太陽能工程基礎

一、Extraterrestrial 大氣層外圍

1. Solar Constant 太陽常數

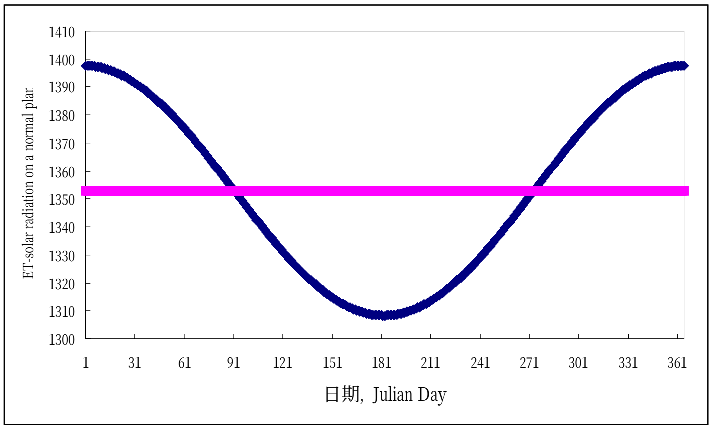
Extraterrestrial solar radiation on a surface normal to the sun's ray on the n-th day of the year：

$G'_{SC} = G_{SC}[1 + 0.033 \cos\{(n/365)(360^0)\}]$ .... [1]

where, G_{SC} = 1353 J s^{-1} m^{-2} or 429 Btu hr^{-1} ft^{-2} or 1.940 langleys min^{-1}

1 langley = 1 cal cm^{-2}

G_{SC} is called "Solar Constant" which is the average value of G'_{SC}



1981 年，世界氣象組織改訂其值為 1367±7 W/m^2。

2. Spectral Distribution 光譜分佈

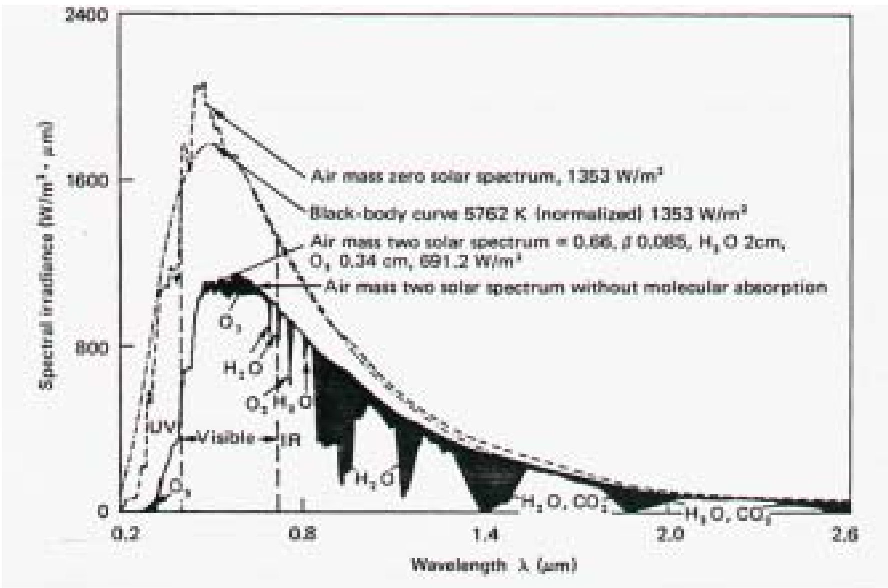


Figure 1 (from Duffie and Beckman, 1980)

Table 1. Extraterrestrial Solar Irradiance (Solar Constant = 1353 W/m^2)

λ	$G_{sc.\lambda}$ [a]	$f_{0-\lambda}$ [b]	λ	$G_{sc.\lambda}$ [a]	$f_{0-\lambda}$ [b]	λ	$G_{sc.\lambda}$ [a]	$f_{0-\lambda}$ [b]
0.24	63.0	0.0014	0.47	2033	0.1817	1.0	748	0.6949
0.25	70.9	0.0019	0.48	2074	0.1968	1.2	485	0.7840
0.26	130	0.0027	0.49	1950	0.2115	1.4	337	0.8433
0.27	232	0.0041	0.50	1942	0.2260	1.6	245	0.8861
0.28	222	0.0056	0.51	1882	0.2401	1.8	159	0.9159
0.29	482	0.0081	0.52	1833	0.2538	2.0	103	0.9349
0.30	514	0.0121	0.53	1842	0.2674	2.2	79	0.9483
0.31	689	0.0166	0.54	1783	0.2808	2.4	62	0.9586
0.32	830	0.0222	0.55	1725	0.2938	2.6	48	0.9667
0.33	1059	0.0293	0.56	1695	0.3065	2.8	39	0.9731
0.34	1074	0.0372	0.57	1712	0.3191	3.0	31	0.9783
0.35	1093	0.0452	0.58	1715	0.3318	3.2	22.6	0.9822
0.36	1068	0.0532	0.59	1700	0.3444	3.4	16.6	0.9850
0.37	1181	0.0615	0.60	1666	0.3568	3.6	13.5	0.9872
0.38	1120	0.0700	0.62	1602	0.3810	3.8	11.1	0.9891
0.39	1098	0.0782	0.64	1544	0.4042	4.0	9.5	0.9906
0.40	1429	0.0873	0.66	1486	0.4266	4.5	5.9	0.9934
0.41	1751	0.0992	0.68	1427	0.4481	5.0	3.8	0.9951
0.42	1747	0.1122	0.70	1369	0.4688	6.0	1.8	0.9972
0.43	1639	0.1247	0.72	1314	0.4886	7.0	1.0	0.9982
0.44	1810	0.1373	0.75	1235	0.5169	8.0	0.59	0.9988
0.45	2006	0.1514	0.80	1109	0.5602	10.0	0.24	0.9994
0.46	2066	0.1665	0.90	891	0.6337	50.0	3.9×10^{-4}	1.0000

a: $G_{sc.\lambda}$ is the solar spectral irradiance in W/ m^2 μm averaged over a small bandwidth centered at λ .

b: $f_{0-\lambda}$ is the fraction of the solar constant associated with wavelengths shorter than λ From Thekaekara (1974).

上表的 $f_{0-\lambda}$ 數據可使用下列兩式計算（方煒，1994，未發表）

For 240 500 nm		
$Y = a + b * X^2 * \sqrt{X} + c / X * \sqrt{X} + d * \exp(-X)$ ……….1st		
a = -0.16661872	b = 6.38928E-08	c = 415.778608
d = -1.3977E+101		R^2 = 0.99974

For 500 3800 nm		
$Y = a + b * X + c * X^2 + d / X + e / X^2$ ……………………………2nd		
a = 1.83579683	b = -0.00025789	C = 2.84687E-08
d = -1081.00849	e = 168404.6274	R^2 = 0.9999928353

The following are the normally measured radiation wavebands and their fr actions of the entire spectrum (0-50.0 micro-m) outside of the atmosphere.

from 1st eq. ：$Y(X{=}280nm) = 0.0056$, $Y(X{=}380nm) = 0.0700$, $Y(X{=}400nm) = 0.0873$
from 2nd eq. ：$Y(X{=}700nm) = 0.4688$, $Y(X{=}850nm) = 0.593875$,
$Y(X{=}1100nm) = 0.7395$, $Y(X{=}2800nm) = 0.9731$

Waveband, micro-m (μm)		Fraction
Total	0.28 - 2.80	0.9731-0.0056=0.9675
PAR*	0.40 - 0.70	0.4688 - 0.0873= 0.3815
Visible	0.38 - 0.78	0.4729
Spectroradiometer	0.30 - 1.1	0.72735
	0.40-1.1	0.7395-0.0873=0.6522

* PAR ：Photosynthetically Active Radiation 光合作用有效光

3. Units

Two concepts of unit systems are commonly used. They are Radiometric (輻射)and Quantum (光量子)units. Radiometric units are energy based and quantum units are photon based：

	Radiometric	Quantum
flux density 通量		
Radiant flux density/ Photon flux density	W m^{-2}	mol s^{-1} m^{-2}
fluence (over a specified time period; time integral of flux density)		
radiant fluence / photon fluence	J m^{-2}	mol m^{-2}

where, 1 mol = 6.022 x 10^{23} photons

In the literature, total radiation is normally given in radiometric units while PAR may be seen in both radiometric and quantum units. The conversion between the two unit systems is a complex matter. It depends on the type of radiation source, wavebands, etc.

To convert a daylight PAR quantity in W m^{-2} to micro-mol s^{-1} m^{-2}, the multiplication factor is 4.6

一個波長為 λ之光子之能量（in J）： $E = h * C / \lambda$

一mole個波長為 λ之光子之能量： $E = \psi * h * C / \lambda$,

ψ = 亞佛加厥常數 = $6.02252 * 10^{23}$

一 μmole個波長為 λ之光子之能量：

$$E = (6.02252*10^{(23-6)}) * h * C / \lambda ,$$

將普郎克常數（h）與光速（$C=2.997925 * 10^{17}$ nm/s）代入上式，可得：

$$E = cst / \lambda$$

其中，$cst = 6.02252 * 6.6256 * 2.997925 * 10^{(23-6) - 34 + 17} = 119.6256$

一 μmole個波長為 λ之光子之能量， $E = 119.6256 / \lambda$

i.e. J / μmole = $119.6256 / \lambda$

i.e. μmole/J = $8.3594 * 10^{-3} * \lambda$ ....A

使用式A，就以下諸波長範圍做計算後，其 J/μmole 轉換因子分別如下：

波長範圍，nm	μmole/J 轉換因子	備 註
400 - 700	4.597677	LI-COR Quantum Sensor
400 - 1100	6.269560	LI-COR Pyranometer
380 - 770	4.764865	LI-COR Photometric Sensor
400 - 850	5.224633	PAR + Far Red
280 - 2800	12.873496	Eppley Pyranometer

Quantum Sensor 之量測值以 μmole/m^2.s 單位表示，假設其值為 Qq
Pyranometer 之量測值以 W/m^2 即 J/m^2.s 單位表示，假設其值為 Py
Photomtric Sensor之量測值以 kLux 單位表示，假設其值為 Ph

定義 Qw 為 Qq 之相當值，惟 Qw 以 W/m^2 為單位，波長範圍仍為 400 700 nm， Qw=Qq/4.597677，(μmole/m^2.s) / (μmole/J) = J/m^2.s = W/m^2。換言之，1 W/m^2 = 4.597677 μmole/m^2.s 約等於 4.6 μmole/m^2.s。

Q: 假設大氣層外的太陽輻射能為H_{ET} (in W/m^2)，則其PAR為多少 mole/m^2.s？

A: PAR (in W/m^2) = 0.3815 * H_{ET} (in W/m^2)

PAR (in mole/m^2.s) = 4.597677 * PAR (in W/m^2)

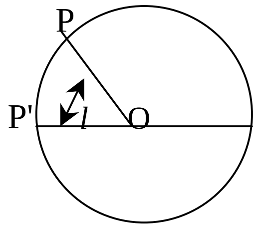
∴ PAR (in mole/m^2.s) = 4.597677 *0.3815 * H_{ET} (in W/m^2)

Note: 此些轉換因數依光源不同而異，以上各值僅適用於太陽光，其它人工光源如日光燈管等，請參考以下兩篇論文：

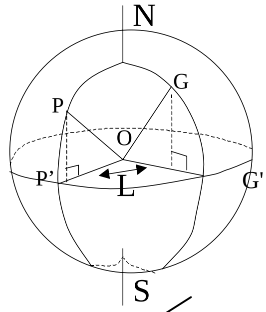
1. 饒，方。1997。螢光燈管照明單位與光量子單位換算因數之探討。中國園藝第43卷第2期，pp.141-148。
2. R.W. Thimijan, R.D. Heins, 1983. Photometric, Radiometric, and Quantum Light Units of Measure: A Review Procedures for Interconversion. HortScience, Vol 18(6) pp.818 -822.

二、Geometry 幾何

1. Orientation of a Point on Earth



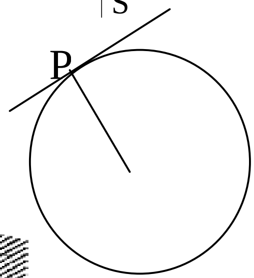
a. latitude, *l* ： The inclined angle between OP and the extension of its projection on the equatorial plane OP’. North being positive, south negative. 北半球為正，南半球為負。



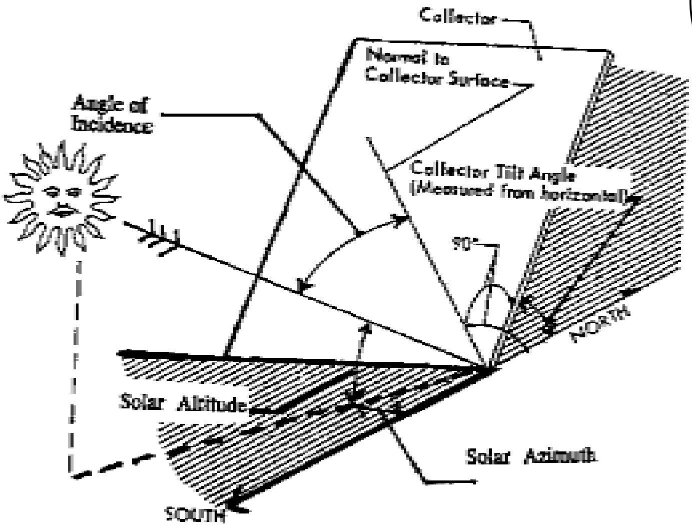
b. longitude, L： The inclined angle between OP’ and OG’. Where OG’ is the extension of the projection of OG on the equatorial plane, and G denotes the location of Greenwich, England. East being negative, west positive. 東經為負，西經為正。

2. Orientation of a Horizontal Plane

The plane tangent to the earth at point P. The ground is a good approximation of a horizontal plane.



3. Orientation of a Tilted Surface 斜面的方位



Specified by the direction angles of the normal line to the surface：

- surface zenith angle, Z_C：(斜面頂角=斜面傾斜角) The angle between the normal to the surface and the normal to the horizontal plane; same as the tilted angle.
- surface azimuth angle, A_C： (斜面方位角)The angle measured in the horizontal plane from due south to the horizontal projection of the normal of the surface. East being negative, west positive.

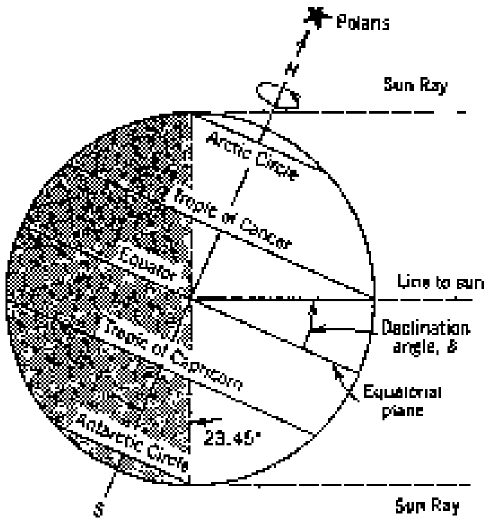
4. Sun-Earth Angles 太陽與地球的相關夾角

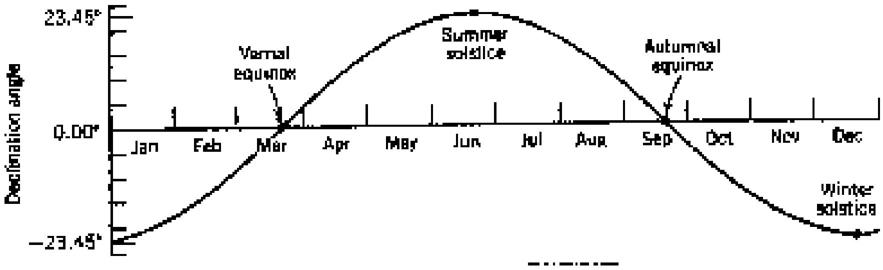
a. sun’s declination, d：(赤緯)

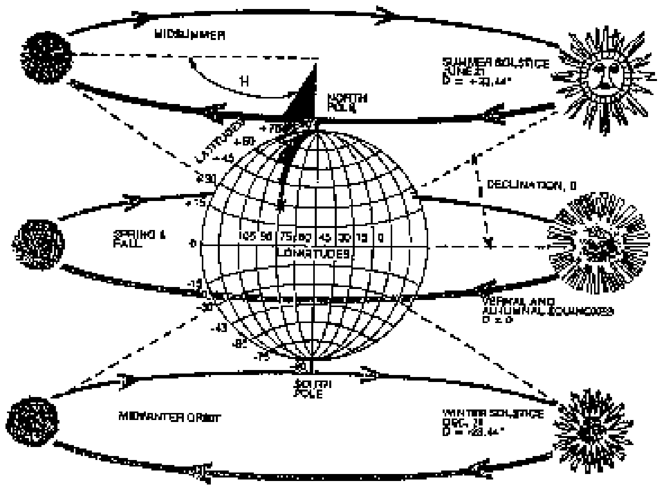
The angle between a line (OS) connecting the centers of the sun and the earth and the projection of this line on the earth ‘s equatorial plane.

$d = 23.45^0 \sin [\{(284+n)/365\}(360^0)]$ -- [2]

n = 81	3/22	d = 0
n = 172	6/21	d = 23.45
n = 264	9/21	d = 0
n = 355	12/21	d = -23.45

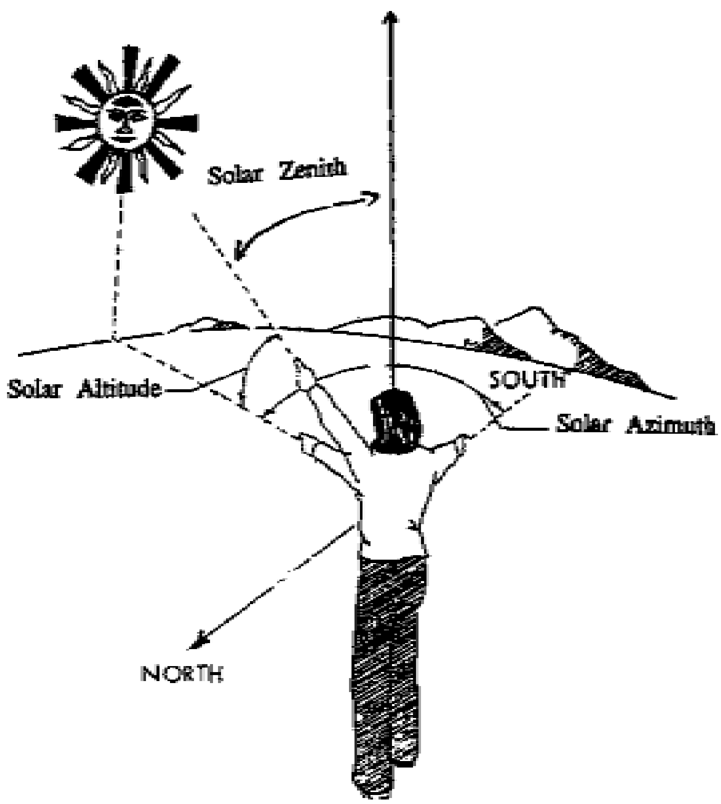




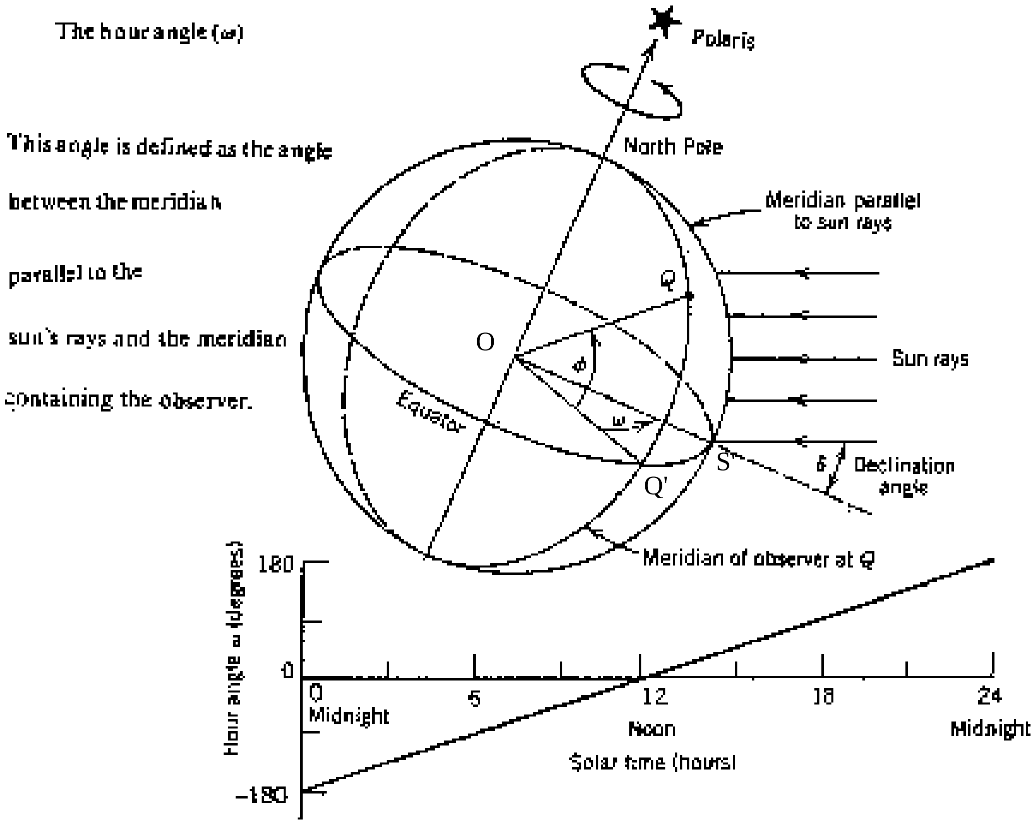


b. direction of sun’s beam: It is consider parallel to OS at any moment for any location on earth.

- solar zenith angle, Z_S ： (太陽頂角 = 90-太陽高度角)The angle between the sun’s beam and the normal of the horizontal plane. (= 90 - solar Altutude β), 日出與日落時為 90 度。
- solar azimuth angle, A_S ： (太陽方位角)The angle measured in the horizontal plane from due south to the horizontal projection of the sun’s beam. East being negative, west positive. 上午為負, 下午為正。



- hour angle (for a location Q on earth), h：(時角) The angle measured in the earth's equatorial plane between OQ' and OS'. In other words, it is the angle between Q's longitude and the longitude through which OS passes. Solar noon being zero, mornings negative and afternoons positive. Fifteen degrees hour angle is equivalent to one hour time. 上午為負, 下午為正, 正午為 0。15 度為 1 小時。



5. Sun-Tilted Surface Angles, S_C 太陽與斜面法線的夾角

The angle between sun's beam and the normal of the surface. 又稱入射角 (Angle of Incidence)。

a. for a given surface at any time：

$$\cos S_C = \sin d \sin l \cos Z_C - \sin Z_C \cos A_C \sin d \cos l + \cos d \cos l \cos Z_C \cos h + \sin Z_C \cos d \cos h \cos A_C \sin l + \cos d \sin Z_C \sin A_C \sin h \quad \text{--- [3]}$$

b. for horizontal surfaces at any time, $Z_C = 0$, then $S_C = Z_S$ ：

$$\cos Z_S = \cos S_C = \sin d \sin l + \cos d \cos l \cos h \quad \text{--------------------------- [4]}$$

also,

$$A_S = (h/\mathrm{abs}[h]) \cos^{-1} ([\sin l \cos h \cos d - \cos l \sin d]/\sin Z_S) \quad \text{------------- [5]}$$

Angle of Incidence 入射角（Sc）

	通式	正南 ($A_c = 0$)	正北(A_c=180)	正東 (-90)	正西 (90)
$\cos S_c$	$= \sin d \sin l \cos Z_c$ $- \sin Z_c \cos A_c \sin d \cos l$ $+\cos d \cos l \cos Z_c \cos h$ $+\sin Z_c$ cd ch $\cos A_c$ s l +cd $\sin Z_c \sin A_c$ sh	sd s l $\cos Z_c$ $-\sin Z_c$ sd c l +cd c l $\cos Z_c$ ch $+\sin Z_c$ cd ch s l +0	sd s l $\cos Z_c$ $+\sin Z_c$ sd c l +cd c l $\cos Z_c$ ch $-\sin Z_c$ cd ch s l +0	sd s l $\cos Z_c$ +0 +cd c l $\cos Z_c$ ch +0 -cd $\sin Z_c$ sh	sd s l $\cos Z_c$ +0 +cd c l $\cos Z_c$ ch +0 +cd $\sin Z_c$ sh

	水平面 $Z_c = 0$	垂直面 $Z_c = 90$（任意方向）	
$\cos S_c$	$= \sin d \sin l + \cos d \cos l \cos h$	$=-\cos A_c \sin d \cos l + \cos d \cos h \cos A_c \sin l + \cos d \sin A_c \sin h$	
	上式與 A_C 無關 且 $\cos Z_s = \cos S_c$ $= \cos (90-\beta) = \sin \beta$	正南	$= -\sin d \cos l + \cos d \cos h \cos l \;+\; 0$
		正北	$= \sin d \cos l \;- \cos d \cos h \sin l \;+\; 0$
		正東	$= \;0 \;+\; 0 \;-\; \cos d \sin h$
		正西	$= \;0 \;+\; 0 \;+\; \cos d \sin h$

Z_s 頂角，S_c 入射角，β 高度角

觀察：由上表知，對水平面而言，$\sin \beta = \sin d \sin l + \cos d \cos l \cos h$,
又是正午時分，$h = 0$ ，$\cos h = 1$，∴ $\sin \beta = \sin d \sin l + \cos d \cos l = \cos (l - d)$,
$\sin \beta = \cos (90 - \beta) = \cos(l - d)$ ，∴ $\boxed{\beta = 90 - l + d}$

6. Day Length and Solar Time 日長與太陽時間

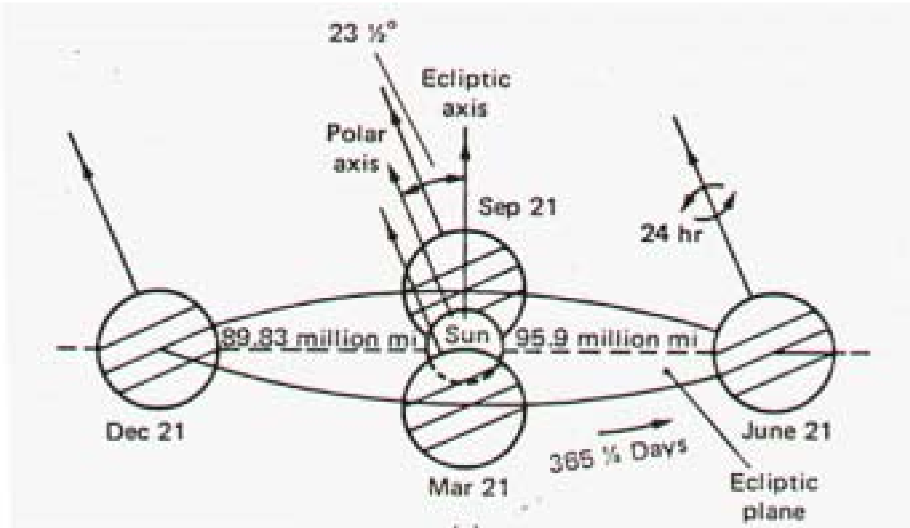
a. for horizontal surfaces at sunset and sunrise, $Z_s = 90^0$ and denote h_{SS} as the hour angle for those moments, then from equation 4.

$$\sin d \sin l + \cos d \cos l \cos h_{SS} = 0 \quad \text{----------------------------------- [6]}$$

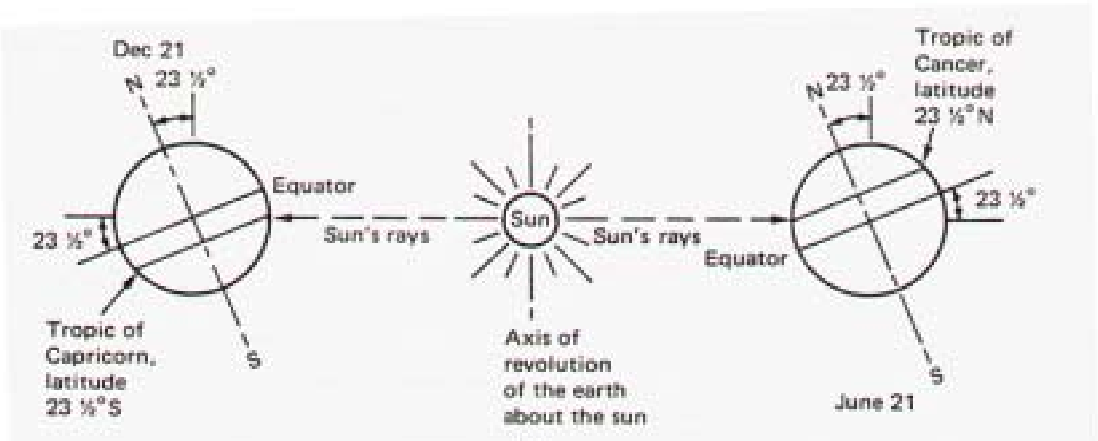
therefore,

$$h_{SS} = \cos^{-1} (-\tan l \tan d) \quad \text{--- [7]}$$

day length = 2 (abs[h_{SS} in degrees] / 15) ---------------------------- [8]



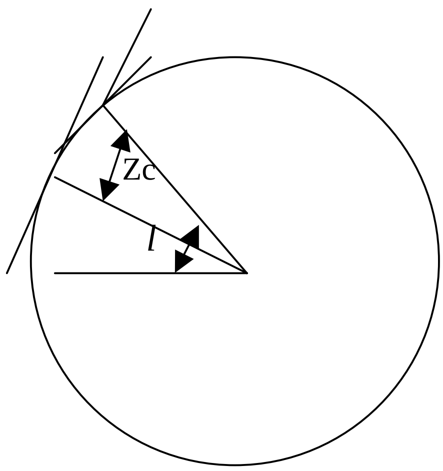
(a)



(b)

b. the sunset hour angle for south facing surfaces tilted at Z_C, h'_{SS}：

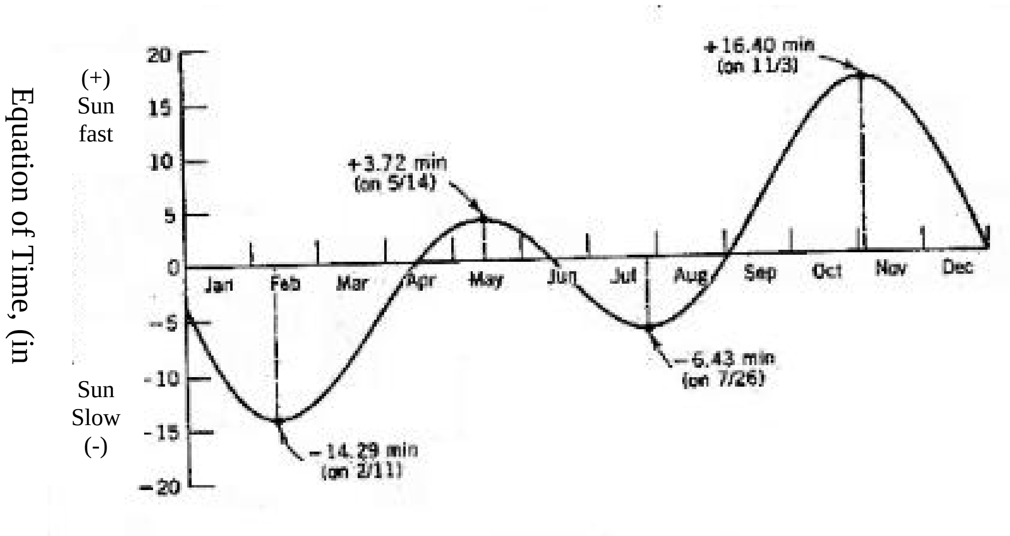
$h'_{SS} = \cos^{-1}(-\tan[l - Z_C] \tan d)$ ------- [9]



c. solar time versus standard time：

$$E = 9.87 \sin 2B - 7.53 \cos B - 1.5 \sin B \quad \text{[10a]}$$

Where, $B = 360^0(n-81) / 364$, E = equation of time , in minutes



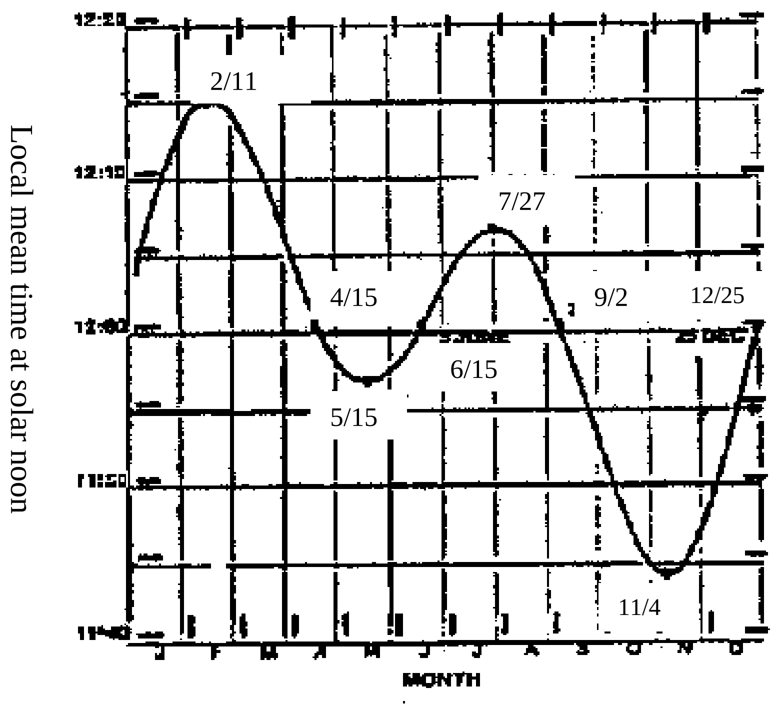
Mean time = standard time + E --- [10b]

Solar time = standard time + E + (4 minutes) (L_{st} - L_{loc}) -------------- [10c]

where , standard time = non-daylight-saving clock time, or daylight-saving clock time less one hour.

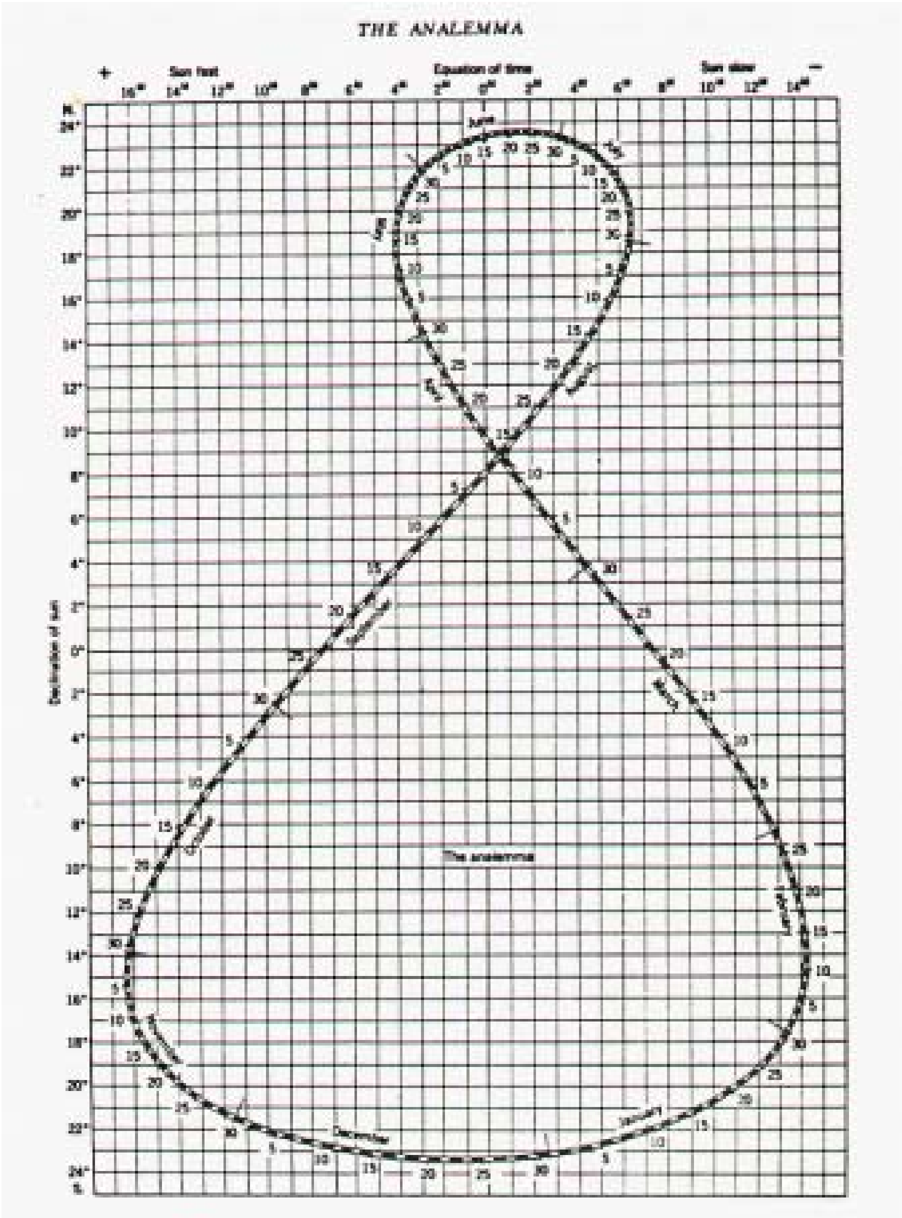
L_{st} = standard longitude for the local time zone, in degrees.

L_{loc} = longitude for the location in question, in degrees.

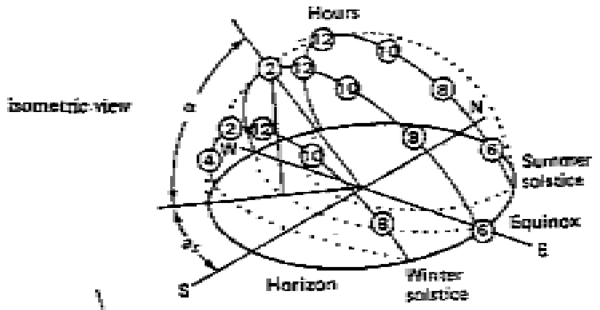


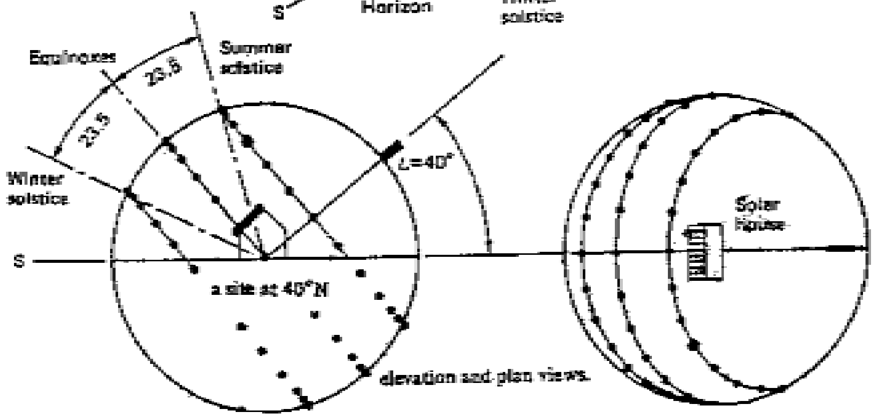
THE ANALEMMA

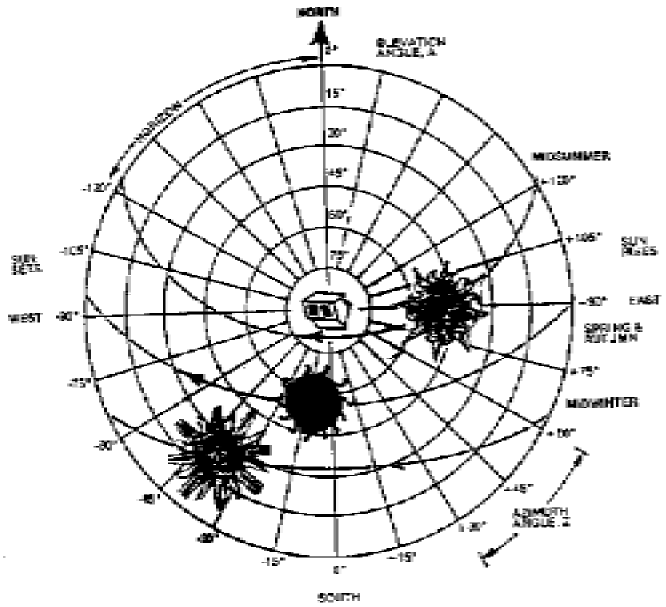
X axis: The Equation of Time, Y axis: Declination

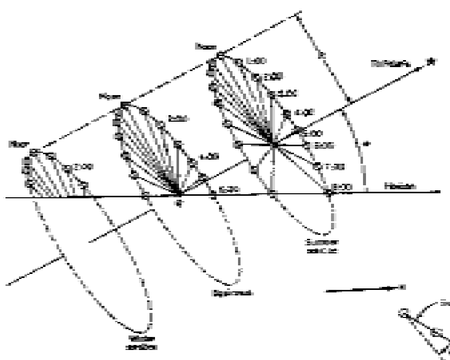


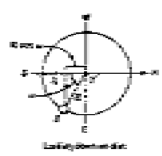
7. Sun path 太陽相對於地球的運動軌跡

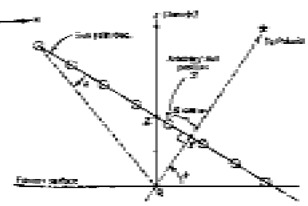












8. ET Radiation on a Horizontal Plane 大氣層外水平面上之輻射能

The time integral of total radiation on a ***horizontal surface*** of unit area outside of the atmosphere on the n-th day of the year：

$$\int_{H1}^{H2} G'_{sc} \cos Z_s \, dh = \int_{H1}^{H2} G'_{sc} \sin \beta \, dh \text{ (in J m}^{-2}\text{)}$$

$$= [(\underline{12})(3600)/\pi]\, G_{sc} [1+ 0.033 \cos (n\, 360^0/365)]\{\cos l \cos d\, (\underline{\sin H_2 - \sin H_1}) + [2\pi (\underline{H_2 - H_1}) / 360] \sin l \sin d\} \quad \text{------} \quad [11]$$

where,

Z_s = solar zenith (in degrees)
β = solar Altutude (in degrees)
H_2 = hour angle at the end of the period ; less than or equal to the sunset hour angle (in degrees)
H_1 = hour angle at the beginning of the period ; greater than or equal to the sunrise angle (in degrees)

The daily extraterrestrial total radiation on a horizontal plane of unit area, H_0 in J m^{-2} day^{-1}, becomes

$$H_0 = [(\underline{24}) (3600) / \pi]\, G_{sc} [1+ 0.033 \cos (n\, 360^0 / 365)] \{\cos l \cos d\, \underline{\sin h_{ss}} + [2\pi\, \underline{h_{ss}} / 360] \sin l \sin d\} \quad \text{------} \quad [12]$$

$$PAR_0 \text{ (in mol m}^{-2}\text{)} = (0.3815)(0.0000046)\, H_0 \quad \text{------} \quad [13]$$

9. ET Radiation on a Vertical Plane 大氣層外垂直面上之輻射能

The time integral of total radiation on a ***vertical surface*** of unit area outside of the atmosphere on the n-th day of the year：

$$\int_{H1}^{H2} G'_{sc} \sin Z_s \, dh = \int_{H1}^{H2} G'_{sc} \cos \beta \, dh \quad \text{(in J m}^{-2}\text{)}$$

三、Terrestrial 大氣層內

1. radiation on a horizontal plane 水平面上之輻射能

The average daily total radiation (but not PAR) on a horizontal plane, H in J m^{-2} day^{-1}, for many locations can be found in the literature.

- daily total radiation clearness index, $k_T = H / H_0$ ------------------------ [14]
- daily total radiation direct and diffuse components：

  $H = H_D + H_d$ --- [15]

  where, H_D is direct radiation and H_d is diffuse radiation.

define $k_d = H_d / H_0$ -- [16]
then $k_d = 0.31\ K_T + 0.319 \sin (264.7^0 K_T)$ --------------------------- [17]

These equations allow the calculation of H_d on the basis of measured H and calculated H_0 (eq. [12]). Note that $k_d / k_T = H_d / H$

The next Figure can be used to determine r_t and r_d, which then can be used to estimate hourly solar radiation on horizontal surfaces based on daily solar radiation on horizontal surfaces. i.e.

$H_h = r_t H$ -- [18]
$H_{dh} = r_d H_d$ --- [19]

where H_h and H_{dh} are hourly total and diffuse radiation, respectively.

欲求 r_t 與 r_d, 亦可透過下列計算式：

$r_t = \pi/24 *\ (a + b * \cos w)(\cos w - \cos w_S)/(\sin w_S - (2*\pi*w_S/360)*\cos w_S)$

where, $a = 0.409 + 0.5016 * \sin (w_S - 60)$

$b = 0.6609 - 0.4767 * \sin (w_S - 60)$

$r_d = \pi/24 * (\cos w - \cos w_S)/(\sin w_S - (2*\pi*w_S/360)*\cos w_S)$

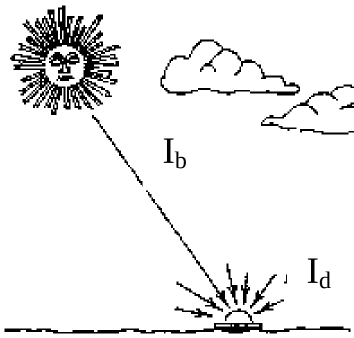
where, w : hour angle, w_S : sunset hour angle in degree

r_d 的計算式相當於 r_t 的計算式但 a=1, b = 0

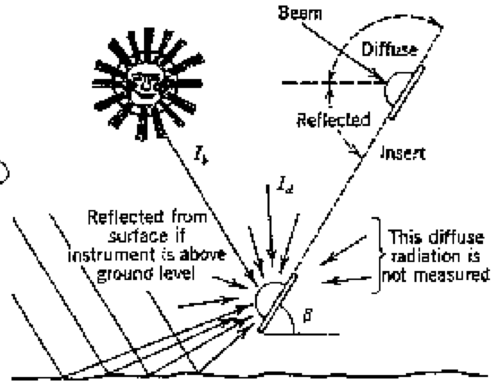
總結：量測 H, 計算 H_o, 求 K_T, 由 eq.17, 求 K_d, 由 eq. 16, 求 Hd, 由圖求 r_t 與 r_d, 亦最後由 eq. 18, 19 求 H_h, H_{dh}。

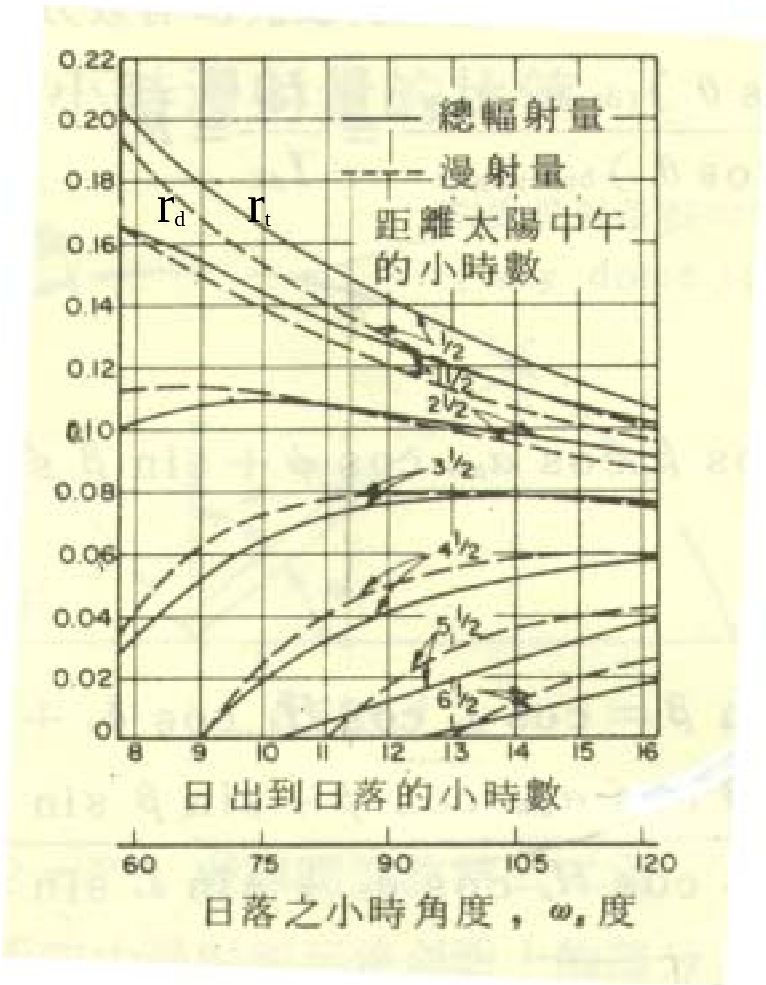
2. Radiation on a Tilted Surface 傾斜面上之輻射能

Hourly total radiation on a tilted surface (I_h) has three components ：
direct from the sun, diffuse from the sky and reflected from the foreground,



Measuring $I_{t,h}$





Hourly total radiation on a tilted surface (I_h) ：

$$I_h = (\cos S_c / \cos Z_s)(r_t H - r_d H_d) + ([1 + \cos Z_c]) / 2)(r_d H_d) + ([1 - \cos Z_c] / 2)\ \rho_g (r_t H) \quad [20]$$

where ρ_g is the reflectivity of the foreground.

3. PAR vs. Total Wavebands 光合作用有效光 vs. 全波段

Ting and Giacomelli, 1987, Availability of Solar Photosynthetically Active Radiation, Transactions of the ASAE 30(5): 1453-1457.

依以上之內容為基礎，筆者於數年前已完成電腦輔助教學軟體之發展，軟體名稱為 SunExe，另有一相關的共享軟體(Shareware)，兩者合併可做為本主題的輔助教材。詳細內容請參見 SunExe 的使用說明。

四、Transmission in a Greenhouse

1. Covering Materials

Aldrich and Bartok, 1985, Greenhouse Engineering, pp2.14-2.15, University of Connecticut.
此部份之內容請參見 "Glazing" 程式。

2. Structures

1. Giacomelli, Ting and Panigrahi, 1987, Solar PAR versus Total Transmission in a Greenhouse, ASAE paper no.87-4549.
2. Rui Rosa, Ana Maria Silva and Antonio Miguel, 1989. Solar Irradiation inside a single span greenhouse. Journal of Agr. Enging. Res. 43, 221-229.

五、Measurements

1. Sensors:

Photometric sensor, Pyranometer, Quantum sensor, Net Radiation sensor, etc.

2. Dataloggers: spectroradiometer (LI-1800), Campbell 21X, CR-10, etc.

3. Diffuse Component - Shadow Band

此部份內容請參考『設施園藝工程與試驗』講義

六、補充

(一)、計算式的另一類表示法

Angle of Incidence 入射角 (θ) 另一種計算式

	通式	對任意傾斜面 $\varepsilon > 0$			
		正南 $\psi = 0$	正北 $\psi = 180$	正東 $\psi = 90$	正西 $\psi = 90$
$\cos\theta$	$=\cos\beta\cos\gamma\sin\varepsilon + \sin\beta\cos\varepsilon$	$=\cos\beta\cos\phi\sin\varepsilon + \sin\beta\cos\varepsilon$	$= -\cos\beta\cos\phi\sin\varepsilon + \sin\beta\cos\varepsilon$	$= -\cos\beta\sin\phi\sin\varepsilon + \sin\beta\cos\varepsilon$	$=\cos\beta\sin\phi\sin\varepsilon + \sin\beta\cos\varepsilon$
	$\cos\gamma = \cos(\phi-\psi) =$	$\cos(\phi - 0) = \cos\phi$	$\cos(\phi - 180) = -\cos\phi$	$\cos(\phi+90) = -\sin\phi$	$\cos(\phi-90) = \sin\phi$
	β：太陽高度角, φ：太陽方位角 (AM < 0 PM>0) ε：斜面傾斜角, ψ：斜面方位角 (E < 0 W > 0) γ = 太陽方位角 - 斜面方位角				

$\cos\theta$	水平面 $\varepsilon = 0$	垂直面 $\varepsilon = 90^0$	
	$=\sin\beta$ $=\sin(90 - Z_s)$ $=\cos Z_s$	$= \cos\beta\cos\gamma = \cos\beta\cos(\phi - \psi)$	
	Zs：太陽頂角	正南	$=\cos\beta\cos(\phi - 0) = \cos\beta\cos\phi$
		正北	$=\cos\beta\cos(\phi - 180) = -\cos\beta\cos\phi$
		正東	$=\cos\beta\cos(\phi + 90) = -\cos\beta\sin\phi = -\cos d \sin h$
		正西	$=\cos\beta\cos(\phi - 90) = \cos\beta\sin\phi = \cos d \sin h$
	$\sin\beta =$	$\cos l \cos d \cos h + \sin l \sin d$	
	$\sin\phi =$	$\cos d \sin h / \cos\beta$	

Total Radiation on a tilted plane：

$$\int_{H1}^{H2} G'_{sc}\cos S_c\, dh = G'_{sc}\int_{H1}^{H2}\cos S_c\, dh \rightarrow 2G'_{sc}\int_{0}^{hss}\cos S_c\, dh$$

其中, H_1：hour angle when sun rise, H_2：hour angle when sun set

A. For a horizontal plane, $\cos S_c = \cos Z_s$

上式可表示成

$$2G'_{sc}\int_{0}^{hss}\cos Z_s\, dh = 2G'_{sc}\int_{0}^{hss}(\sin d \sin l + \cos d \cos l \cos h)dh$$

$$= 2G'_{sc}[\sin d \sin l\,(hss - 0) + \cos d \cos l\,(\sin h_{ss} - 0)]$$

G'_{sc} 之單位為 $J/sec\text{-}m^2$,
[sin d sin l (hss - 0) + cos d cos l (sin h_{ss} - 0)] 為強度單位, 包括 hss
[ ] / π x 180/15 = [ ]/ π x 12 = 半天時間的小時數
2 G'_{sc} [ ]・12/π ・3600 = ET radiation 單位 J/m^2
$\rightarrow 24/\pi \cdot 3600 \cdot 1353 \cdot [1+0.033 \cos (n \cdot 360^0/365)][\sin d \sin l\, h_{ss}$
$+\cos d \cos l \sin h_{ss}] = H_{0,\ horizontal\ ET} \rightarrow 24/\pi \cdot 3600 \cdot G'_{sc} \cdot Fo_{,\ horizontal\ ET}$

B. For a vertical plane $Z_c = 90^0$ (任意方向)

$\cos S_c = - \cos A_c \sin d \cos l + \cos d \cos h \cos A_c \sin l + \cos d \sin A_c \sin h$

H_1=sr, H_2=ss

$H_{o,\ vertical,ET} = \int_{H1}^{H2} G'_{sc} \cos S_c\, dh = G'_{sc} \int_{H1}^{H2} \cos S_c\, dh = 2\, G'_{sc} \int_{0}^{hss} \cos S_c\, dh$

$= 2 \cdot G'_{sc} \cdot \int_{0}^{hss} (-\cos A_c \sin d \cos l + \cos d \cos A_c \sin l \cos h + \cos d \sin A_c \sin h)dh$

$= 2 \cdot G'_{sc} \cdot [-\cos A_c \sin d \cos l\, (h_{ss}) + \cos d \cos A_c \sin l \sin h_{ss} + \cos d \sin A_c (-\cos h_{ss}-1)]$

$\rightarrow (24/\pi) \cdot 3600 \cdot G'_{sc} \cdot [-\cos A_c\, sd\, cl\, h_{ss} + cd \cos A_c\, sl \sin h_{ss} - cd \sin A_c (\cos h_{ss} +1)]$

$\rightarrow (24/\pi) \cdot 3600 \cdot G'_{sc} \cdot F_{0,vertical,ET}$

C. For a plane always normal to the sun-ray

$H_{0,N} = \int_{H1}^{H2} G'_{sc}\, dh = G'_{sc} \int_{H1}^{H2} dh \rightarrow 2\, G'_{sc}\, h_{ss}$

$= 24/\pi \cdot 3600 \cdot G'_{sc} \cdot h_{ss}$

D. For a horizontal plane at solar noon (h=0)

Given $\sin \beta = \cos l \cos d \cos h + \sin l \sin d$
Due to h = 0 , thus, $\sin \beta = \cos l \cos d + \sin l \sin d = \cos(l - d)$
We know that $\sin \beta = \cos (90 - \beta)$, thus, $90 - \beta = l - d$
Derived: $\beta = 90 - l + d$
When in 春分、秋分, d= 0, thus, $\beta = 90 - l$ 又, by definition $\beta = 90 - Zs$,
Thus, $Zs = l$ for a horizontal plane at solar noon in 春分 and 秋分.

Daily Total E.T. Radiation on a tilted plane：

$H_0 = 24/\pi \cdot 3600 \cdot G'_{sc} \cdot F_0$，其中 F_0 如下表：

通式	任意傾斜面 $Z_c > 0$			
$F_{0,general}=$	正南	正北	正東	正西
水平面	垂直面			
$F_{0,horizontal}$=sdsl h_{ss} + cd cl sin h_{ss}	= -cos A_c sdcl h_{ss} + cd cl cos A_c sl sin h_{ss} - cd sin A_c (cos h_{ss} +1)			
正南				
正北				
正東				
正西				

(二)、台灣的太陽能輻射現況

(三)、Julian Day

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
1 月	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
2 月	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	
	47	48	49	50	51	52	53	54	55	56	57	58	59			
3 月	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	
	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90
4 月	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	
	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	
5 月	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	
	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150	151
6 月	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	
	167	168	169	170	171	172	173	174	175	176	177	178	179	180	181	
7 月	182	183	184	185	186	187	188	189	190	191	192	193	194	195	196	
	197	198	199	200	201	202	203	204	205	206	207	208	209	210	211	212
8 月	213	214	215	216	217	218	219	220	221	222	223	224	225	226	227	
	228	229	230	231	232	233	234	235	236	237	238	239	240	241	242	243
9 月	244	245	246	247	248	249	250	251	252	253	254	255	256	257	258	
	259	260	261	262	263	264	265	266	267	268	269	270	271	272	273	
10 月	274	275	276	277	278	279	280	281	282	283	284	285	286	287	288	
	289	290	291	292	293	294	295	296	297	298	299	300	301	302	303	304
11 月	305	306	307	308	309	310	311	312	313	314	315	316	317	318	319	
	320	321	322	323	324	325	326	327	328	329	330	331	332	333	334	
12 月	335	336	337	338	339	340	341	342	343	344	345	346	347	348	349	
	350	351	352	353	354	355	356	357	358	359	360	361	362	363	364	365

太陽能工程基礎

作業 之手算篇

1. 請完成下表 (以台北之經緯度計算)

	1/15	2/15	3/15	4/15	5/15	6/15	7/15	8/15	9/15	10/15	11/15	12/15
N =												
日出 h_{ss}												
日長(h:m)												
正午 local time												

2. 請求出春分、夏至、秋分、冬至四天中台北地區之逐時的太陽頂角(Z_s)、太陽高度角(β)與方位角(A_c)。數據需包括日出及日落時刻。

	春分 3/21			夏至 6/21			秋分 9/21			冬至 12/21		
	Z_s	β	A_c	Z_s	β	A_c	Z_s	β	A_c	Z_s	β	A_c
5:00am												
6:00am												
....												
5:00pm												
6:00pm												

3. 繪出春分、夏至、秋分、冬至四天中台北地區之太陽高度角 (Y axis: 0 - 90 度)與方位角 (X axis: -160 度- 160 度)之關係圖。

4. 繪圖表示 Daily variation and the year-round average of the daily ET solar radiation on a horizontal surface in the northern hemisphere for the locations at 0, 40 and 80 degree latitude. Y axis in MJ/m^2 and X axis is from day 1 to day 365. There are 6 curves on the graph, 3 for daily variation and 3 for year-round average.

太陽能工程基礎

作業 之軟體篇

5. 使用 Geoclock Windows 版軟體，進行以下設定，請描述你的觀察與體會。

(1). 圖中太陽的位置之緯度值即為赤緯(declination, d)，3/21 至 9/21 期間 d>=0。
(2). 經度為 0 的線經過 Greenwich, England。
(3). 夏至，at solar noon，太陽在正南方，位置在北緯 23.5 度上(緯度 + 23.5 度)。高度角 =90-當地之緯度+d = 90 - 25 +23.5 = 88.5 度。
(4). 冬至，at solar noon，太陽在正南方，位置在南緯 23.5 度上(緯度 - 23.5 度)。高度角 =90-當地之緯度+d = 90 - 25 -23.5 = 41.5 度。
(5). 春分、秋分，at solar noon，太陽在正南方，位置在赤道上(緯度 0 度)。
(6). 春分、秋分，at solar noon，太陽頂角(Zenith)= 當地之緯度，高度角 =90-當地之緯度。台北緯度為 25 度，此時之高度角為 65 度。
(7). 觀察春分、夏至、秋分、冬至，4 天中，每小時之太陽方位角。(在軟體中以正北方為 0 度，與本文所提計算公式以正南方為 0 度有所不同)。
(8). Time control，每 1 小時 update 一次，觀察太陽與月亮的軌跡。
(9). Time control，每 24 小時 (1day) update 一次，觀察太陽與月亮的軌跡。
(10). Time control，每 720 小時 (1 month) update 一次，觀察太陽的軌跡。
(11). Time control，輸入 3/21, 6/21. 9/21, 12/21，觀察太陽的位置。
(12). Time control，輸入 3/21, 5:58 ，觀察太陽的位置，包括方向與經緯度。
(13). 同上，改輸入當日日落時間，觀察太陽的位置，包括方向與經緯度。
(14). Time control，輸入 6/21, 5:05 ，觀察太陽的位置，包括方向與經緯度。
(15). 同上，改輸入當日日落時間，觀察太陽的位置，包括方向與經緯度。
(16). Time control，輸入 12/21，當日日出時間 ，觀察太陽的位置，包括方向與經緯度。
(17). 同上，改輸入當日日落時間，觀察太陽的位置，包括方向與經緯度。
(18). Map list，選北極圈，重複 1,2,3 的動作，觀察太陽的軌跡，注意永夜與永晝現象。
(19). 同上，改輸入 3/21, 9/21 觀察晨昏線是否通過北極。
(20). 同上，改輸入 6/21, 12/21 觀察晨昏線的位置。