King Abdulaziz University Faculty of Engineering, Mechanical Engineering
Thermal Engineering and Desalination Technology Department

MEP 451

Refrigeration & Air Conditioning

Solar Radiation

Part I Angle Definitions

1

Contents

2

Objectives

- Know solar and surface angles
- Be able to calculate various angles
- Be able to calculate solar radiation intensity on a surface
- Be able to calculate the Solar Heat Gain through windows
- Be able to calculate & find the Solar Heat Gain Coefficient [SHGC] for different windows

3

6-2 The Earth's Motion about the Sun 163

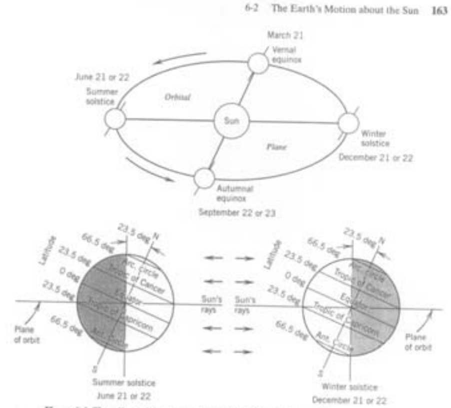
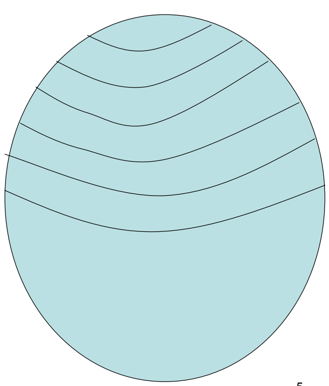


Figure 6-1 The effect of the earth's tilt and rotation about the sun.

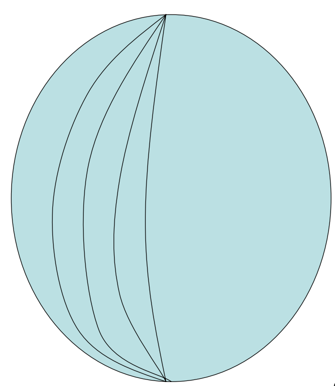
4

Latitude lines



5

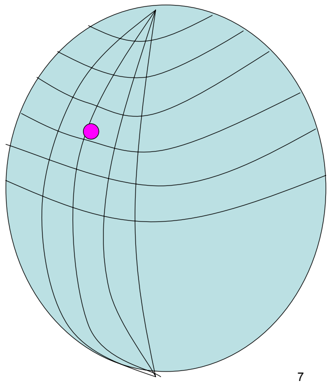
Longitude lines



For Greenwich

Long=0°

6



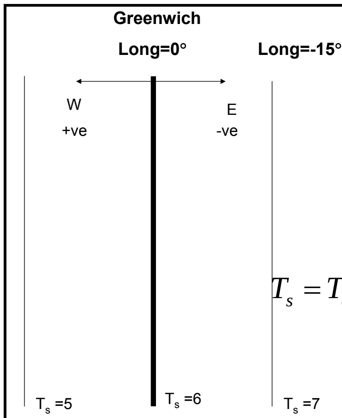
Latitude angle and longitude define the location on the earth surface

For Jeddah:

Latitude ℓ=21.5 N

$Long_{loc}$=-39.5°

7



$$T_s = T_c + 4(Long_{st} - Long_{loc})$$

8

Sun-Earth Relations

- Sun can be considered as a black body source at T=6000 K
- The spectrum of sun rays cover the whole range of wave lengths
- Part of the spectrum is absorbed by atmosphere
- Solar constant is the solar intensity outside the earth atmosphere [G_{sc} =1367 W/m^2]
- The solar radiation on a given surface is less than G_{sc}
- The total radiation on a surface is the sum of direct, diffuse from sky and diffuse from ground
- $G_t=G_D+G_{ds}+G_{dG}$

9

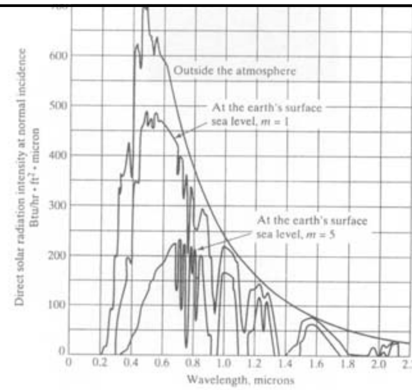


Figure 13.18 Spectral distribution of direct solar-radiation intensity at normal incidence for the upper limit of the atmosphere and at the earth's surface during clear days. [Adapted by permission from *ASHRAE Trans.*, 64 (1958), 50.]

10

Sun-Earth Relations

Determining the position of a location on earth surface

$Long_{loc}$ is the longitude of the location

$Long_{st}$ is the standard longitude of the location

Since earth completes one revolution in 24 hrs: 360 degrees=24 hr. or 1 deg=4 min.

Latitude angle ℓ

11

Sun-Earth Relations

24 hr $\rightarrow$ 360 °

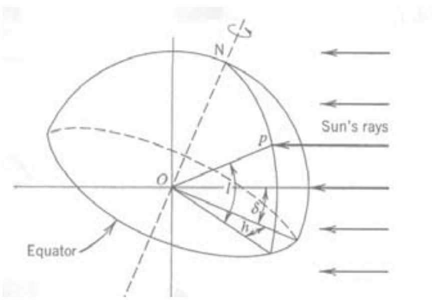
1 hr $\rightarrow$ 15 °

60 min $\rightarrow$ 15 °

4 min $\rightarrow$ 1 °

12

Latitude angle, Declination angle and Hour angle



13

Latitude angle, Solar declination angle and hour angle

Latitude angle, ℓ

Angle between the line connecting the location P on earth surface and its projection on equatorial plane

Solar Declination angle, δ

Angle between sun ray connecting sun to earth center and its projection on equatorial plane

Hour angle, h

Angle on the equatorial plane between the sun projection at a given time and the sun projection at noon

14

Declination angle, δ

$$\delta = 23.45 \ \sin\left[\frac{(284+n)*360}{365}\right]$$

15

			For the average day of the month		
month	month	n for i[th] day of the month	Date	n	d, Sun declination [deg]
1	Jan.	i	17	17	-20.9
2	Feb.	31+i	16	47	-13.0
3	March	59+i	16	75	-2.4
4	April	90+i	15	105	9.4
5	May	120+i	15	135	18.8
6	June	151+i	11	162	23.1
7	July	181+i	17	198	21.2
8	Aug.	212+i	16	228	13.5
9	Sep.	243+i	15	258	2.2
10	Oct.	273+i	15	288	-9.6
11	Nov.	304+i	14	318	-18.9
12	Dec.	334+i	10	344	-23.0

16

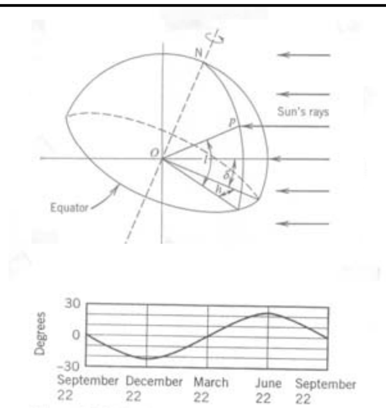


Figure 6-3 Variation of sun's declination.

17

Equation of time

$$E.o.t = 9.87 \ \sin(2E) - 7.53 \ \cos(E) - 1.5\sin(E)$$

$$E = \frac{(n-81)}{364}360$$

E.o.t in minutes

18

Solar time

$$T_s = T_c + 4(Long_{st} - Long_{loc}) + E.o.t. - DT$$

hr:min min min hr.

T_c Civil Time hr:min

DT = Day saving time, if any

19

Hour angle, h

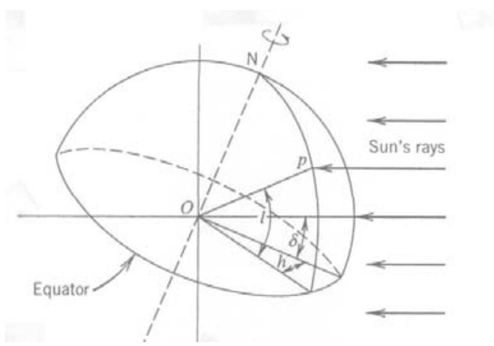
$$h = (T_s - 12) * 15$$

Solar Time

After noon, $T_s > 12$. For Example at 2pm T_s=14

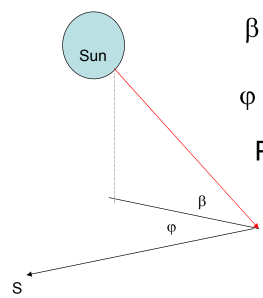
20

Latitude angle, Declination angle and Hour angle



21

Sun position



β =sun altitude angle

φ =sun azimuth angle

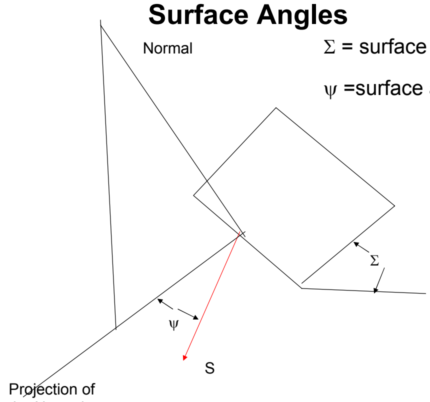
Positive East of South

22

Surface Angles

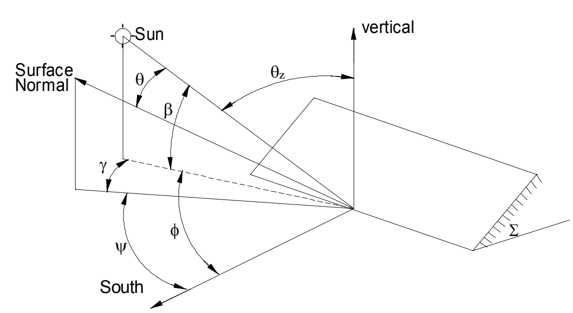
Σ = surface tilt angle

ψ =surface azimuth angle



23

Solar and surface position



24

Solar altitude angle, β

$$\sin(\beta) = \cos(l)\cos(\delta)\cos(h) + \sin(l)\sin(\delta)$$

At sunset, β=0.0

$$\cos(h) = -\tan(l) * \tan(\delta)$$

Use this equation to find sun rise and sun set times

25

Solar zenith angle, θ_Z

$$\theta_z = 90 - \beta$$

26

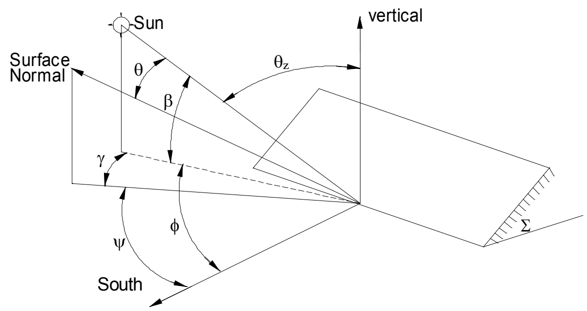
Solar azimuth angle, φ

$$\cos(\phi) = \frac{\sin(\beta)\sin(l) - \sin(\delta)}{\cos(\beta)\cos(l)}$$

Positive East of South

27

Surface azimuth angle, ψ +ve E. of South



28

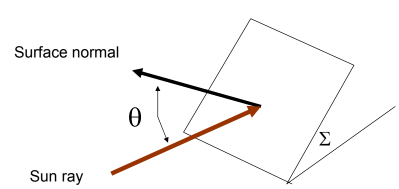
Solar-surface azimuth angle, γ

$$\gamma = |\phi - \psi|$$

29

Incident angle, θ

$$\cos(\theta) = \cos(\beta)\cos(\gamma)\sin(\Sigma) + \sin(\beta)\cos(\Sigma)$$



Angle between sun ray and surface normal

30

Latitude and Longitude for different Saudi Cities

31

Table 3A Heating and Wind Design Conditions—World Locations (I-P)

Station	WMO#	Lat.	Long.	Elev, ft	StdP, psia	Dates	Heating DB 99.6%	Heating DB 99%	Extreme Wind Speed, mph 1%	2.5%	5%	Coldest Month 0.4% WS	0.4% MDB	1% WS	1% MDB	MWS/MWD to DB 99.6% MWS	99.6% MWD	0.4% MWS	0.4% MWD	Annual Daily Extreme Mean DB Max.	Mean DB Min.	StdD DB Max.	StdD DB Min.
SAUDI ARABIA																								
Abha	411120	18.23 N	42.65 E	6837	11.413	8293	41	44	23	21	19	25	59	22	60	2	180	13	20	92	35	5.6	2.9
Al Jawf	403610	29.78 N	40.10 E	2244	13.546	8293	32	35	26	22	19	26	49	22	52	5	50	9	320	111	23	4.5	3.6
Al Madinah	404300	24.55 N	39.70 E	2070	13.633	8293	48	50	20	18	16	19	65	17	67	7	60	9	300	114	42	2.2	4.0
Al Wajh	404000	26.20 N	36.47 E	52	14.672	8293	53	55	28	25	23	27	68	24	69	7	20	13	270	105	47	3.4	4.7
Ar'ar	403570	30.90 N	41.13 E	1811	13.763	8293	32	34	22	19	17	21	51	18	52	4	270	7	240	111	23	2.0	3.1
At Ta'if	410360	21.48 N	40.55 E	4753	12.344	8293	42	45	23	21	19	24	65	22	66	5	90	10	50	101	35	3.2	2.9
Az Zahran	404160	26.27 N	50.15 E	55	14.670	8293	45	47	26	23	20	22	61	19	61	9	290	13	360	116	40	2.3	3.8
Ha'il	403940	27.43 N	41.68 E	3323	13.018	8293	31	34	23	20	18	23	57	20	60	4	180	8	180	108	25	3.6	4.9
Hafar Al Batin	403730	28.33 N	46.17 E	1165	14.092	8293	36	39	27	23	21	24	56	22	56	6	270	10	240	117	31	2.3	1.8
Jiddah	410240	21.67 N	39.15 E	39	14.679	8293	59	61	23	21	19	23	78	21	77	6	30	13	330	114	54	4.5	3.4
Jizan	411400	16.90 N	42.58 E	9	14.695	8293	68	70	20	18	16	17	82	16	82	5	100	10	230	107	58	4.5	10.3
Khamis Mushayt	411140	18.30 N	42.80 E	6738	11.456	8293	40	43	21	18	16	22	61	20	61	2	150	10	30	97	35	6.8	4.1
Makkah	410300	21.48 N	39.83 E	1017	14.168	8293	59	62	14	12	11	15	77	13	78	4	20	8	300	118	53	2.0	4.3
Qasim	404050	26.30 N	43.77 E	2132	13.602	8293	37	39	21	18	16	20	60	17	57	2	30	8	90	115	32	3.8	3.2
Rafha	403620	29.63 N	43.48 E	1466	13.937	8293	33	35	25	22	20	24	54	22	56	4	270	9	300	115	27	2.7	2.7
Riyadh	404380	24.72 N	46.72 E	2007	13.664	8293	41	44	22	19	17	21	60	18	60	4	320	11	360	115	35	1.4	2.7
Tabuk	403750	28.37 N	36.63 E	2526	13.407	8293	34	37	25	20	17	25	60	20	60	2	110	10	270	107	30	2.2	2.3
Turayf	403560	31.68 N	38.67 E	2667	13.337	8293	29	32	25	22	20	26	46	22	46	6	270	9	270	108	25	2.3	3.4
Yanbu'al Bahr	404390	24.15 N	38.07 E	3	14.036	8293	52	54	26	23	21	25	72	22	72	3	10	17	270	114	47	1.8	2.0

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WMO# = World Meteorological Organization no. Elev. = elevation, ft WS = wind speed, mph MDB = mean coincident dry-bulb temp., °F DB = dry-bulb temp, °F
Lat = North latitude, ° Long. = West longitude, ° StdP = standard pressure at station elev, psia MWS = mean coincident wind speed, mph MWD = mean wind dirnc, °

Table 3B Cooling and Dehumidification Design Conditions—World Locations (I-P)

Station	DB/MWB 0.4% DB	0.4% MWB	1% DB	1% MWB	2% DB	2% MWB	WB/MDB 0.4% WB	0.4% MDB	1% WB	1% MDB	2% WB	2% MDB	DP/MDB and HR 0.4% DP	0.4% HR	0.4% MDB	1% DP	1% HR	1% MDB	2% DP	2% HR	2% MDB	Range of DB
SAUDI ARABIA																						
Abha	87	58	86	58	84	56	67	76	66	75	65	74	65	119	72	63	111	71	62	108	71	21.4
Al Jawf	105	63	103	62	101	61	65	96	64	95	63	96	57	76	67	56	70	66	52	63	67	26.3
Al Madinah	113	65	110	65	109	64	69	97	68	97	67	98	62	91	74	60	82	75	57	78	73	23.8
Al Wajh	95	72	93	76	91	78	83	90	82	89	82	89	82	167	88	81	159	88	79	152	87	13.1
Ar'ar	107	68	105	68	103	67	73	103	71	100	69	98	62	90	92	60	81	90	57	75	88	25.6
At Ta'if	97	65	95	65	94	65	72	89	70	87	69	87	67	117	80	65	109	80	63	102	79	20.9
Az Zahran	111	71	109	71	107	72	86	94	84	94	83	92	84	180	91	82	168	90	80	158	90	23.9
Ha'il	106	65	104	64	102	64	68	96	67	97	65	97	59	85	71	57	80	72	56	74	71	28.3
Hafar Al Batin	113	67	112	66	110	66	71	99	69	100	67	100	64	94	74	61	85	72	59	78	71	27.5
Jiddah	104	72	102	73	100	74	83	94	82	94	81	92	81	159	89	79	151	89	79	150	88	22.0
Jizan	102	83	100	83	99	83	87	98	86	98	85	97	84	178	96	83	171	96	82	168	96	12.6
Khamis Mushayt	88	57	87	57	86	56	66	75	65	74	64	74	63	111	71	62	106	71	61	102	70	22.1
Makkah	113	76	111	76	109	75	82	104	81	102	80	101	77	147	93	76	139	94	74	133	94	27.2
Qasim	110	67	109	65	107	64	74	97	70	99	68	98	66	111	84	63	92	80	59	81	75	29.3
Rafha	111	69	109	68	107	67	72	104	70	104	69	103	63	90	75	61	83	72	58	75	75	29.7
Riyadh	111	64	110	64	108	64	69	96	67	97	66	96	62	91	73	60	83	72	57	76	72	25.2
Tabuk	104	64	102	63	100	63	68	95	67	95	65	94	59	80	77	56	74	77	55	71	76	26.8
Turayf	102	64	99	63	97	62	68	92	66	91	65	90	60	87	78	58	78	75	56	73	74	27.4
Yanbu'al Bahr	109	76	100	75	104	76	83	96	82	95	81	94	81	159	90	79	150	89	77	142	88	25.7

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DB = dry-bulb temperature, °F WB = wet-bulb temperature, °F HR = humidity ratio, grains (water vapor)/lb (dry air)
MWB = mean coincident wet-bulb temp., °F MDB = mean coincident dry-bulb temp. °F DP = dew-point temperature, °F StdD = standard deviation, °F

Profile Angle, Ω

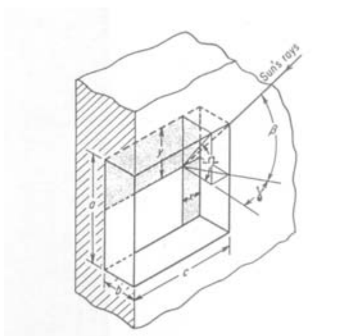


Figure 14.14 Shading of a window set back from the plane of a building.

34

Profile angle,Ω

$$\tan(\Omega) = \frac{\tan(\beta)}{\cos(\gamma)}$$

35

1-Equation of time, E.o.t $E.o.t = 9.87\ \sin(2E) - 7.53\ \cos(E) - 1.5\sin(E)$ …. (min)

$$E = \frac{(n-81)}{364}360$$

2-Declination angle, δ $\delta = 23.45\ \sin\left[\frac{(284+n)*360}{365}\right]$

3- Solar time, T_s $T_s = T_c + 4(Long_{st} - Long_{loc}) + E.o.t. - DT$

4-Hour angle, h $h = (T_s - 12)*15$

5-Solar altitude angle, β $\sin(\beta) = \cos(l)\cos(\delta)\cos(h) + \sin(l)\sin(\delta)$

6-Solar zenith angle, θ_z $\theta_z = 90 - \beta$

7-Solar azimuth angle, φ $\cos(\phi) = \frac{\sin(\beta)\sin(l) - \sin(\delta)}{\cos(\beta)\cos(l)}$

8- Surface azimuth, ψ Usually given. Measured from south. East of South positive

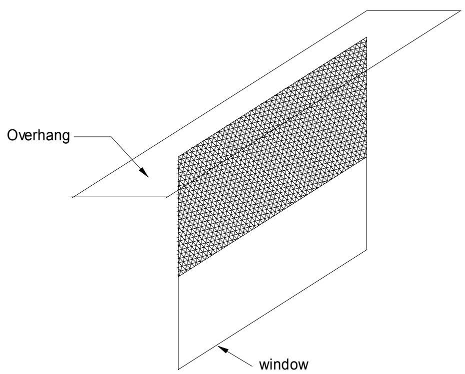
9-Solar-suface azimuth angle, γ $\gamma = |\phi - \psi|$

10-Incident angle, θ $\cos(\theta) = \cos(\beta)\cos(\gamma)\sin(\Sigma) + \sin(\beta)\cos(\Sigma)$

11- Profile angle, Ω $\tan(\Omega) = \frac{\tan(\beta)}{\cos(\gamma)}$

36

Shaded window due to an overhang



37

Externally Shaded Windows by Overhang

A_w=Window area

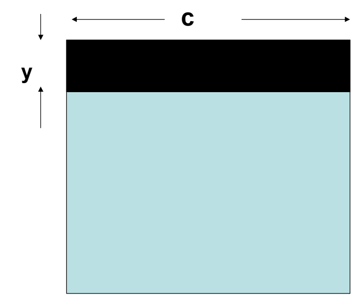
A_{sh}=Shaded area

A_{sh}=y*c

A_{sl}= Sunlit area

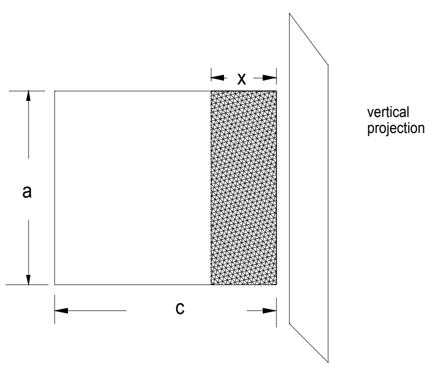
$A_{sl}=A_w-A_{sh}$

Fraction of sunlit window = A_{sl}/A_w



38

Shaded window due to vertical projection

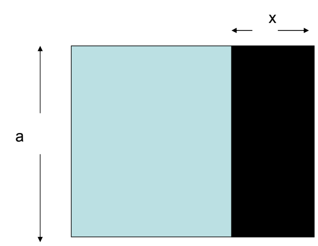


39

Externally Shaded Windows by vertical projection

A_{sh}=Shaded area

A_{sh}=a*x



40

Shaded window due to setback distance

Window area =ac

Setback distance=b

$$A_w = a*c$$

$$A_{sh} = c*y + a*x - x*y$$

$$A_{sl} = A_w - A_{sh}$$

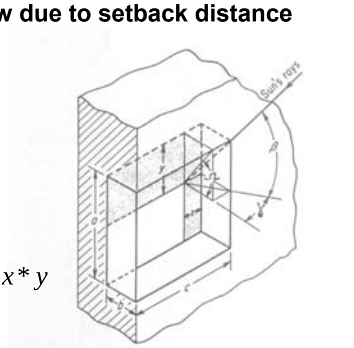


Figure 14.14 Shading of a window set back from the plane of a building.

41

Shaded window due to setback distance

$$x = b \ \tan(\gamma)$$

$$y = b \ \tan(\Omega)$$

Shaded area=cy+ax-yx

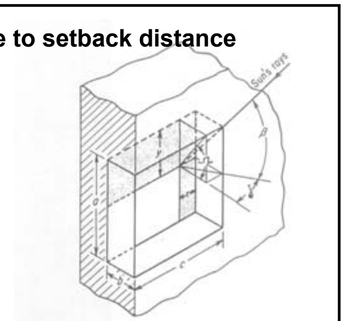


Figure 14.14 Shading of a window set back from the plane of a building.

Fraction of sunlit area=(glass area-shaded area)/glass area

$$\frac{A_{sl}}{A_w} = 1-(b/a)\tan(\Omega)-(b/c)\tan(\gamma)+(b/a)(b/c)*\tan(\Omega)\tan(\gamma)$$

42