11th PV Performance and Modeling Workshop (PVPMC)

Model of In-Plane Solar Irradiance for Front and Rear Side of PV Arrays

光伏方阵正反面辐照度的计算模型

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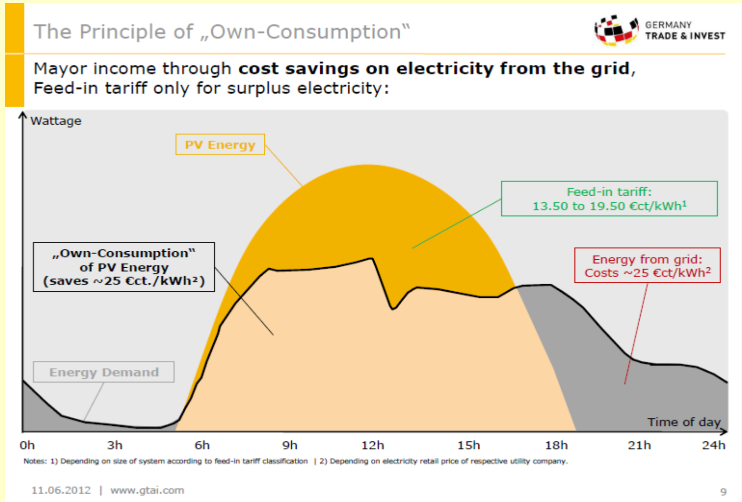
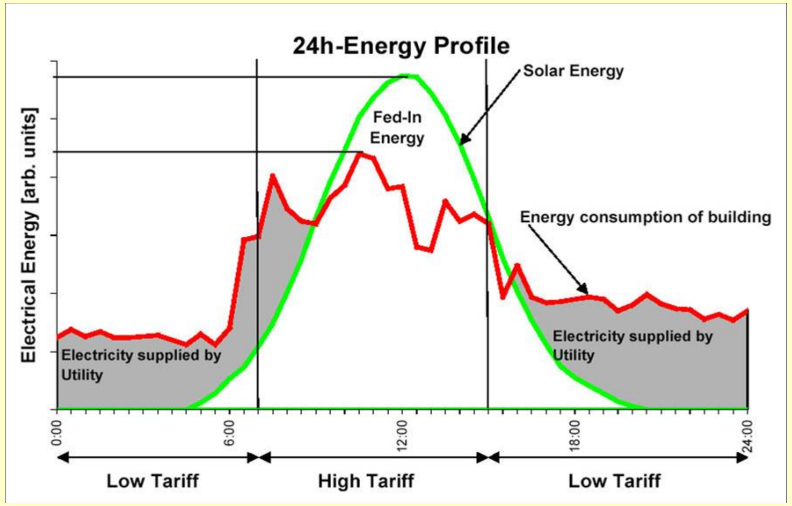
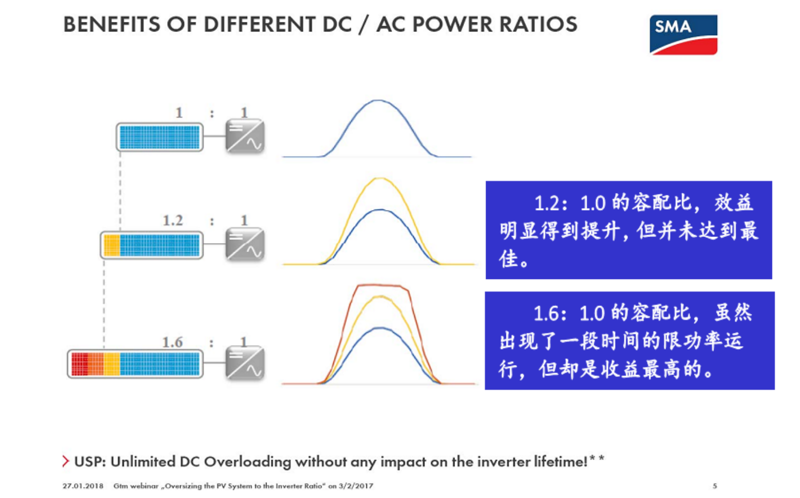
Dec. 4-5, 2018, Weihai, China

In-plane solar irradiance is the basic data to estimate PV power generation and useful in PV system designes:







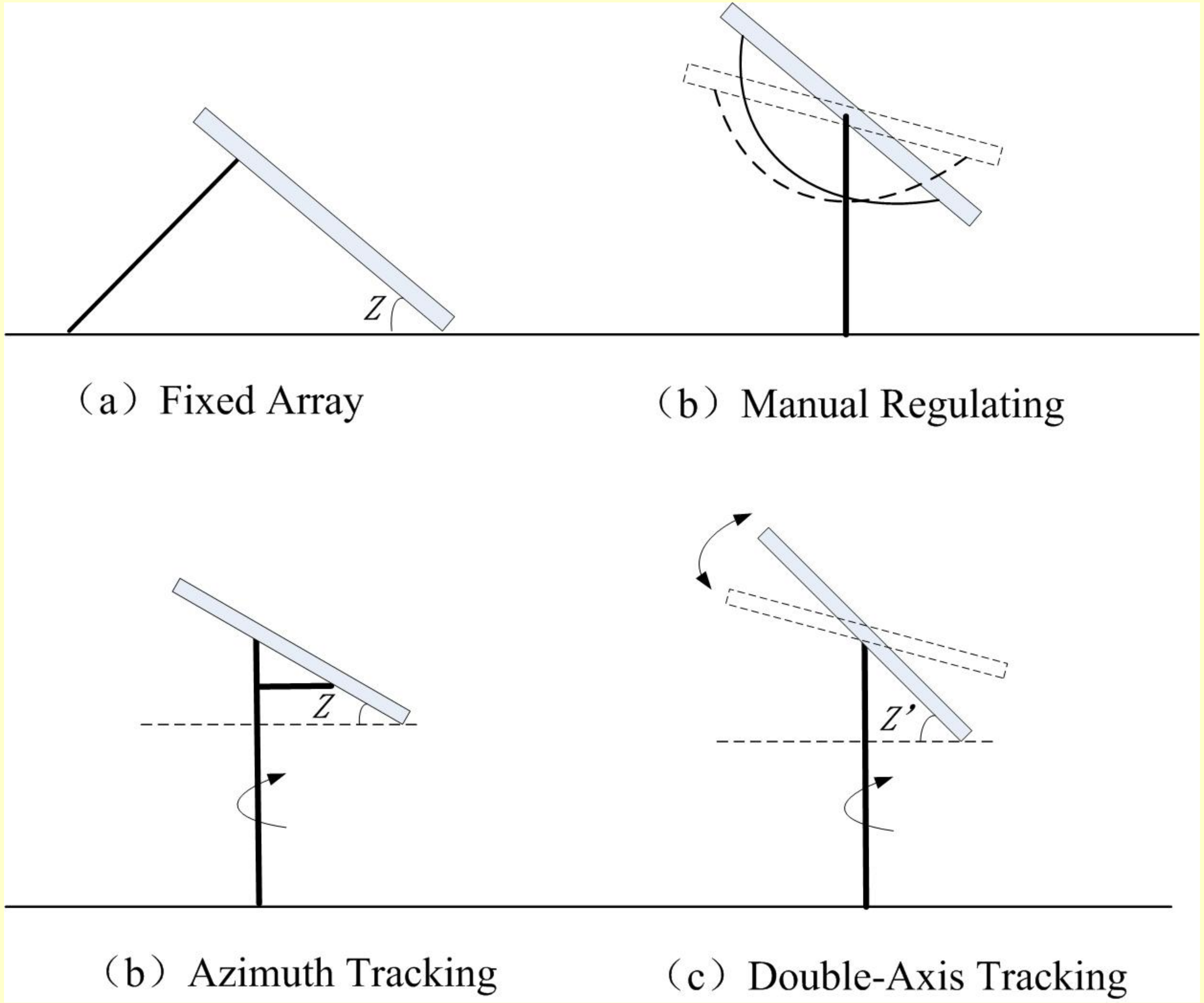
Battery Capacity Sizing
蓄电池容量设计

Balancing of Load Profile
发电与负荷的平衡

PV-Inverter Capacity Ratio
光伏-逆变器容配比

In-plane solar irradiance can not be got from weather stations, they only have horizontal solar data. 气象局没有方阵面辐射量和辐照度的数据，只能提供水平面辐照度和辐射量的数据。

PV Arrays in Ground Horizontal Coordinates



The solar trackers are tracking the solar altitude and the solar azimuth by regulating the array tilted angle and array azimuth.

Ground Horizontal PV Arrays

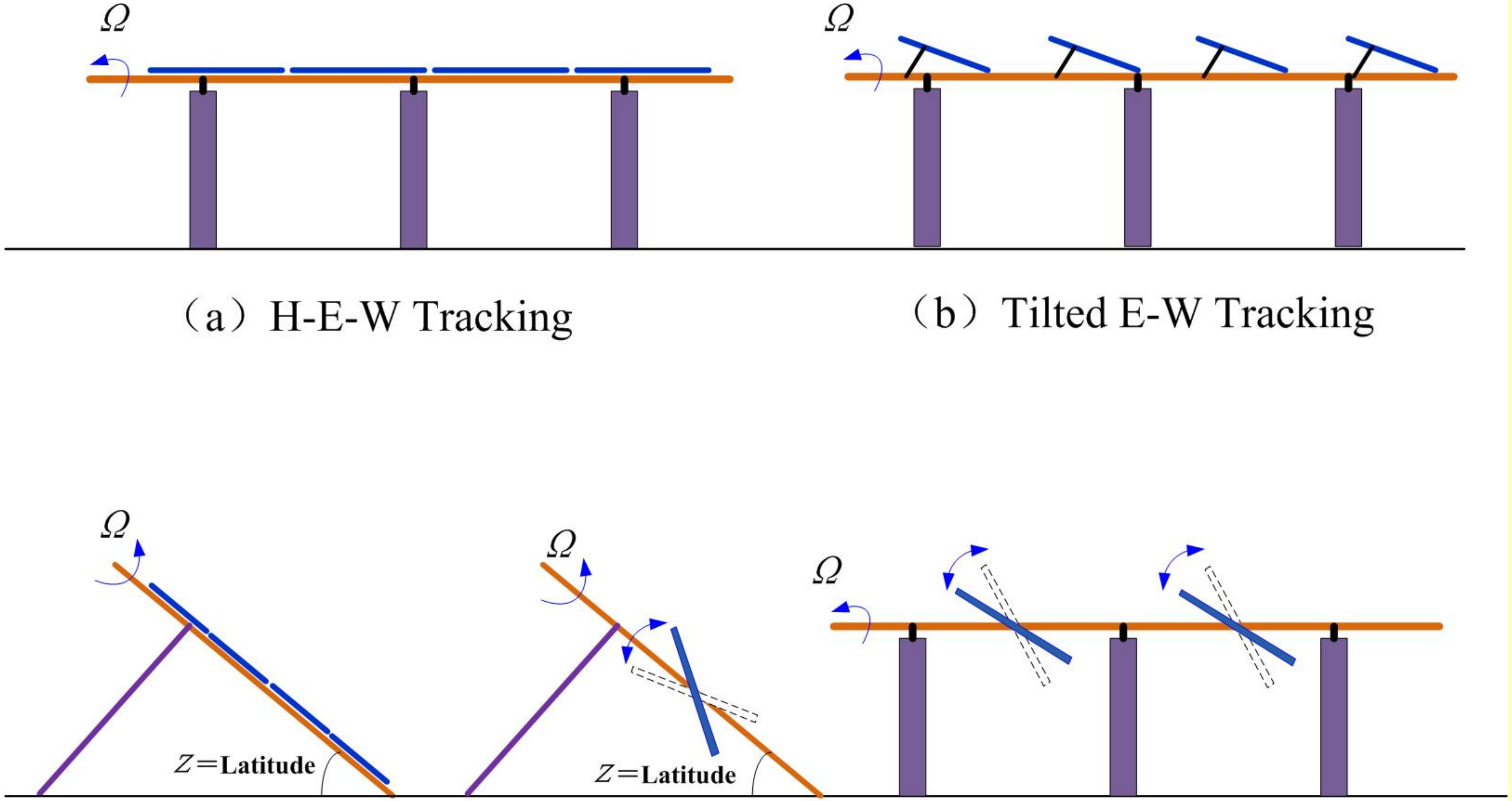
Fixed PV Array

Manual Regulated Arrays

Solar Azimuth Trackers

Double Axis Trackers

PV Arrays in Equatorial Coordinates



（a）H-E-W Tracking （b）Tilted E-W Tracking

（c）Pole Axis-Tracking （d1）D-Tracking-1 （d2）D-Tracking-2

The solar trackers are tracking the <u>solar declination</u> and the <u>solar hour angle</u> by regulating the <u>array tilted angle</u> and <u>rotating angle of main axis</u>.

Equatorial Tracking Systems

Horizontal
E-W Tracking

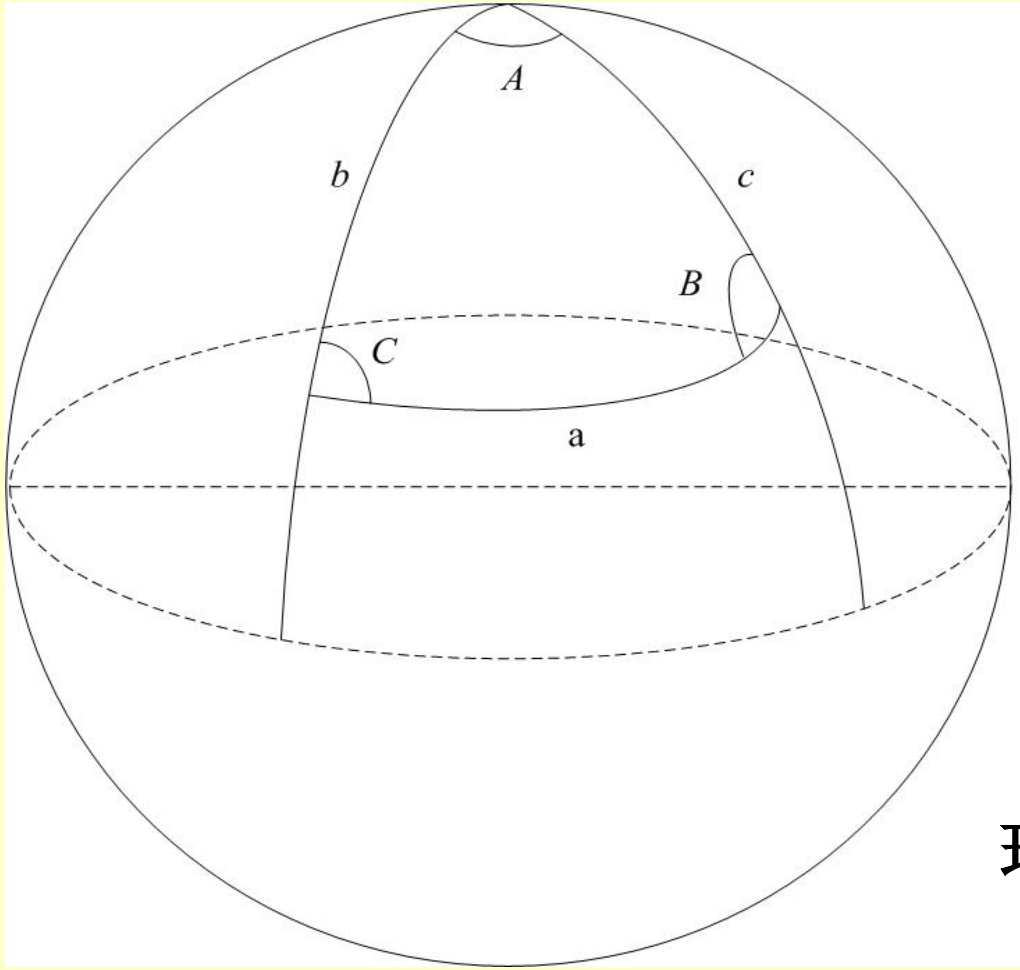
Pole-Axis
Tracking

Tilted E-W
Tracking

Double Axis
Tracking

3 Basic Rules and Concept

1. Cosine Rule of Arc in Spherical Tringles[5]



The tringle at celestial sphere

Arc: a, b, c

Angle: A, B, C

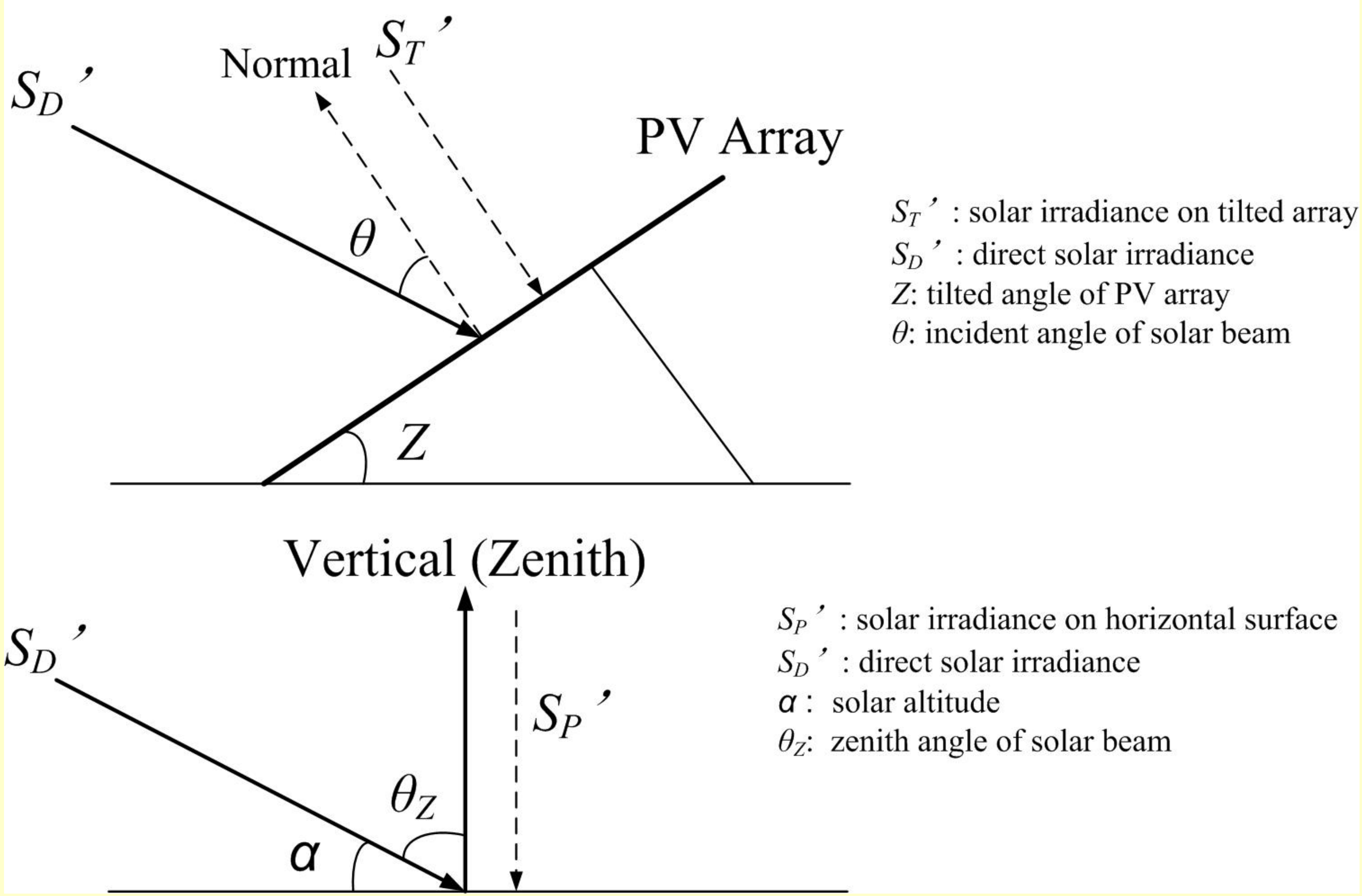
Cosine Rule:

$$\cos a = \cos b \cos c + \sin b \sin c \cos A$$

球面三角边的余弦定律

球面三角中的“边”是角度（弧），不是长度。

2. Cosine Rule of Direct Incidence (直接辐射的余弦定律)



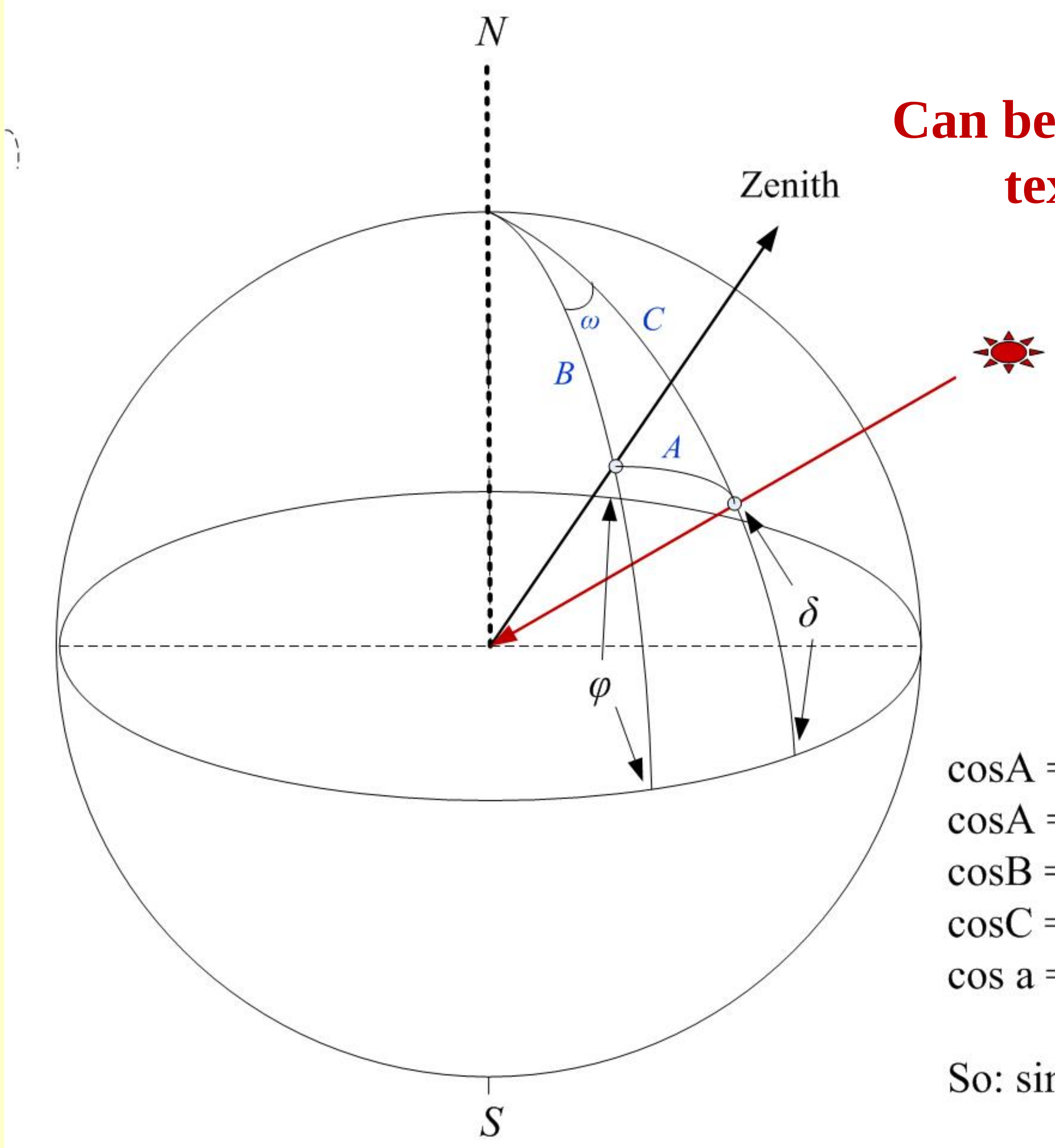
$S_T' = S_D' \cos\theta$ $\qquad$ $S_H' = S_D' \cos\theta_Z = S_D' \sin\alpha$

$S_D' = S_H' / \sin\alpha$ $\qquad$ So: $S_T' = S_H' \cos\theta / \sin\alpha$

3. Formula of Solar Altitude α [3,11]

<u>太阳高度角的公式</u>
能够在很多教科书上找到。

Can be found from any text book [3,11]



A: Solar zenith angle Za,

$Za = 90° - \alpha$;

$B = 90° - \varphi$;

$C = 90° - \delta$;

ω: *hour angle.* $a = \omega$

$\cos A = \cos B \cos C + \sin B \sin C \cos a$

$\cos A = \sin\alpha$

$\cos B = \sin\varphi \quad \sin B = \cos\varphi$

$\cos C = \sin\delta \quad \sin C = \cos\delta$

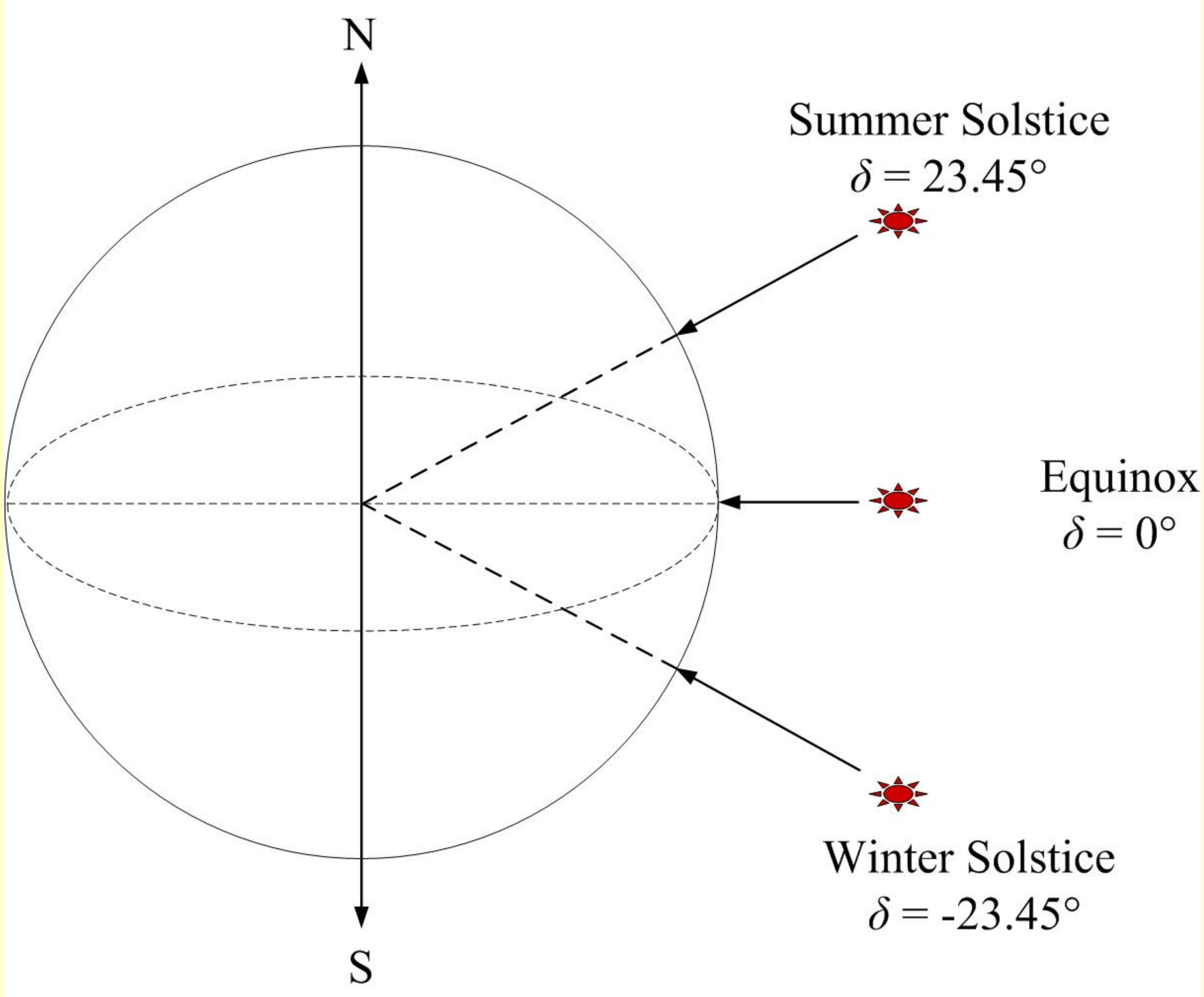
$\cos a = \cos\omega$

So: $\sin\alpha = \sin\varphi\sin\delta + \cos\varphi\cos\delta\cos\omega$

Solar Declination
太阳赤纬角

Cooper’s Formula:

$$\delta = 23.5 \sin\left[360\frac{284+N}{365}\right]$$



How to get the Irradiance on PV front surface?

$$Q'_T = S'_T + D'_T + R'_T$$

$$S'_T = S'_H \text{ x } \cos\theta/\sin\alpha = S'_H \text{ x } R_b$$

($R_b = \cos\theta/\sin\alpha$ is the ratio of tilted irradiance to the horizontal irradiance)

$$D'_T = D'_H(1 + \cos Z')/2 \qquad R'_T = \rho Q'_H(1 - \cos Z')/2$$

5 variables are required for the calculation of in-plane total irradiance Q'_T:

1) Q'_H :Total irradiance on horizontal surface (kW/m2)

2) S'_H: Direct irradiance on horizontal surface (kW/m2)

3) D'_H: Diffuse irradiance on horizontal surface (kW/m2)

4) $\cos\theta$: cosine of solar incident angle

5) $\cos Z'$: the instantaneous tilted angle of PV array

Diffuse Irradiance can be either Isotropic or Anisotropic

Isotropic model [1][2] **is for low irradiation and cloudy days:**

$$D'_T = D'_H(1 + \cos Z')/2 \quad \text{(by RetScreen)}$$

For clear and sunny day, anisotropic model should be used: [6][8][9]

$$D_T' = D_H' \left(K(\cos\theta/\sin\alpha) + 1/2(1 + \cos Z')(1 - K) \right)$$

anisotropic diffuse from circumsolar ***isotropic sky diffuse***

$K = S_H / Q_0$ K: the share of circumsolar diffuse which has the same characteristic of direct irradiance.

How to get Horizontal Irradiance Data?

$$Q'_H = D'_H + S'_H$$

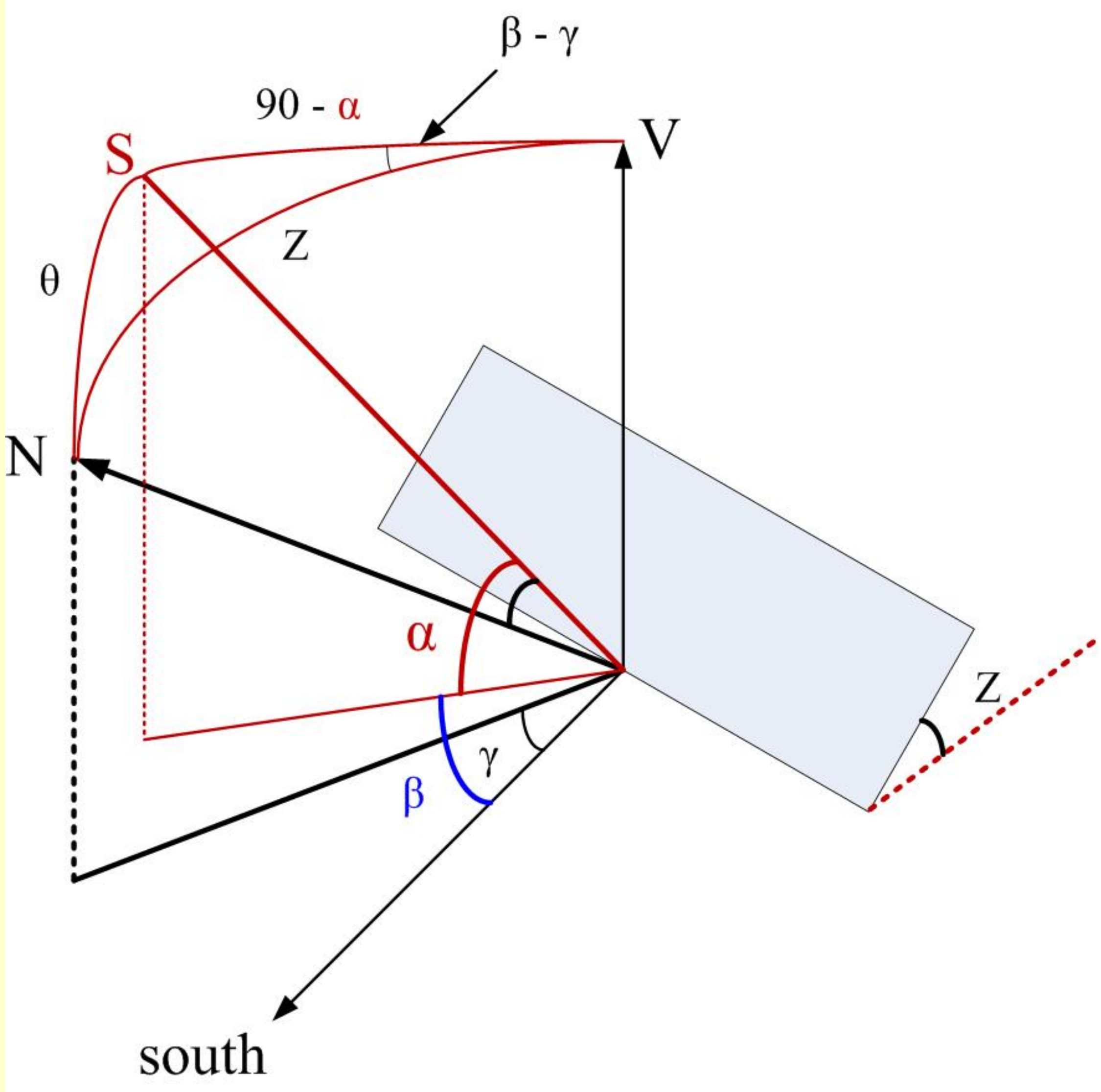
Q'_H: global irradiance at each hour (kW/m2)
D'_H: diffuse irradiance at each hour (kW/m2)
S'_H: direct irradiance at each hour (kW/m2)

1. Multi-Year average real-tested hourly data: can be found at Weather station or the database of NASA , PVSyst or Meteonorm database or NREL database. 多年平均实测数据（小时量）
2. The horizontal hourly data can be got from Daily global and diffuse irradiation data by the distribution models (Klein distribution [2,9,10] or Bouguer-Lambert distribution[4]). 从日总辐射量和日散射辐射量，通过日辐射分布模型得到。
3. Daily Irradiation data can be got from Monthly Irradiation Data by the way of interpolation [4]. 日辐射量可以通过插值从月辐射量得到。

$\cos\theta$ for

Ground Horizontal Coordinates [3,11]

By J.E. Braun and J.C. Mitchell and used by RetScreen [3,10,11].



V:vertical Axis from ground to sky;
N: Normal of PV array;
Z: Tilted angle of PV array;
S: Solar beam;
α: Solar altitude;
β: Solar azimuth
r: PV array azimuth

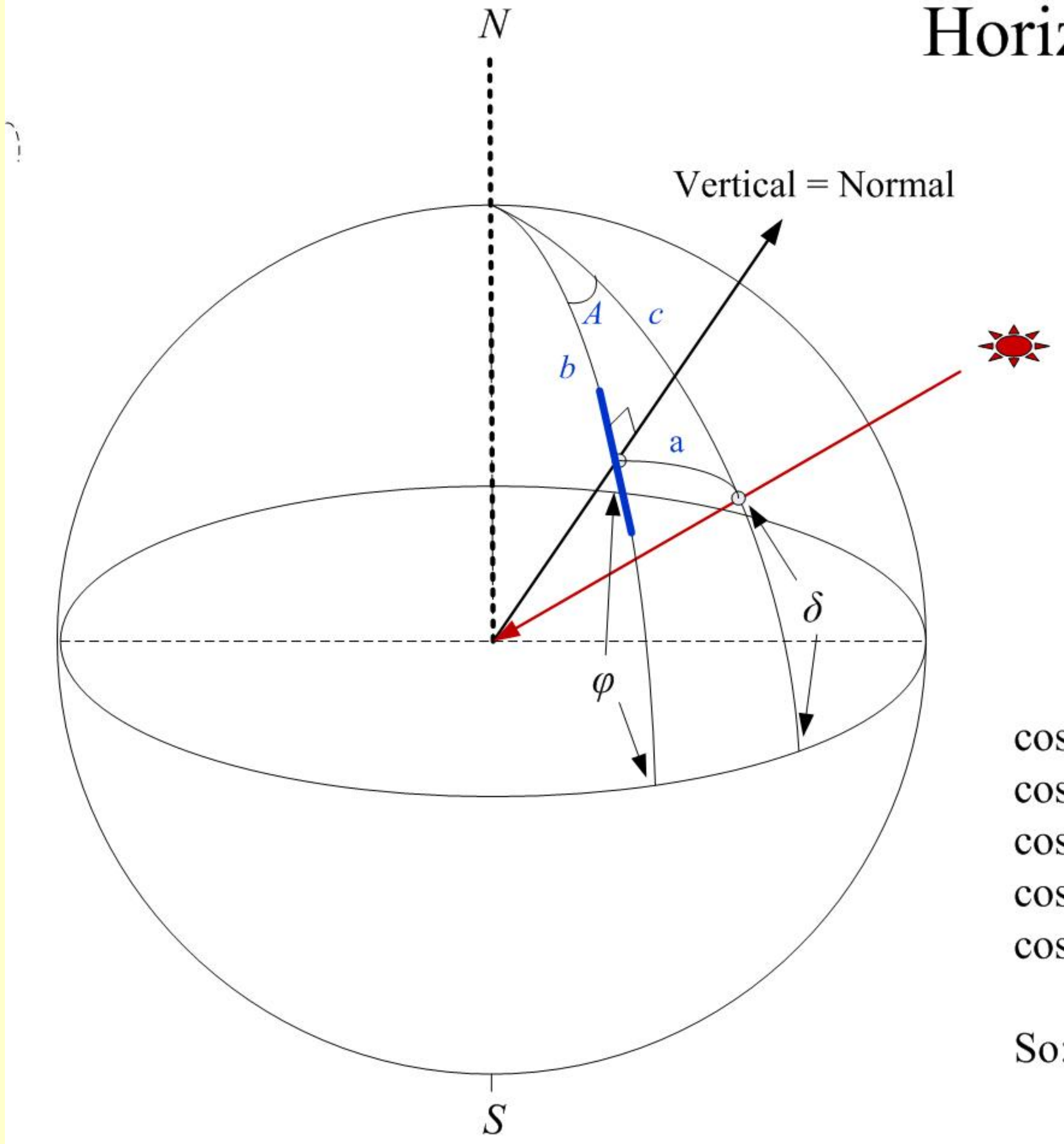
Derived from the rule of spherical tringle:

$$\cos\theta = \cos Z'\sin\alpha + \sin Z'\cos\alpha \cos(\beta - \gamma)$$

$\cos\theta$ for

Equatorial H-E-W Tracking [Wang Sicheng]

Horizontal *E-W* Tracking



a: Solar zenith angle θ_Z, equal to solar incidence angle θ.

$\theta = 90° - \alpha$;

$b = 90° - \varphi$;

$c = 90° - \delta$;

$A = \omega - \Omega$

ω: hour angle.

Ω: rotating angle of PV axis

$\cos a = \cos b \cos c + \sin b \sin c \cos A$

$\cos a = \cos\theta = \sin\alpha$

$\cos b = \sin\varphi \quad \sin b = \cos\varphi$

$\cos c = \sin\delta \quad \sin c = \cos\delta$

$\cos A = \cos(\omega - \Omega)$

So: $\cos\theta = \sin\varphi\sin\delta + \cos\varphi\cos\delta\cos(\omega - \Omega)$

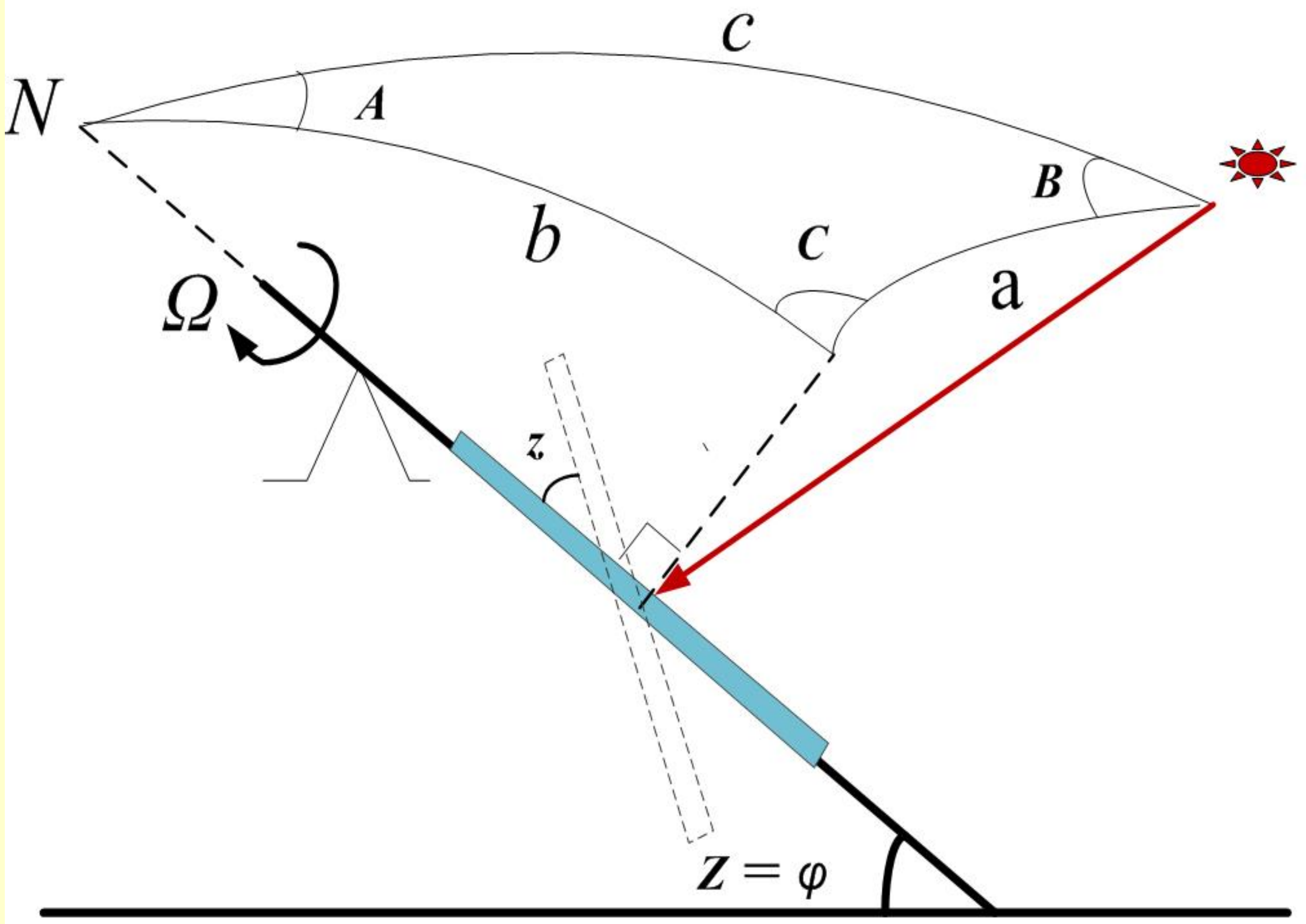
Referenced by the formula of solar altitude α, we can get:

$$\cos\theta = \sin\varphi\sin\delta + \cos\varphi\cos\delta\cos(\omega - \Omega)$$

General formula of cosθ

can be derived for Equatorial Coordinates

[Wang Sicheng]



$a = \theta$

$A = \omega - \Omega$;

$b = 90° - \varphi + Z + z$;

$c = 90° - \delta$;

θ: solar incident angle

ω : solar hour angle

Ω : main axis rotating angle

δ : *solar declination*

Z: tilted angle of main axis

z : module tilt on main axis

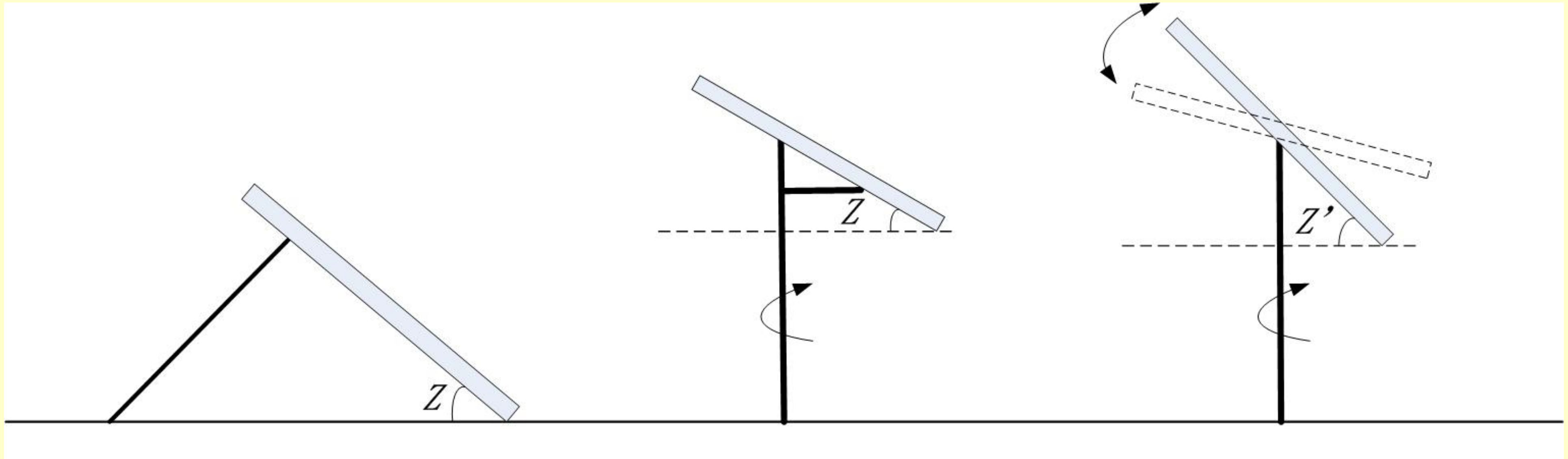
Key Facor: $b = 90° - \varphi + Z + z$

$$\cos a = \cos b \cos c + \sin b \sin c \cos A$$

$$\cos\theta = \cos(90°-\varphi+Z+z)\cos\delta+\sin(90°-\varphi+Z+z)\sin\delta\cos(\omega-\Omega)$$

Instantaneous Tilted Angle of Array *Z'* [3,11]

Ground Horizontal Coordinates



(a) Fixed Array (b) Azimuth Tracking (c) Double-Axis Tracking

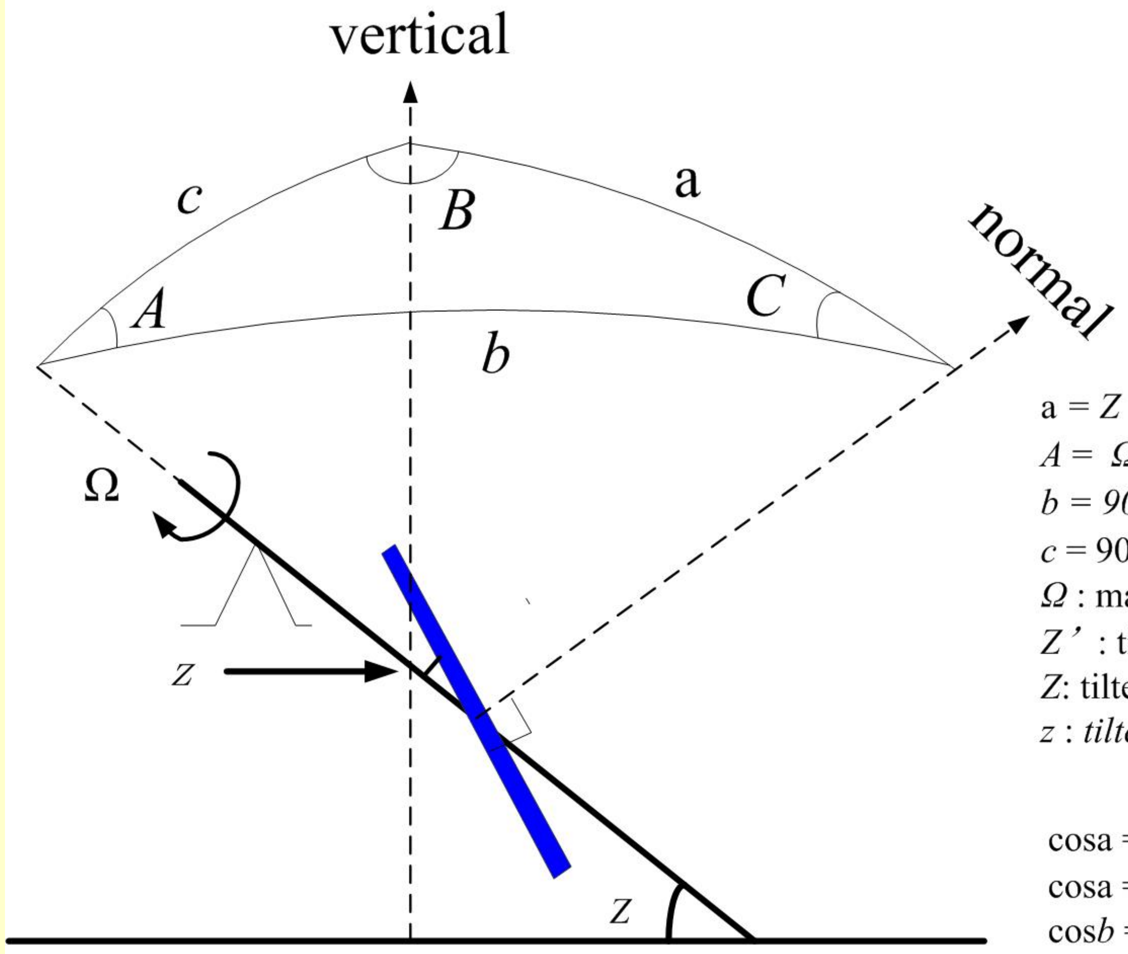
(a) Fixed Array: $Z' = Z$; (it is the same with manual regulated arrays)

(b) Azimuth Tracking: $Z' = Z$;

(c) Double Axis Tracking: $Z' = 90° - \alpha$。

Instantaneous Tilted Angle of Array *Z'* *for* Equatorial Coordinates can be derived from the rule of spherical tringle.

[4, Wang Sicheng]



$a = Z'$

$A = \Omega$;

$b = 90° + z$;

$c = 90° - Z$;

Ω : main axis rotating angle

Z' : tilted angle of array at any time

Z: tilted angle of main axis

z : *tilted angle of array on main axis*

$\cos a = \cos b \cos c + \sin b \sin c \cos A$

$\cos a = \cos Z'$

$\cos b = \sin z \quad \sin b = \cos z$

$\cos c = \sin Z \quad \sin c = \cos Z$

$\cos A = \cos \Omega$

$$\cos Z' = \sin z \sin Z + \cos z \cos Z \cos \Omega$$

For double-axis tracking in ground horizontal coordinates, we have:

$Z' = 90° - \alpha$

If we set $z = \delta$ **and**

$b = 90° - z$

We will have:

$\cos Z' = \sin\alpha$ **Then:** $Z' = 90 - \alpha$

(a) H-E-W Tracking: $Z = 0, z = 0$, $\cos Z' = \cos\Omega$ $Z' = \Omega$;

(b) Tilted E-W Tracking: $Z = 0$, $z = z$, $\cos Z' = \cos z \cos\Omega$;

(c) Pole-Axis Tracking: $Z = \varphi$, $z = 0$, $\cos Z' = \cos\varphi\cos\Omega$;

(d) Double Axis Tracking: $Z = \varphi$, $z = -\delta$, $\Omega = \omega$ $\cos Z' = \sin(-\delta)\sin\varphi + \cos(-\delta)\cos\varphi\cos\omega$

Now we have all required formulas for θ and Z'

For θ:

Ground Horizontal Coordinates:

$$\cos\theta = \cos Z'\sin\alpha + \sin Z'\cos\alpha \cos(\beta - \gamma)$$

Equatorial Coordinates:

$$\cos\theta = \sin(90-\varphi+Z+z)\ \sin\delta + \cos(90-\varphi+Z+z)\cos\delta\cos(\omega-\Omega)$$

For Z':

Ground Horizontal Coordinates: Z' is always known.

Equatorial Coordinates:

$$\cos Z' = \sin z \sin Z + \cos z \cos Z \cos\Omega$$

The In-plane Solar Irradiance for Front-side

$Q_T' = S_T' + D_T' + R_T'$

$S'_T = S'_D \cos\theta = S'_H \, \mathrm{R_b}$ ($R_b = \cos\theta / \sin\alpha$)

$D'_T = D'_H (1+\cos Z')/2$ (take diffuse irradiance as isotropic)

$R'_T = \rho Q'_H (1-\cos Z')/2$

The in-plane solar daily irradiation by integrating the irradiance from sunrise (ω_r) to sunset (ω_s):

$$S_T = \int_{\omega_r}^{\omega_s} S_T' \, d\omega = \int_{\omega_r}^{\omega_s} \frac{S_{H'} \cos\theta}{\sin\alpha} \, d\omega$$

$$D_T = \int_{\omega_r}^{\omega_s} D_T' \, d\omega = \int_{\omega_r}^{\omega_s} \frac{D_{H'}(1+\cos Z')}{2} \, d\omega$$

$$R_T = \int_{\omega_r}^{\omega_s} R_T' \, d\omega = \int_{\omega_r}^{\omega_s} \frac{\rho Q_{H'}(1-\cos Z')}{2} \, d\omega$$

The monthly and yearly irradiation on PV array can be got simply sum-up the daily solar irradiations on PV array.

If we use anisotropic model for diffuse irradiance

$Q_T' = S_T' + D_T' + R_T'$

$S'_T = S'_D \cos\theta = S'_H R_b \quad (R_b = \cos\theta / \sin\alpha)$

$D'_T = D'_H \left[\frac{S_H}{Q_0} R_b + \frac{1}{2}\left(1 - \frac{S_H}{Q_0}\right)(1 + \cos Z')\right]$

$R'_T = \rho Q'_H (1 - \cos Z')/2$

And the in-plane daily irradiation by integrating the irradiance from sunrise (ω_r) to sunset (ω_s):

$$S_T = \int_{\omega_r}^{\omega_s} S_T' \, d\omega = \int_{\omega_r}^{\omega_s} \frac{S_H' \cos\theta}{\sin\alpha} \, d\omega$$

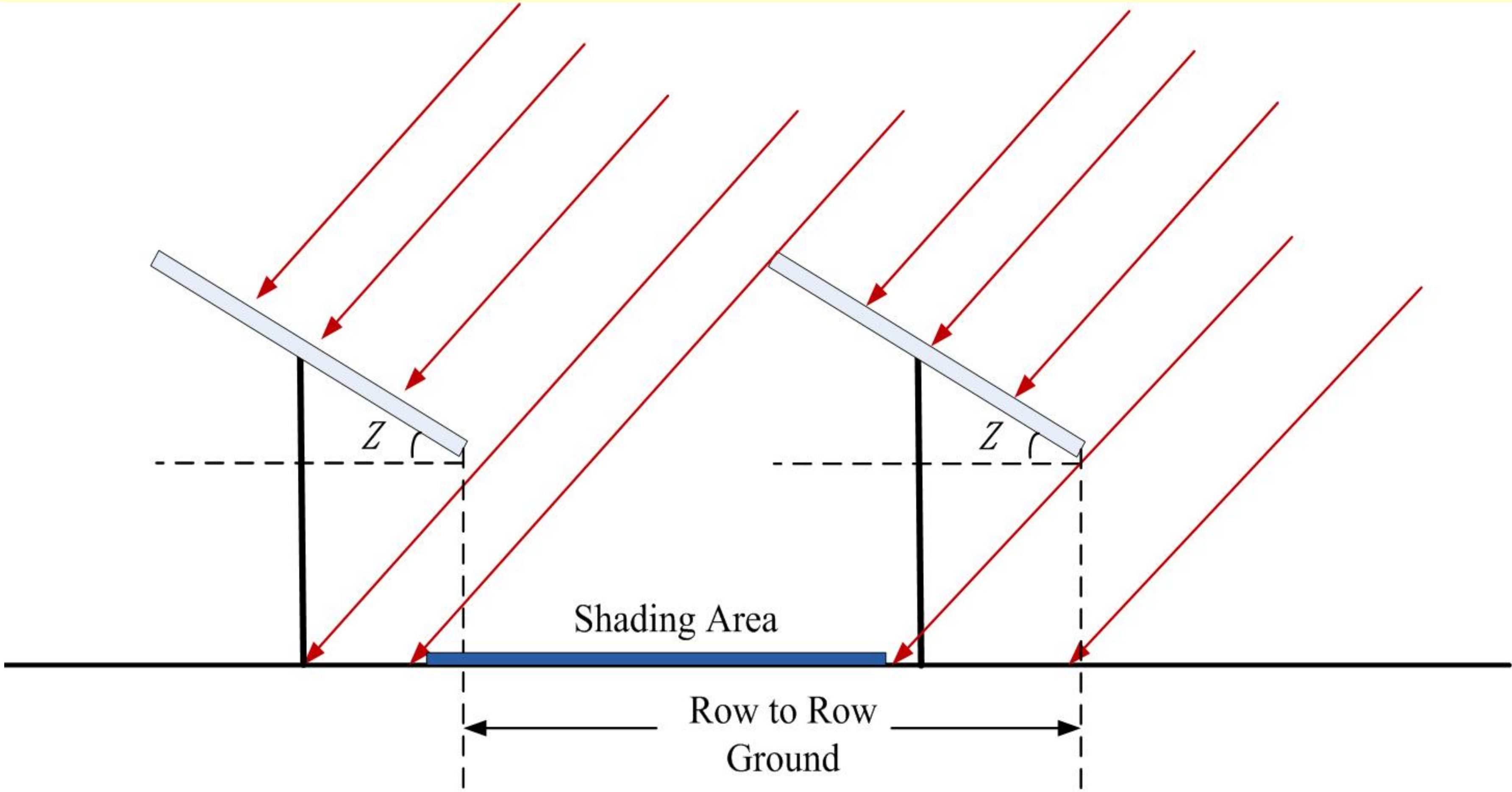
$$D_T = \int_{\omega_r}^{\omega_s} D_T' \, d\omega = \int_{\omega_r}^{\omega_s} \frac{D_H' \left[\frac{S_H}{Q_0} R_b + \frac{1}{2}\left(1 - \frac{S_H}{Q_0}\right)(1 + \cos Z')\right]}{2} \, d\omega$$

$$R_T = \int_{\omega_r}^{\omega_s} R_T' \, d\omega = \int_{\omega_r}^{\omega_s} \frac{\rho Q_H' (1 - \cos Z')}{2} \, d\omega$$

How about Bifacial PV Modules?

How to calculate the irradiance on the rear side surface?

The Main Differences between Front side and Rear side



1、All irradiance received by front side and rear side: direct irradiance, diffuse irradiance (anisotropic circumsolar and isotropic sky diffuse), and reflected irradiance by the ground;
2、The models for direct and circumsolar diffuse on backside, and the sky diffuse irradiance on backside are the same as that for front side;
3、The main difference is the reflected irradiance.

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Reference [1]

A Practical Irradiance Model for Bifacial PV Modules

Preprint

Bill Marion, Sara MacAlpine, and Chris Deline
National Renewable Energy Laboratory

Amir Asgharzadeh and Fatima Toor
University of Iowa

Daniel Riley, Joshua Stein, and Clifford Hansen
Sandia National Laboratories

Presented at 2017 IEEE 44th Photovoltaic Specialists Conference (PVSC)
Washington, DC
June 25–30, 2017

$$\mathrm{BSI} = b \cdot F_b \cdot (\mathrm{DNI} + I_{cir}) + \sum_{i=1^\circ}^{180^\circ} CF_i \cdot F_i \cdot I_i \qquad (4)$$

where b = maximum (0, cosine of the AOI of the DNI); F_b is the AOI correction for the DNI using the air-glass model of Sjerps-Koomen et al. [10]; CF_i is the CF for the ith one-degree segment; F_i is the AOI correction for the ith one-degree segment; and I_i is the irradiance viewed by the ith one-degree segment (either I_{sky}, I_{hor}, $\rho \cdot GRI_n$, or I_{refl}). The CF_i is represented by Eqn. 5:

$$CF_i = ½ \cdot [\cos(i - 1) - \cos(i)] \qquad (5)$$

where i is in degrees with a range from 1° to 180°. The field-of-view corresponding to a CF_i is shown in Fig. 2.

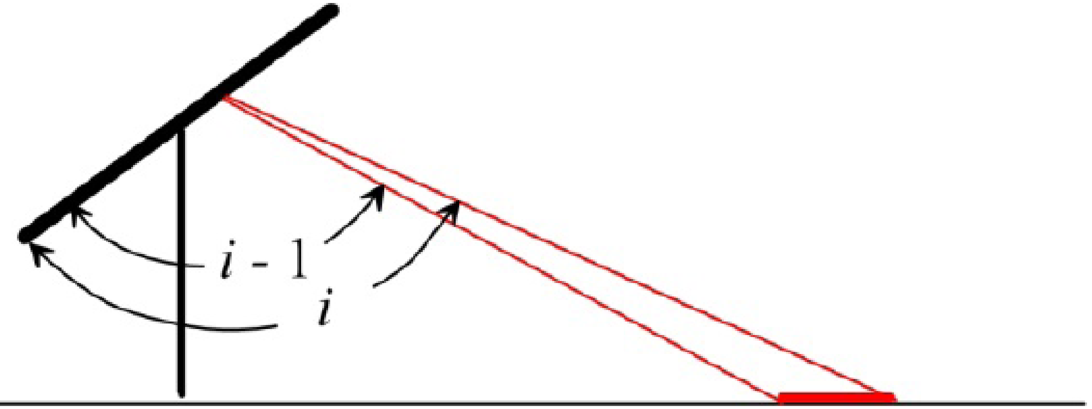


Fig. 2. Field-of-view of the ground for a one-degree segment depicted by the angles i and i-1.

Sum of Sky Diffuse Irradiance and the Reflected Irradiance by Ground Segment

Direct Irradiation and circumsolar diffuse

German Paper： Model for Rear side Ground Reflection

4th International Conference on Silicon Photovoltaics, SiliconPV 2014

Simulation of energy production by bifacial modules with revision of ground reflection

Ufuk Alper Yusufoglu[a,*], Tae Hun Lee[a], Tobias Markus Pletzer[a], Andreas Halm[b], Lejo Joseph Koduvelikulathu[b], Corrado Comparotto[b], Radovan Kopecek[b], Heinrich Kurz[a]

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[b]*International Solar Energy Research Center Konstanz e.V., Rudolf-Diesel-Str. 15, D-78467, Konstanz, Germany*

Reference [2]

Key Points：

1. The beam and diffuse sky irradiance components received on the backside may be modeled with the same model used for the front side. This paper only study on reflected irradiance；
2. Assuming that the shadowing is caused only by the direct irradiance, and the reflected direct part of irradiance to the backside only from area outside of the shading.
3. The principle of **View Factor (Fv)** can be applied for the calculation of ground reflected irradiance at the module rear side.
4. The View Factor denotes the ratio of the irradiance reaching the back surface to the available irradiance on the ground.

German Reference： the Backside Reflected Irradiance

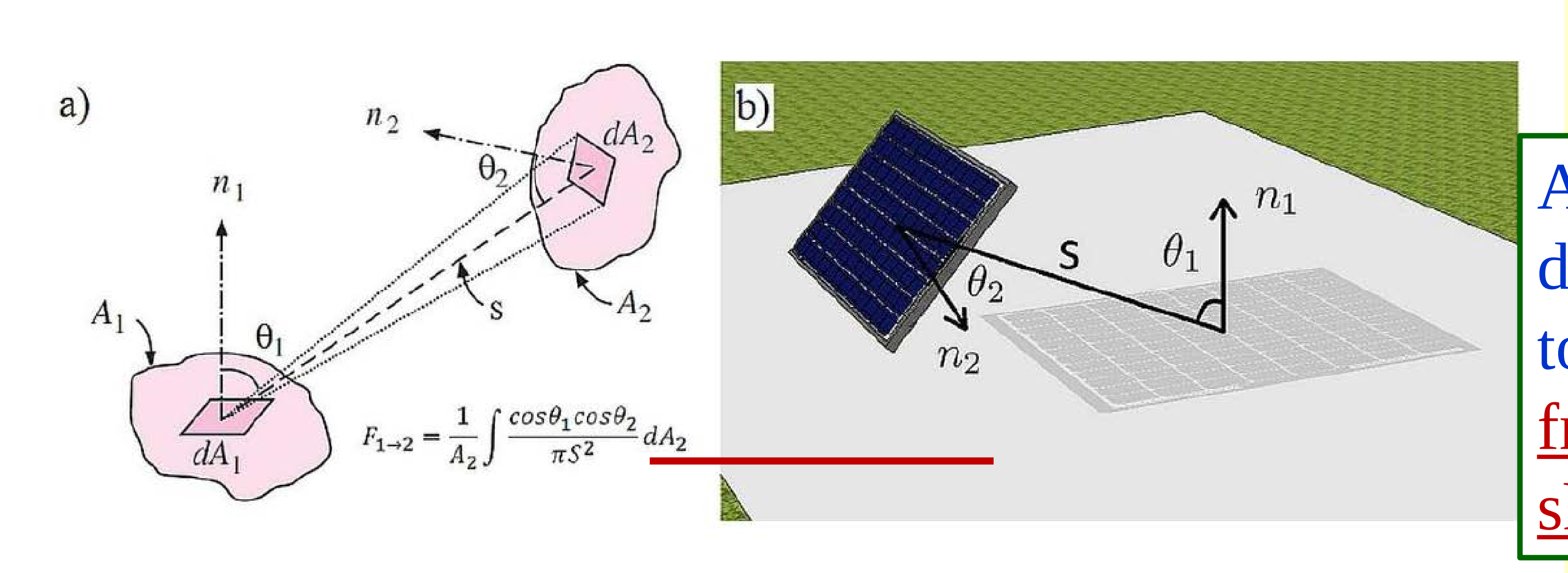


Fig. 1. (a) Definition of view factor and; (b) its implementation for the ground reflected radiation.

View Factor (Fv)

Assuming the reflected direct part of irradiance to the rear side only from area outside of the shading.

The Reflected Irradiance to the backside:

$$E_{POM,Albedo,rear} = \alpha DHI \frac{1+\cos\beta}{2} + \alpha\left(GHI - DHI\right)\left(\frac{1+\cos\beta}{2} - F_V\right)$$

Diffuse Part ↑ **Direct Part** ↑

Fraunhofer Developed a Ray Tracing Model

RAY TRACING

- **2nd approach : ray tracing**
  - Tracing back the path of light: from the PV cell to the light source (= sun and diffuse) by taking into account its encounters with obstacles
  - Rays of light = straight lines
  - Diffuse and/or specular reflection
  - Example : one PV cell→ 1 million of rays are sent by Monte Carlo, equiprobably distributed on the hemisphere → by successive reflections, they reach the light sources : sun and diffuse from the sky

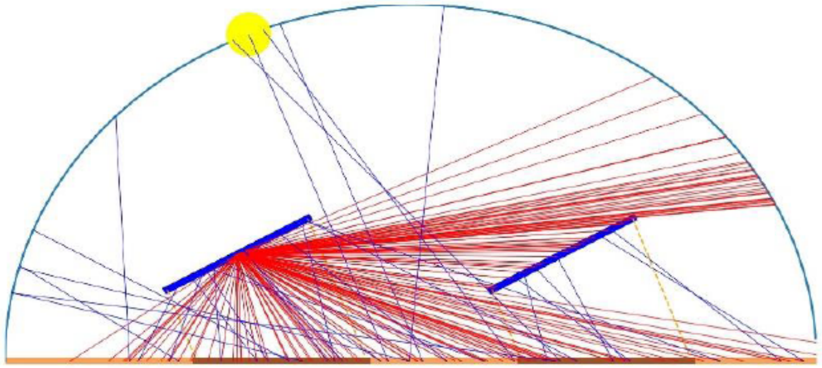


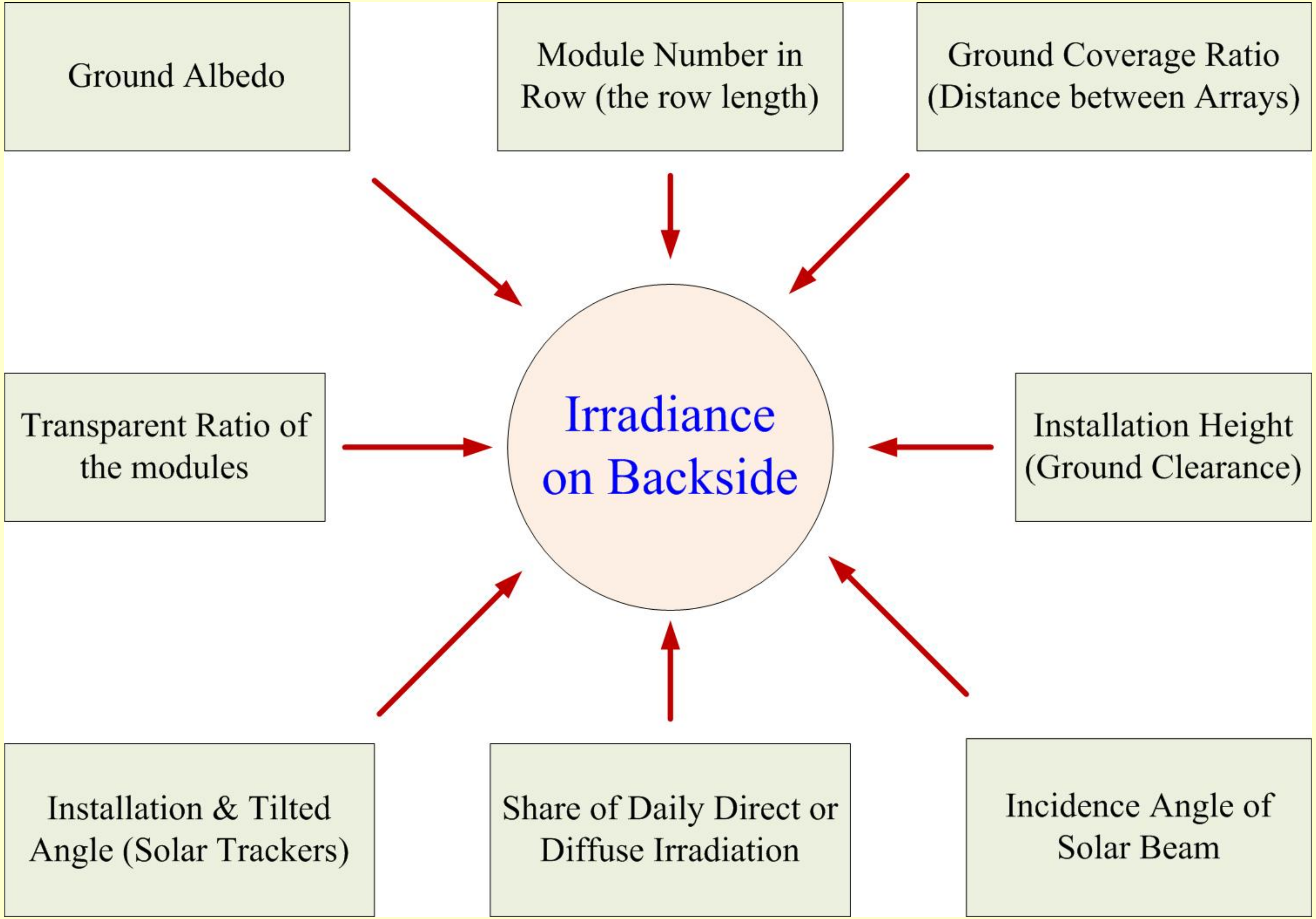
Illustration of ray-tracing in 2D from one cell on the rear of a bifacial module

A large number of rays (only 80 are shown) are sent from the cell in every directions

Rays reaching the ground are randomly reflected

For a 3MWp plant, about 20 billions rays are sent, calculation time is about tens of minutes

The Main Factors to Affect the Irradiance on Rear Side



Assumptions for the model on rear side irradiance

1) the direct and isotropic sky diffuse irradiation on backside will follow the same models as that of front side;

2) the Direct and Circumsolar Diffuse part can only be reflected by the area without shading;

3) the installation height above the ground is high enough, so the non-uniformity on backside can be neglected, otherwise we need calculate the backside irradiance column by column （string by string) from bottom to top. ;

4) the installation height above the ground is high enough, so the transparent ratio does not further affect the backside irradiance. Or, we add a percentage of transparent ratio to the formulas;

5) The affect from the incident angle will be ignored, if calculating the power generation from backside, we can add a coefficient;

6) the reflected Direct part of irradiance will relay on the Shading Ratio or Shining Ratio, and not relevant to GCR.

We may define several View Factors

F_{SR}: denotes the shading ratio or shading factor to the total used land.

F_{SR} = shading area/total land usage of PV array (%)
(How to get shading area and total land usage can be found in IEC/TR 63149-2018)

1-F_{SR}: effective land ratio without shading (%)

$(1+\cos Z')/2$: sky view factor for front side F_{SF} (0 – 100%)

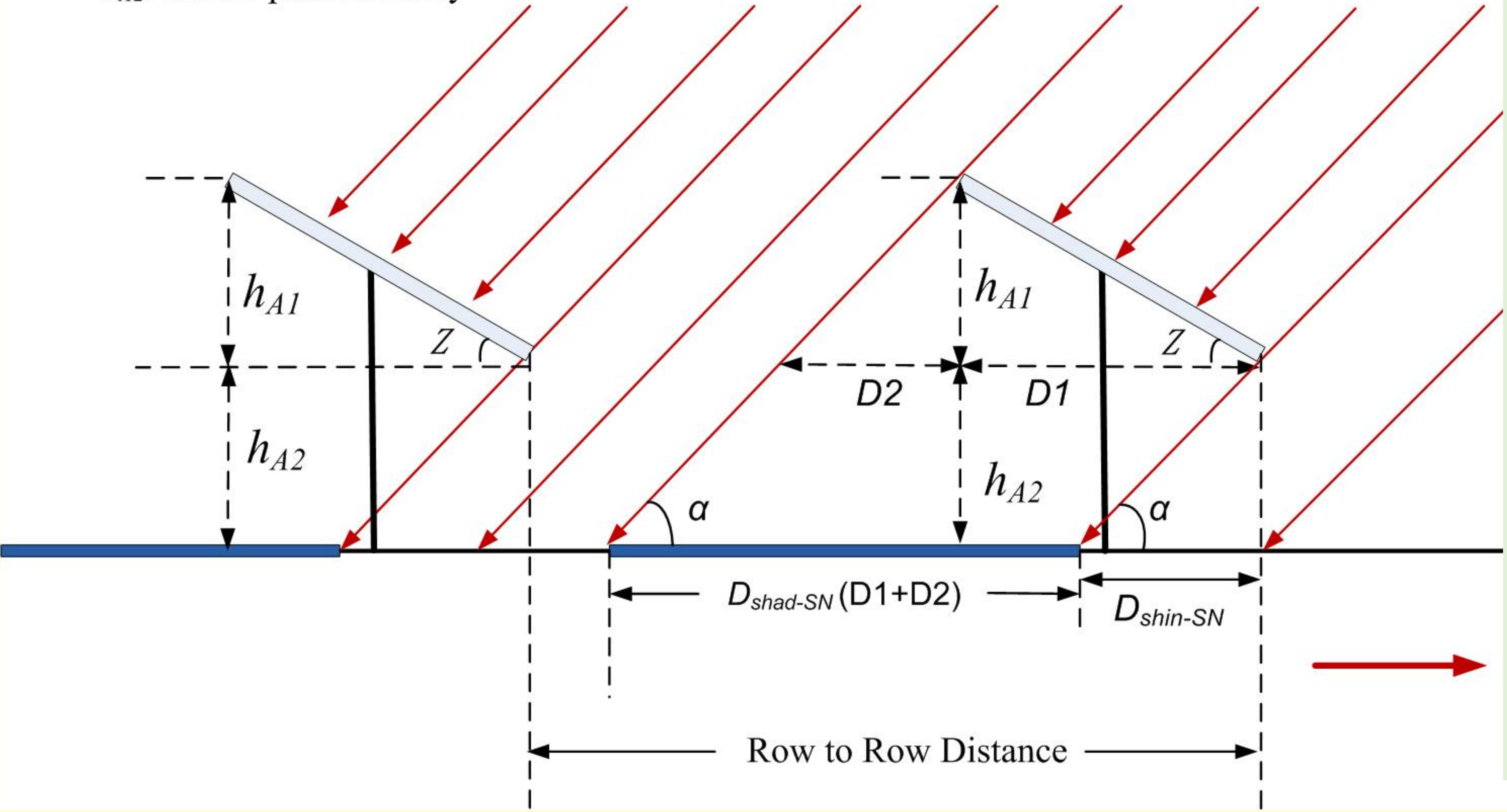
$(1-\cos Z')/2$: sky view factor for backside F_{SB} (0 – 100%)

$(1-\cos Z')/2$: ground view factor for front side F_{GF} (0 – 100%)

$(1+\cos Z')/2$: ground view factor for backside F_{GB} (0 – 100%)

F_{SR} : Shading Ratio
K: Array width
$D_{shad\text{-}SN}$: shading distance, S-N direction
$D_{shin\text{-}SN}$: shined distance under PV array, S-N direction
$D_{rtr\text{-}SN}$: row to row distance, S-N direction
h_{A1}: the array height
h_{A2}: lowest point of array

$F_{SR} = (K \times D_{shad\text{-}SN} / K \times D_{rtr\text{-}SN}) = D_{shad\text{-}SN} / D_{rtr\text{-}SN}$
$D_{shad\text{-}SN} = D1 + D2$ (IEC/TR 63149)
$D_{rtr\text{-}SN}$: is known (IEC/TR 63149)
$D_{shin\text{-}SN} = \cos\beta \times h_{A2} / \tan\alpha$

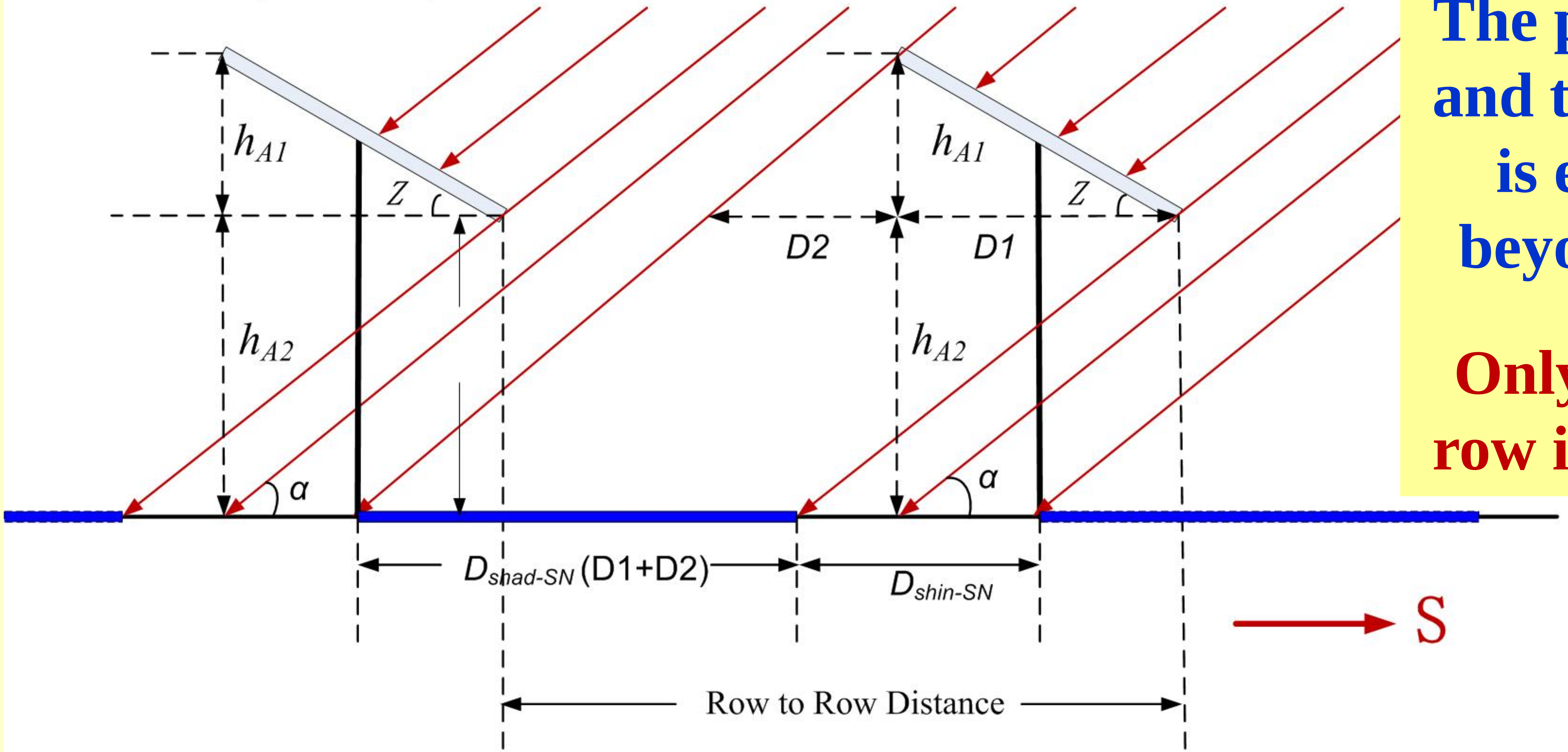


The Key Issue is how to calculate the Shading Ratio?
IEC/TR 63149

How about the front side? Never considered before?

F_{SR} : shading ratio
K: Array width
$D_{shad\text{-}SN}$: shading distance, S-N direction
$D_{shin\text{-}SN}$: shined distance under PV array, S-N direction
$D_{rtr\text{-}SN}$: row to row distance, S-N direction
h_{A1}: the height of array
h_{A2}: lowest point of array

$F_{SR} = (K \times D_{shad\text{-}SN} / K \times D_{rtr\text{-}SN}) = D_{shad\text{-}SN} / D_{rtr\text{-}SN}$
$D_{shad\text{-}SN} = D1 + D2$ (IEC/TR 63149)
$D_{rtr\text{-}SN}$: is known (IEC/TR 63149)
$D_{shin\text{-}SN} = \cos\beta \times h_{A2} / \tan\alpha$



The pole is high and the shading is extended beyond $D_{rtr\text{-}SN}$

Only the front row is different.

Formulas for rear side irradiance (1)

If we take **diffuse irradiance** as **isotropic**, we have:

$$Q'_{TB} = S'_{TB} + D'_{TB} + R'_{TB}$$

$$S'_{TB} = \cos\theta\, S'_{DB} = S'_H R_b \quad (R_b = \cos\theta / \sin\alpha)$$

(when β > 90°, S'_{TB} will shine on backside of fixed arrays)

$$D'_{TB} = D'_H [1+\cos(Z'+180°)]/2 = D'_H (1-\cos Z')/2$$

$$R'_{TB} = \rho D'_H \left(\frac{1+\cos Z'}{2}\right) + \rho (G'_H - D'_H) \left(\frac{1+\cos Z'}{2}\right)(1-F_v)$$

$$= \rho D'_H \left(\frac{1+\cos Z'}{2}\right) + \rho S'_H \left(\frac{1+\cos Z'}{2}\right)(1-F_v)$$

$$G'_H = D'_H + S'_H$$

Formulas for rear side irradiance (2)

If we take **diffuse irradiance** as **anisotropic**, we have:

For the front side: $D'_T = D'_H \left[\frac{S_H}{Q_0} R_b + \frac{1}{2}\left(1 - \frac{S_H}{Q_0}\right)(1 + \cos Z')\right]$

Circumsolar Sky Isotropic Diffuse

For the backside: $D'_{TB} = D'_H \left[\frac{S_H}{Q_0} R_b + \frac{1}{2}\left(1 - \frac{S_H}{Q_0}\right)(1 - \cos Z')\right]$

Circumsolar Sky Isotropic Diffuse

S_H: direct daily irradiation on horizontal surface

Q_0: is the extraterrestrial total daily solar irradiation on horizontal surface. [6]

So, we propose the rear side irradiance models as the followings:

$Q'_{TB} = S'_{TB} + D'_{TB} + R'_{TB}$

S'_{TB} + Diffuse of Circumsolar $= S'_H R_b + D'_H \left(\frac{S_H}{Q_0} R_b\right)$

$= \left[S'_H + D'_H \left(\frac{S_H}{Q_0}\right)\right] R_b$ ($R_b = \cos\theta / \sin\alpha$) (when $\beta > 90^\circ$)

$D'_{TB} = D'_H \left[\frac{1}{2}\left(1 - \frac{S_H}{Q_0}\right)(1 - \cos Z')\right]$

$R'_{TB} = \rho D'_H \left[\frac{1}{2}\left(1 - \frac{S_H}{Q_0}\right)\right] \left(\frac{1+\cos Z'}{2}\right) + \rho \left(S'_H + D'_H \frac{S_H}{Q_0}\right) \left(\frac{1+\cos Z'}{2}\right)(1 - \mathbf{Fv})$

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Thank You for Your Attention!