irradiance. Implements Equation 16 from Appelbaum & Flood (1990).

Usage

```
G_dh(
  Ls,
  phi,
  longitude,
  Ts = NULL,
  z = Z(Ls = Ls, phi = phi, Ts = Ts),
  tau,
  al = albedo(latitude = phi, longitude = longitude, tau = tau)
)
```

Arguments

Ls	Areocentric longitude [deg]
phi	Planetary latitude [deg]
longitude	Planetary longitude [deg]
Ts	Solar time [h]. Can be NULL for daily calculations
z	Sun zenith angle [deg]. If not provided, calculated from Ls, phi, and Ts
tau	Atmospheric optical depth (dimensionless)
al	Surface albedo (dimensionless, 0-1). If not provided, calculated from latitude, longitude, and tau

Value

Diffuse irradiance on horizontal surface [W/m²]

`G_di` *Diffuse irradiance on Mars inclined surface*

Description

Calculates the diffuse solar irradiance (scattered by atmospheric dust) incident on an inclined surface on Mars. Accounts for the view factor of the sky from the tilted surface.

Usage

```
G_di(
  Ls,
  phi,
  longitude,
  Ts,
  z = Z(Ls = Ls, phi = phi, Ts = Ts),
  tau,
  al = albedo(latitude = phi, longitude = longitude, tau = tau),
  beta
)
```

Arguments

`Ls`	Areocentric longitude [deg]
`phi`	Planetary latitude [deg]
`longitude`	Planetary longitude [deg]
`Ts`	Solar time [h]
`z`	Sun zenith angle [deg]. If not provided, calculated from Ls, phi, and Ts
`tau`	Atmospheric optical depth (dimensionless)
`al`	Surface albedo (dimensionless, 0-1). If not provided, calculated from latitude, longitude, and tau
`beta`	Surface tilt/slope angle from horizontal [deg]

Value

Diffuse irradiance on inclined surface [W/m²]

G_h — *Global irradiance on Mars horizontal surface*

Description

Calculates the total solar irradiance (direct beam + diffuse + albedo) incident on a horizontal surface on Mars. Implements Equation 17 from Appelbaum & Flood (1990).

Usage

```
G_h(
  Ls,
  phi,
  longitude,
  Ts = NULL,
  z = Z(Ls = Ls, phi = phi, Ts = Ts),
  tau,
  al = albedo(latitude = phi, longitude = longitude, tau = tau)
)
```

Arguments

`Ls`	Areocentric longitude [deg]
`phi`	Planetary latitude [deg]
`longitude`	Planetary longitude [deg]
`Ts`	Solar time [h]
`z`	Sun zenith angle [deg]. If not provided, calculated from Ls, phi, and Ts
`tau`	Atmospheric optical depth (dimensionless)
`al`	Surface albedo (dimensionless, 0-1). If not provided, calculated from latitude, longitude, and tau

Value

Global irradiance [W/m²]

G_i — *Global irradiance on Mars inclined surface*

Description

Calculates the total solar irradiance (direct beam + diffuse + albedo-reflected) incident on an inclined surface on Mars. Implements Equation 3 from Appelbaum, Flood & Norambuena (1994).

Usage

```
G_i(
  Ls,
  phi,
  longitude,
  Ts,
  z = Z(Ls = Ls, phi = phi, Ts = Ts),
  tau,
  al = albedo(latitude = phi, longitude = longitude, tau = tau),
  beta,
  gamma_c
)
```

Arguments

`Ls`	Areocentric longitude [deg]
`phi`	Planetary latitude [deg]
`longitude`	Planetary longitude [deg]
`Ts`	Solar time [h]
`z`	Sun zenith angle [deg]. If not provided, calculated from Ls, phi, and Ts
`tau`	Atmospheric optical depth (dimensionless)
`al`	Surface albedo (dimensionless, 0-1). If not provided, calculated from latitude, longitude, and tau
`beta`	Surface tilt/slope angle from horizontal [deg]
`gamma_c`	Surface azimuth angle [deg]. Zero facing equator, east negative, west positive (-180 to +180)

Value

Global irradiance on inclined surface [W/m²]

`G_ob` *Beam irradiance at top of Martian atmosphere*

Description

Calculates the solar beam irradiance at the top of the Martian atmosphere (before any atmospheric effects) as a function of Mars' orbital position. Accounts for Mars' elliptical orbit which causes seasonal variation in solar intensity. Implements Equation 4 from Appelbaum & Flood (1990).

Usage

```
G_ob(Ls)
```

Arguments

`Ls`	Areocentric longitude [deg]

Value

Beam irradiance at top of atmosphere [W/m²]

`G_obh` *Beam irradiance on horizontal surface at top of Mars atmosphere*

Description

Calculates the solar beam irradiance on a horizontal surface at the top of the Martian atmosphere (before atmospheric attenuation). Implements Equation 5 from Appelbaum & Flood (1990).

Usage

```
G_obh(Ls, phi = NULL, Ts = NULL, z = Z(Ls = Ls, phi = phi, Ts = Ts))
```

Arguments

`Ls`	Areocentric longitude [deg]
`phi`	Planetary latitude [deg]. Can be NULL if z is provided
`Ts`	Solar time [h]. Can be NULL if z is provided
`z`	Sun zenith angle [deg]. If not provided, calculated from Ls, phi, and Ts

Value

Beam irradiance at top of atmosphere [W/m²]

`H_ali` *Albedo-reflected daily insolation on Mars inclined surface*

Description

Calculates the ground-reflected solar energy received over a full Martian day on an inclined surface. Obtained by integrating albedo-reflected irradiance from sunrise to sunset.

Usage

```
H_ali(
  Ls,
  phi,
  longitude,
  tau,
  al = albedo(latitude = phi, longitude = longitude, tau = tau),
  beta,
  gamma_c
)
```

Arguments

Ls	Areocentric longitude [deg]
phi	Planetary latitude [deg]
longitude	Planetary longitude [deg]
tau	Atmospheric optical depth (dimensionless)
al	Surface albedo (dimensionless, 0-1). If not provided, calculated from latitude, longitude, and tau
beta	Surface tilt/slope angle from horizontal [deg]
gamma_c	Surface azimuth angle [deg]. Zero facing equator, east negative, west positive (-180 to +180)

Value

Albedo-reflected daily insolation on inclined surface [Wh/m²-day]

H_bh *Beam daily insolation on Mars horizontal surface*

Description

Calculates the direct beam solar energy received over a full Martian day on a horizontal surface. Obtained by integrating beam irradiance from sunrise to sunset.

Usage

```
H_bh(Ls, phi, tau)
```

Arguments

Ls	Areocentric longitude [deg]
phi	Planetary latitude [deg]
tau	Atmospheric optical depth (dimensionless)

Value

Beam daily insolation [Wh/m²-day]

`H_bi` *Beam daily insolation on Mars inclined surface*

Description

Calculates the direct beam solar energy received over a full Martian day on an inclined surface. Obtained by integrating beam irradiance from sunrise to sunset.

Usage

```
H_bi(Ls, phi, tau, beta, gamma_c)
```

Arguments

Ls	Areocentric longitude [deg]
phi	Planetary latitude [deg]
tau	Atmospheric optical depth (dimensionless)
beta	Surface tilt/slope angle from horizontal [deg]
gamma_c	Surface azimuth angle [deg]. Zero facing equator, east negative, west positive (-180 to +180)

Value

Beam daily insolation on inclined surface [Wh/m²-day]

`H_dh` *Diffuse daily insolation on Mars horizontal surface*

Description

Calculates the diffuse solar energy (scattered by atmospheric dust) received over a full Martian day on a horizontal surface. Obtained by integrating diffuse irradiance from sunrise to sunset.

Usage

```
H_dh(
  Ls,
  phi,
  longitude,
  tau,
  al = albedo(latitude = phi, longitude = longitude, tau = tau)
)
```

Arguments

Ls	Areocentric longitude [deg]
phi	Planetary latitude [deg]
longitude	Planetary longitude [deg]
tau	Atmospheric optical depth (dimensionless)
al	Surface albedo (dimensionless, 0-1). If not provided, calculated from latitude, longitude, and tau

Value

Diffuse daily insolation [Wh/m²-day]

H_di — *Diffuse daily insolation on Mars inclined surface*

Description

Calculates the diffuse solar energy (scattered by atmospheric dust) received over a full Martian day on an inclined surface. Obtained by integrating diffuse irradiance from sunrise to sunset.

Usage

```
H_di(
  Ls,
  phi,
  longitude,
  tau,
  al = albedo(latitude = phi, longitude = longitude, tau = tau),
  beta,
  gamma_c
)
```

Arguments

Ls	Areocentric longitude [deg]
phi	Planetary latitude [deg]
longitude	Planetary longitude [deg]
tau	Atmospheric optical depth (dimensionless)
al	Surface albedo (dimensionless, 0-1). If not provided, calculated from latitude, longitude, and tau
beta	Surface tilt/slope angle from horizontal [deg]
gamma_c	Surface azimuth angle [deg]. Zero facing equator, east negative, west positive (-180 to +180)

Value

Diffuse daily insolation on inclined surface [Wh/m²-day]

H_h — *Global daily insolation on Mars horizontal surface*

Description

Calculates the total solar energy received over a full Martian day on a horizontal surface. Obtained by integrating global hourly insolation from sunrise to sunset.

Usage

```
H_h(
  Ls,
  phi,
  longitude,
  tau,
  al = albedo(latitude = phi, longitude = longitude, tau = tau)
)
```

Arguments

`Ls`	Areocentric longitude [deg]
`phi`	Planetary latitude [deg]
`longitude`	Planetary longitude [deg]
`tau`	Atmospheric optical depth (dimensionless)
`al`	Surface albedo (dimensionless, 0-1). If not provided, calculated from latitude, longitude, and tau

Value

Global daily insolation [Wh/m²-day]

H_i — *Global daily insolation on Mars inclined surface*

Description

Calculates the total solar energy received over a full Martian day on an inclined surface. Obtained by integrating global hourly insolation from sunrise to sunset. Based on Appelbaum, Flood & Norambuena (1994).

Usage

```
H_i(
  Ls,
  phi,
  longitude,
  tau,
  al = albedo(latitude = phi, longitude = longitude, tau = tau),
  beta,
  gamma_c
)
```

Arguments

Ls	Areocentric longitude [deg]
phi	Planetary latitude [deg]
longitude	Planetary longitude [deg]
tau	Atmospheric optical depth (dimensionless)
al	Surface albedo (dimensionless, 0-1). If not provided, calculated from latitude, longitude, and tau
beta	Surface tilt/slope angle from horizontal [deg]
gamma_c	Surface azimuth angle [deg]. Zero facing equator, east negative, west positive (-180 to +180)

Value

Global daily insolation on inclined surface [Wh/m^2-day]

H_obh — *Daily beam insolation at top of Mars atmosphere*

Description

Calculates the solar beam energy over a full Martian day on a horizontal surface at the top of the Martian atmosphere (before atmospheric attenuation). Implements Equation 13 from Appelbaum & Flood (1990).

Usage

```
H_obh(Ls, phi)
```

Arguments

`Ls`	Areocentric longitude [deg]
`phi`	Planetary latitude [deg]

Value

Daily beam insolation at top of atmosphere [Wh/m²-day]

is_irradiated — *Check if surface is receiving solar irradiance*

Description

Determines whether a surface at a given location and time is receiving solar irradiance. Accounts for polar night/day conditions, sunrise/sunset times, and sun position below horizon.

Usage

```
is_irradiated(Ls, phi, Ts, z = Z(Ls, Ts, phi), beta = NULL, gamma_c = NULL)
```

Arguments

`Ls`	Areocentric longitude [deg]
`phi`	Planetary latitude [deg]
`Ts`	Solar time [h]
`z`	Sun zenith angle [deg]. If not provided, calculated from Ls, phi, and Ts
`beta`	Surface tilt/slope angle from horizontal [deg]. Optional, for inclined surfaces
`gamma_c`	Surface azimuth angle [deg]. Optional, for inclined surfaces

Value

TRUE if surface is receiving irradiance, FALSE otherwise

is_polar_day *Check if location is experiencing polar day*

Description

Determines whether a given location on Mars is experiencing polar day (24-hour sunlight) for the specified season. During polar day, the sun remains above the horizon continuously.

Usage

```
is_polar_day(Ls, phi)
```

Arguments

Ls	Areocentric longitude [deg]
phi	Planetary latitude [deg]

Value

TRUE if experiencing polar day, FALSE otherwise

is_polar_night *Check if location is experiencing polar night*

Description

Determines whether a given location on Mars is experiencing polar night (24-hour darkness) for the specified season. During polar night, the sun remains below the horizon continuously.

Usage

```
is_polar_night(Ls, phi)
```

Arguments

Ls	Areocentric longitude [deg]
phi	Planetary latitude [deg]

Value

TRUE if experiencing polar night, FALSE otherwise

I_ali *Albedo-reflected insolation on Mars inclined surface over time period*

Description

Calculates the ground-reflected solar energy received on an inclined surface between specified start and end times. Obtained by integrating albedo-reflected irradiance over the time period.

Usage

```
I_ali(
  Ls,
  phi,
  longitude,
  tau,
  Ts_start,
  Ts_end,
  al = albedo(latitude = phi, longitude = longitude, tau = tau),
  beta,
  gamma_c
)
```

Arguments

`Ls`	Areocentric longitude [deg]
`phi`	Planetary latitude [deg]
`longitude`	Planetary longitude [deg]
`tau`	Atmospheric optical depth (dimensionless)
`Ts_start`	Start of integration period [h]
`Ts_end`	End of integration period [h]
`al`	Surface albedo (dimensionless, 0-1). If not provided, calculated from latitude, longitude, and tau
`beta`	Surface tilt/slope angle from horizontal [deg]
`gamma_c`	Surface azimuth angle [deg]. Zero facing equator, east negative, west positive (-180 to +180)

Value

Albedo-reflected insolation on inclined surface over specified time period [Wh/m²]

I_bh *Beam insolation on Mars horizontal surface over time period*

Description

Calculates the direct beam solar energy received on a horizontal surface between specified start and end times. Implements Equation 19 from Appelbaum & Flood (1990).

Usage

```
I_bh(Ls, phi, tau, Ts_start, Ts_end)
```

Arguments

Ls	Areocentric longitude [deg]
phi	Planetary latitude [deg]
tau	Atmospheric optical depth (dimensionless)
Ts_start	Start of integration period [h]
Ts_end	End of integration period [h]

Value

Beam insolation over specified time period [Wh/m²]

I_bi *Beam insolation on Mars inclined surface over time period*

Description

Calculates the direct beam solar energy received on an inclined surface between specified start and end times. Obtained by integrating beam irradiance over the time period.

Usage

```
I_bi(Ls, phi, tau, Ts_start, Ts_end, beta, gamma_c)
```

Arguments

Ls	Areocentric longitude [deg]
phi	Planetary latitude [deg]
tau	Atmospheric optical depth (dimensionless)
Ts_start	Start of integration period [h]
Ts_end	End of integration period [h]
beta	Surface tilt/slope angle from horizontal [deg]
gamma_c	Surface azimuth angle [deg]. Zero facing equator, east negative, west positive (-180 to +180)

Value

Beam insolation on inclined surface over specified time period [Wh/m²]

I_dh — *Diffuse insolation on Mars horizontal surface over time period*

Description

Calculates the diffuse solar energy (scattered by atmospheric dust) received on a horizontal surface between specified start and end times. Computed as difference between global and beam insolation.

Usage

```
I_dh(
  Ls,
  phi,
  longitude,
  tau,
  Ts_start,
  Ts_end,
  al = albedo(latitude = phi, longitude = longitude, tau = tau)
)
```

Arguments

Ls	Areocentric longitude [deg]
phi	Planetary latitude [deg]
longitude	Planetary longitude [deg]
tau	Atmospheric optical depth (dimensionless)
Ts_start	Start of integration period [h]
Ts_end	End of integration period [h]
al	Surface albedo (dimensionless, 0-1). If not provided, calculated from latitude, longitude, and tau

Value

Diffuse insolation over specified time period [Wh/m²]

I_di *Diffuse insolation on Mars inclined surface over time period*

Description

Calculates the diffuse solar energy (scattered by atmospheric dust) received on an inclined surface between specified start and end times. Obtained by integrating diffuse irradiance over the time period.

Usage

```
I_di(
  Ls,
  phi,
  longitude,
  tau,
  Ts_start,
  Ts_end,
  al = albedo(latitude = phi, longitude = longitude, tau = tau),
  beta,
  gamma_c
)
```

Arguments

Ls	Areocentric longitude [deg]
phi	Planetary latitude [deg]
longitude	Planetary longitude [deg]
tau	Atmospheric optical depth (dimensionless)
Ts_start	Start of integration period [h]
Ts_end	End of integration period [h]
al	Surface albedo (dimensionless, 0-1). If not provided, calculated from latitude, longitude, and tau
beta	Surface tilt/slope angle from horizontal [deg]
gamma_c	Surface azimuth angle [deg]. Zero facing equator, east negative, west positive (-180 to +180)

Value

Diffuse insolation on inclined surface over specified time period [Wh/m²]

`I_h` *Global insolation on Mars horizontal surface over time period*

Description

Calculates the total solar energy received on a horizontal surface between specified start and end times. Obtained by integrating global irradiance over the time period.

Usage

```
I_h(
  Ls,
  phi,
  longitude,
  tau,
  Ts_start,
  Ts_end,
  al = albedo(latitude = phi, longitude = longitude, tau = tau)
)
```

Arguments

`Ls`	Areocentric longitude [deg]
`phi`	Planetary latitude [deg]
`longitude`	Planetary longitude [deg]
`tau`	Atmospheric optical depth (dimensionless)
`Ts_start`	Start of integration period [h]
`Ts_end`	End of integration period [h]
`al`	Surface albedo (dimensionless, 0-1). If not provided, calculated from latitude, longitude, and tau

Value

Global insolation over specified time period [Wh/m²]

`I_i` *Global insolation on Mars inclined surface over time period*

Description

Calculates the total solar energy received on an inclined surface between specified start and end times. Obtained by integrating global irradiance over the time period.

Usage

```
I_i(
  Ls,
  phi,
  longitude,
  tau,
  Ts_start,
  Ts_end,
  al = albedo(latitude = phi, longitude = longitude, tau = tau),
  beta,
  gamma_c
)
```

Arguments

`Ls`	Areocentric longitude [deg]
`phi`	Planetary latitude [deg]
`longitude`	Planetary longitude [deg]
`tau`	Atmospheric optical depth (dimensionless)
`Ts_start`	Start of integration period [h]
`Ts_end`	End of integration period [h]
`al`	Surface albedo (dimensionless, 0-1). If not provided, calculated from latitude, longitude, and tau
`beta`	Surface tilt/slope angle from horizontal [deg]
`gamma_c`	Surface azimuth angle [deg]. Zero facing equator, east negative, west positive (-180 to +180)

Value

Global insolation on inclined surface over specified time period [Wh/m²]

`I_obh` *Beam insolation at top of Mars atmosphere over time period*

Description

Calculates the solar beam energy on a horizontal surface at the top of the Martian atmosphere (before atmospheric attenuation) between specified start and end times. Implements Equation 11 from Appelbaum & Flood (1990).

Usage

```
I_obh(Ls, phi, Ts_start, Ts_end)
```

Arguments

`Ls`	Areocentric longitude [deg]
`phi`	Planetary latitude [deg]
`Ts_start`	Start of integration period [h]
`Ts_end`	End of integration period [h]

Value

Beam insolation at top of atmosphere over specified time period [Wh/m²]

`optical_depth` *Atmospheric optical depth on Mars*

Description

Calculates the optical depth of the Martian atmosphere as a function of latitude and season. The optical depth varies spatially and temporally, with peaks during global dust storms. Implements Equations 1 and 2 from Appelbaum, Landis & Sherman (1991).

Usage

```
optical_depth(Ls, phi, model = 1)
```

Arguments

`Ls`	Areocentric longitude [deg]
`phi`	Planetary latitude [deg]
`model`	Dust storm model (1 or 2). Model 1 assumes both storms originated at -30° latitude. Model 2 assumes storms at -30° (Ls=215°) and -10° (Ls=295°)

Value

Atmospheric optical depth (dimensionless, minimum 0.5)

Examples

```
# Calculate optical depth at Viking Lander 1 site during dust storm season
tau <- optical_depth(Ls = 215, phi = 22.3, model = 1)
```

`optimal_angle` *Optimal tilt angle for maximum daily insolation*

Description

Calculates the optimal surface tilt angle (beta) that maximizes daily solar energy collection for a given location and season on Mars. The surface is assumed to face the equator. Based on Equations 40 and 43 from Appelbaum (1993).

Usage

```
optimal_angle(Ls, phi, unit = 1)
```

Arguments

`Ls`	Areocentric longitude [deg]
`phi`	Planetary latitude [deg]
`unit`	Output unit: 1 for radians, 2 for degrees (default: 1)

Value

Optimal tilt angle [rad] or [deg] depending on unit parameter

`sunrise` *Sunrise time on Mars*

Description

Calculates the sunrise time for a horizontal or inclined surface on Mars. Returns NA during polar night/day periods.

Usage

```
sunrise(Ls, phi, beta = NULL, gamma_c = NULL, unit = 1)
```

Arguments

`Ls`	Areocentric longitude [deg]
`phi`	Planetary latitude [deg]
`beta`	Surface tilt angle [deg]. Optional, for inclined surfaces
`gamma_c`	Surface azimuth angle [deg]. Optional, for inclined surfaces. Zero facing equator, east negative, west positive (-180 to +180)
`unit`	Output unit: 1 for radians, 2 for degrees, 3 for solar hours (default: 1)

Value

Sunrise time [rad], [deg], or [h] depending on unit parameter, or NA during polar night/day

---

`sunset` *Sunset time on Mars*

Description

Calculates the sunset time for a horizontal or inclined surface on Mars. Returns NA during polar night/day periods.

Usage

```
sunset(Ls, phi, beta = NULL, gamma_c = NULL, unit = 1)
```

Arguments

`Ls`	Areocentric longitude [deg]
`phi`	Planetary latitude [deg]
`beta`	Surface tilt angle [deg]. Optional, for inclined surfaces
`gamma_c`	Surface azimuth angle [deg]. Optional, for inclined surfaces. Zero facing equator, east negative, west positive (-180 to +180)
`unit`	Output unit: 1 for radians, 2 for degrees, 3 for solar hours (default: 1)

Value

Sunset time [rad], [deg], or [h] depending on unit parameter, or NA during polar night/day

---

`T_d` *Number of Mars daylight hours*

Description

Calculates the duration of daylight (time between sunrise and sunset) for a given location and season on Mars. Implements Equation 10 from Appelbaum & Flood (1990).

Usage

```
T_d(Ls, phi)
```

Arguments

`Ls`	Areocentric longitude [deg]
`phi`	Planetary latitude [deg]

Value

Number of daylight hours [h]

Z *Solar zenith angle*

Description

Calculates the angle between the sun's rays and the vertical (zenith) direction. A zenith angle of 0° means the sun is directly overhead, while 90° means the sun is at the horizon. Implements Equation 6 from Appelbaum & Flood (1990).

Usage

```
Z(Ls, phi, Ts)
```

Arguments

`Ls`	Areocentric longitude [deg]
`phi`	Planetary latitude [deg]
`Ts`	Solar time [h]

Value

Sun zenith angle [deg]

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