Calculation Models for Land Usage of PV Farms

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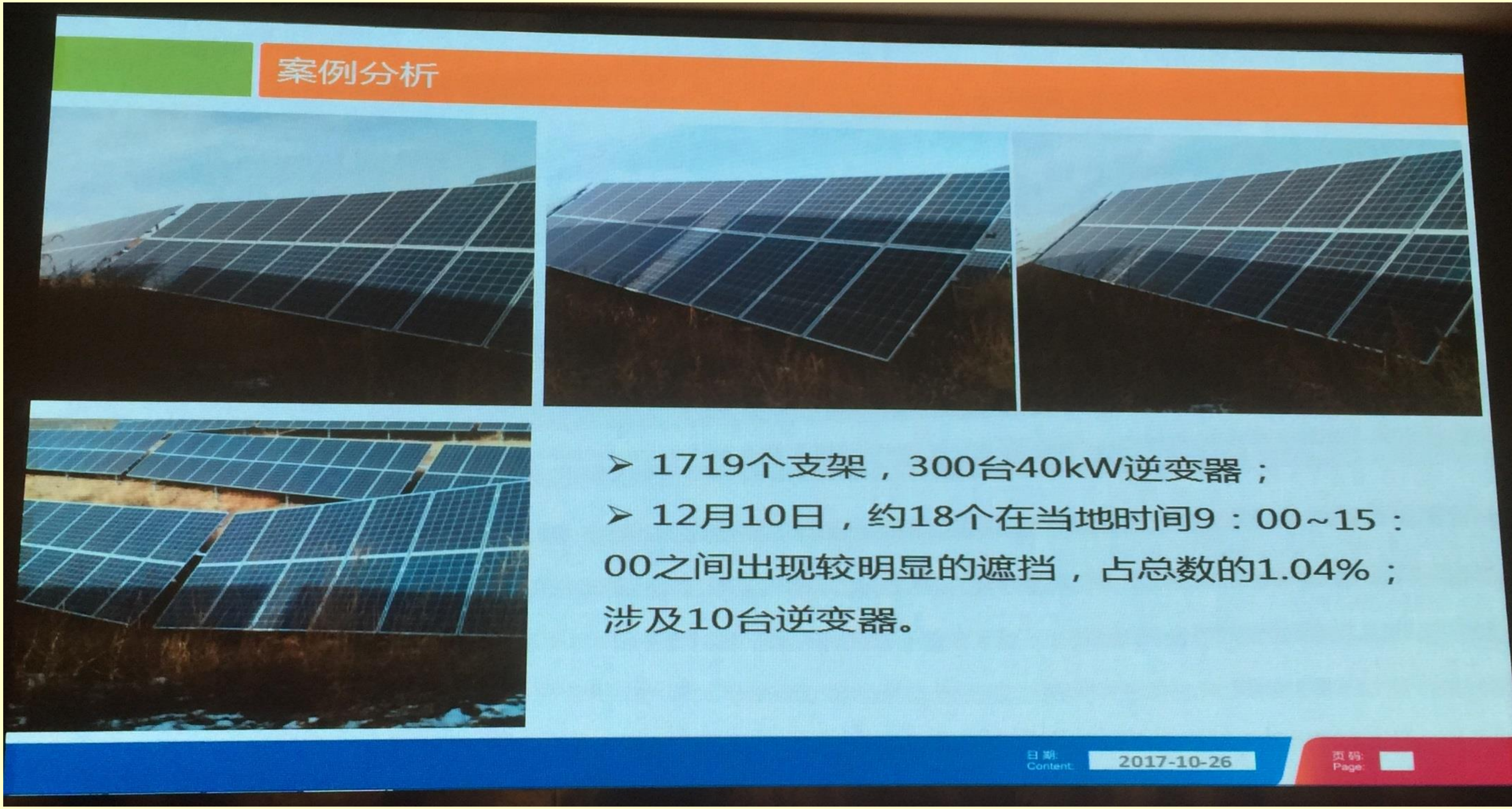
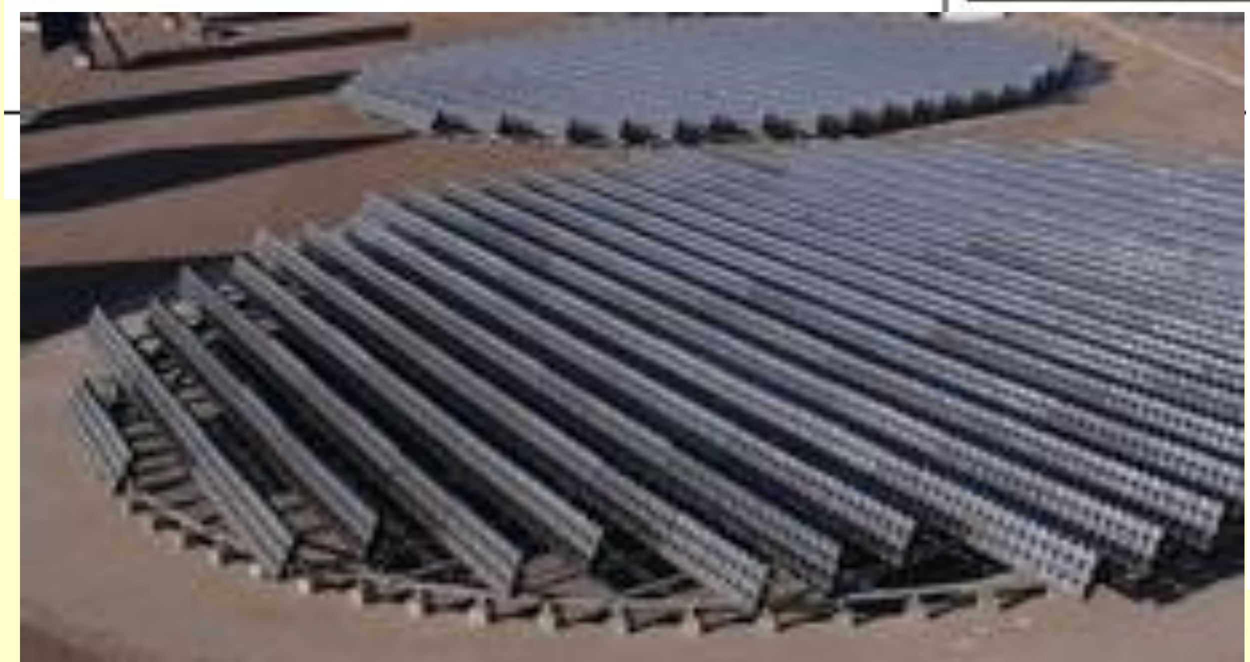
Dec. 5-7, 2017 Weihai, China

Un-Reasonable Design leads to Serious Shading between PV Arrays or Too Large Distance to Waste land



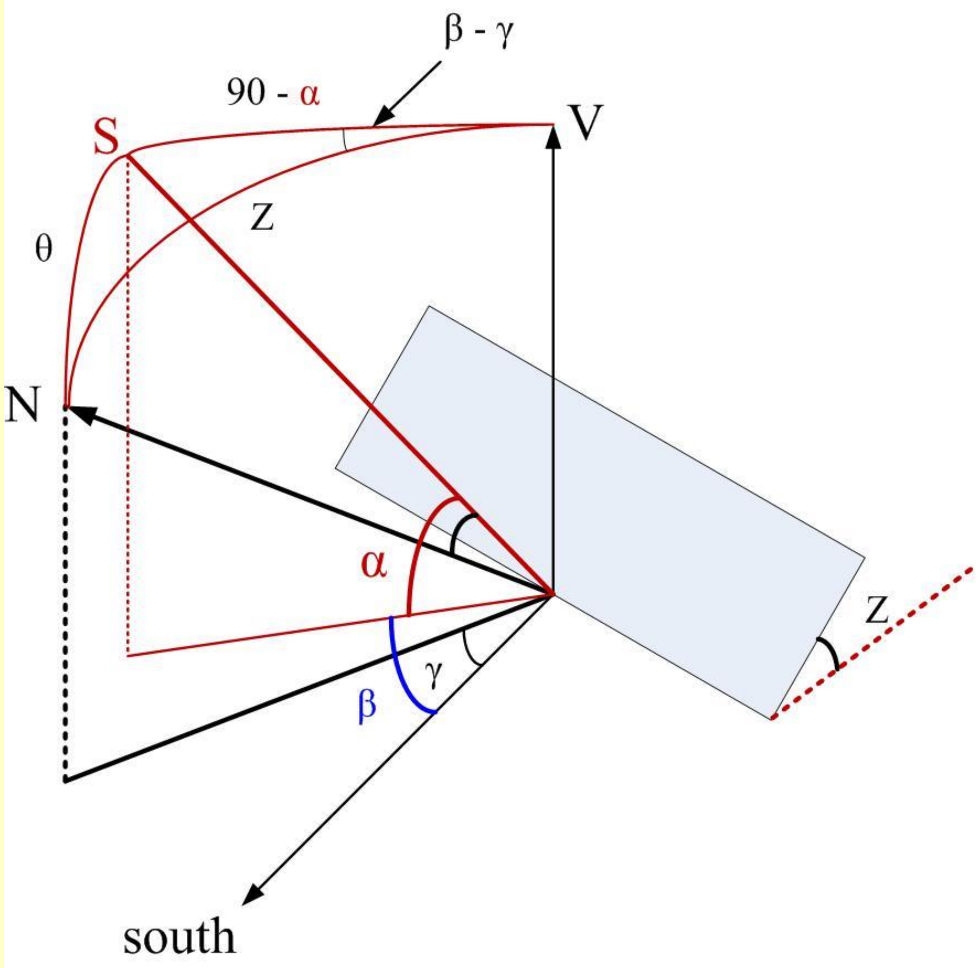
Shading Problems are Popular in Existing Projects



Shading Problems accrued in both fixed PV arrays and tracking systems.

2 Type of Coordinates

Ground Horizontal Coordinates



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

1. From this picture, we can get relationship between solar beam and PV array;
2. Taking ground horizontal surface as the reference;
3. Tracking the Sun by solar altitude, and solar azimuth;
4. Regulate the tilted-angle and azimuth of PV arrays.

Ground Horizontal Tracking Systems – Flat Plate

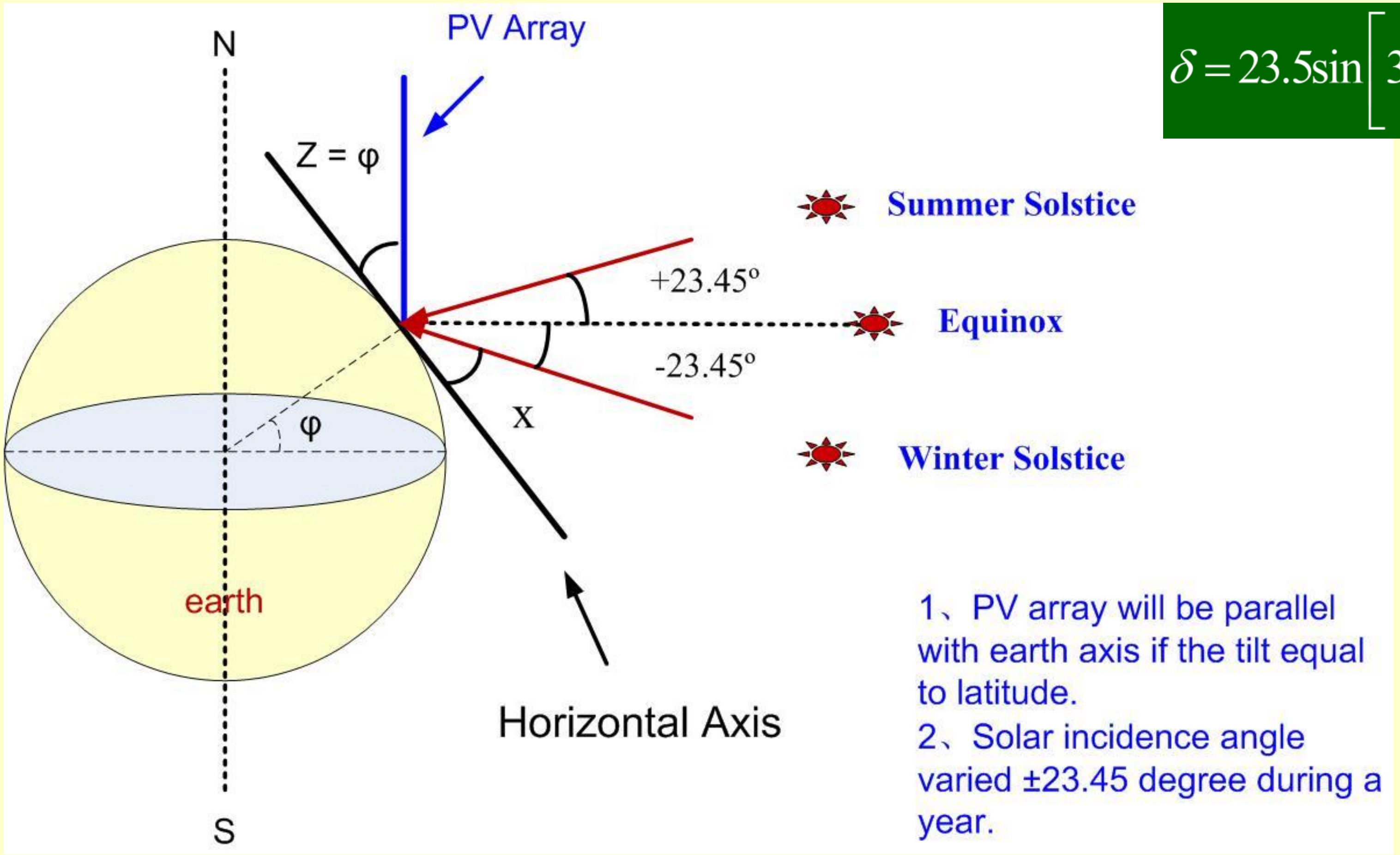
Fixed PV Array

Solar Altitude Trackers

Solar Azimuth Trackers

Double Axis Trackers

Equatorial Coordinates



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

1. **Taking equator plane and earth axis as reference;**
2. **Tracking the Sun by solar declination (±23.45 degree changing annually) and solar hour angle (turning 15 degree in one hours) ;**
3. **Regulate the rotating angle of main axis and the tilted angle of PV arrays.**

Equatorial Tracking Systems

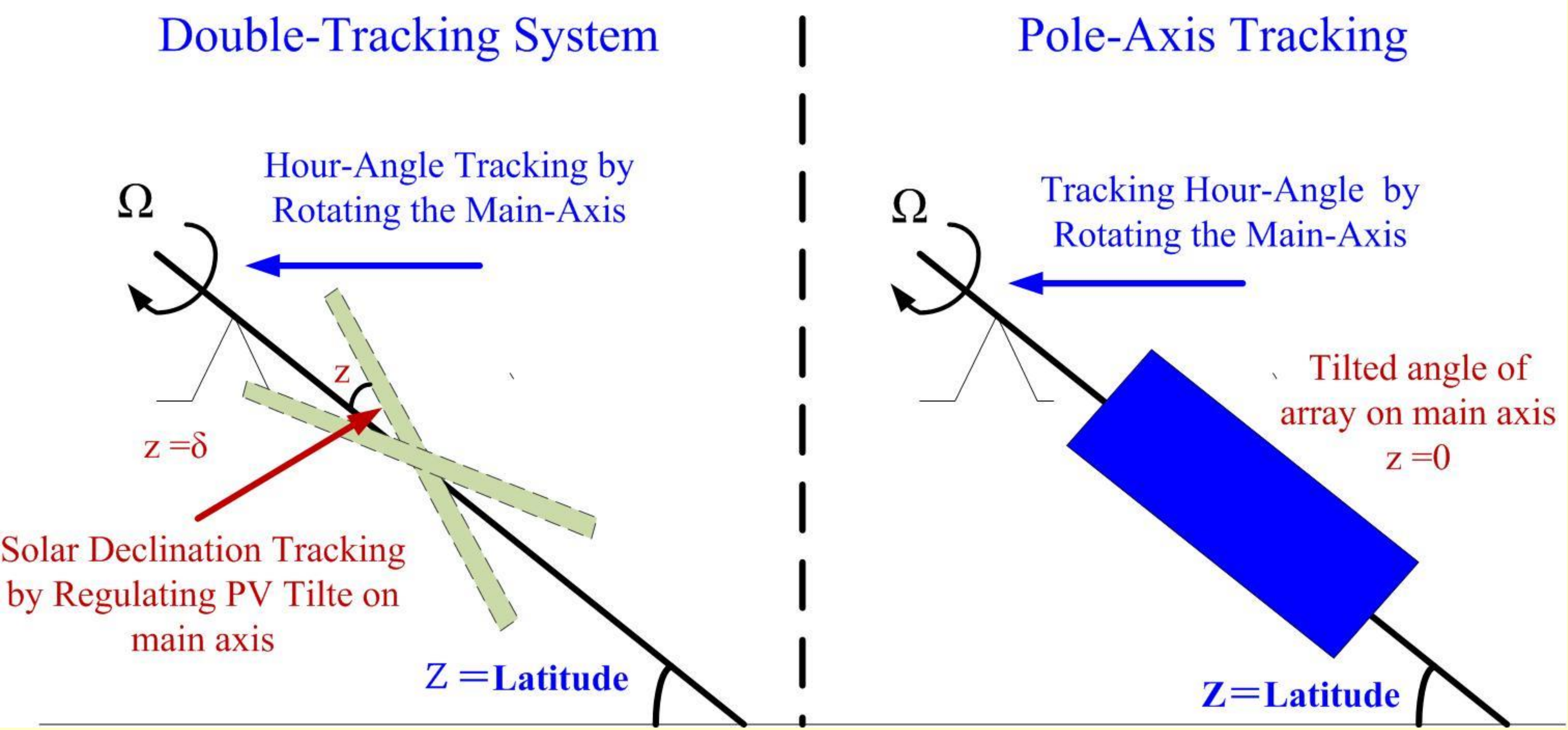
Horizontal E-W Tracking

Pole-Axis Tracking

Tilted E-W Tracking

Double Axis Tracking

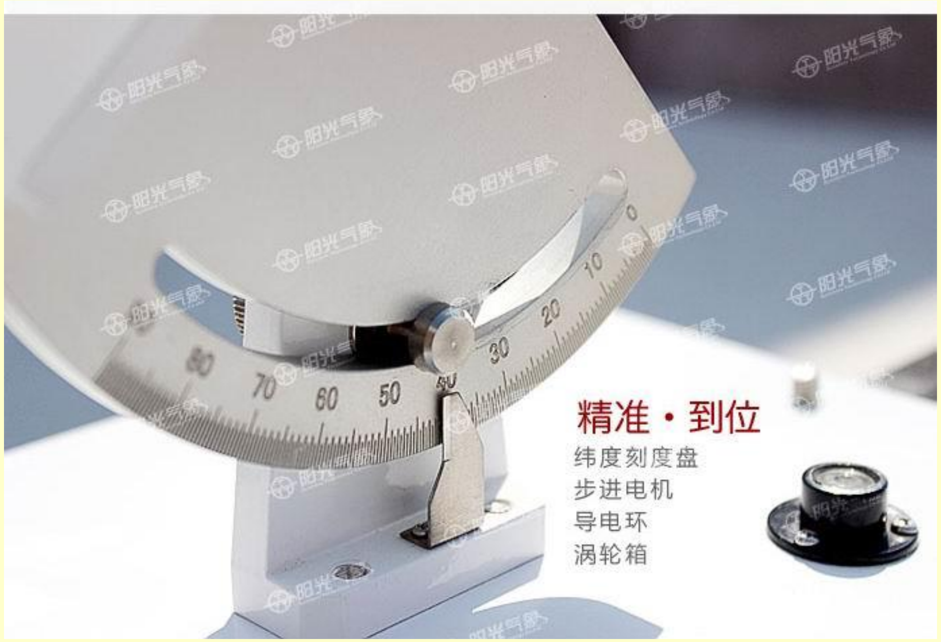
Equatorial Tracking Systems



The largest incidence error：±23.45 degree；

COS23.45 = 0.917, highest cos losses is only 8.3%， the average cos losses annually is only：4% comparing with accurate double axis tracking.

Direct Radiometer (One Motor Drive)



Firstly regulate Latitude

Follow the Rule of Equatorial Tracking:

1）One axis track the Hour-Angle；

2）Solar declination angle is regulated one degree every 4 days；

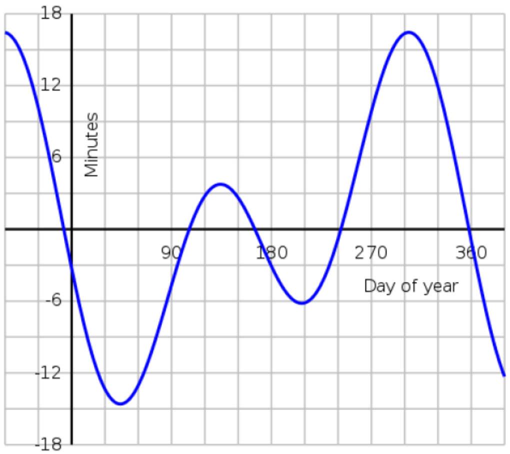
3）The allowed error of solar declination angle is 5 degree.

INSTALLATION OF DIRECT RADIOMETER

1、Set Latitude: Unstuck the screw on Latitude Plate, turning the pointer to local latitude, fastening the screw;

2、Regulate the time to local true-solar time:

True Solar Time = Beijing Time -（120°-Local Longitude）/15°+Time Difference (the Equation of Time) /60



The equation of time — above the axis a sundial will appear *fast* relative to a clock showing local mean time, and below the axis a sundial will appear *slow*.

3、Regulate the tilt of light-receiver:

a) According to solar declination table (Annex 3) to regulate the tilt of the light-receiver. Generally, 4 days to regulate about one degree.
Declination change per day = (23.45 x 4)/365 = 0.257 degree

b) Regulate the direction to face to south;

c) Regulate the horizontal level to make the gas-bulb just in the middle.

Direct Radiometer

附表三　　太阳赤纬角　　单位：度

Annex3　　Solar Declination　　Unit: degree

日期 day		月份 Month											
平年	闰年	一	二	三	四	五	六	七	八	九	十	十一	十二
1	2	-23.0	-17.2	-7.3	4.4	15.0	22.0	23.1	18.1	8.4	-3.1	-14.3	-21.8
2	3	-22.9	-16.9	-7.3	4.4	15.3	22.1	23.1	17.8	8.0	-3.4	-14.7	-21.9
3	4	-22.9	-16.6	-6.9	5.2	15.6	22.3	23.0	17.6	7.7	-3.0	-15.0	-22.1
4	5	-22.7	-16.3	-6.6	5.6	15.9	22.4	22.9	17.3	7.3	-4.2	-15.3	-22.2
5	6	-22.6	-16.0	-6.2	6.0	16.2	22.5	22.8	17.1	6.9	-4.6	-15.6	-22.3
6	7	-22.6	-15.7	-5.8	6.3	16.4	22.6	22.7	16.8	6.6	-5.0	-15.9	-22.5
7	8	-22.4	-15.4	-5.4	6.7	16.7	22.7	22.6	16.5	6.2	-5.4	-16.2	-22.6
8	9	-22.3	-15.1	-5.0	7.1	17.0	22.8	22.5	16.2	5.8	-5.8	-16.5	-22.7
9	10	-22.1	-14.6	-4.6	7.5	17.3	22.9	22.4	16.0	5.4	-6.1	-16.8	-22.8
10	11	-22.0	-14.4	-4.2	7.8	17.5	23.1	22.3	15.7	5.1	-6.5	-17.1	-22.9
11	12	-21.8	-14.1	-3.8	8.2	17.8	23.2	22.1	15.4	4.7	-6.8	-17.3	-23.0

Annex 3 Solar Declination Unit: degree

Low-Concentrating PV (LCPV)

PV array turning around the main axis 24 hours and 360 degree during a day to follow the solar hour-angle.

One-Drive, but double axis tracking.

This system was developed by Pro. Li Jiewu, University of Science and Technology, Inner-Mongolia.

China

Spain

I surprised! The different PV developers in Spain and China developed nearly the same Equatorial double-axis Solar Trackers independently!

Differences between the 2 Coordinates

Ground Horizontal Coordinates:

1) Sun position is determined by solar altitude and solar azimuth.
2) Solar altitude and solar azimuth changed un-linearly.
3) For CPV, there must be 2 driving force to regulate array tilt and array azimuth to follow solar altitude and solar azimuth.
4) Land usage will be affected by length and width ratio for azimuth tracking and double tracking system.

Equatorial Coordinates:

1) Sun position is determined by solar declination and solar hour-angle.
2) Solar declination is follow the sine rule during a year and solar hour-angle is follows the clock-rule during a day linearly.
3) For CPV, 1 driving force to follow hour-angle and 4 days to regulate 1 degree to follow solar declination manually is possible .
4) Land usage will never be affected by length and width ratio for double tracking.

Land Usage Models will Cover the Following 9 PV array Operations

1. **Fixed Array: Flat-land and face to the south**
2. **Fixed Array: Tilted-land and any direction**
3. **Horizontal Azimuth Tracking**
4. **Horizontal Altitude Tracking (manual regulation)**
5. **Horizontal Double-Axis Tracking**
6. **Equatorial Horizontal East-West tracking**
7. **Equatorial Pole-Axis tracking**
8. **Equatorial Tilted East-West tracking**
9. **Equatorial Double-Axis tracking**

Differences between Tilted E-W tracking and the other 3 Equatorial Tracking Systems

Horizontal E-W Tracking **Pole-Axis Tracking** **Double Axis Tracking**

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Direct Radiometer

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Tilted E-W Tracking

Boundary Conditions

Decoupled Treatment is required to the calculation for S-N distance and E-W distance

Boundary Condition for S-N Distance

Latitude φ	Declination δ	Hour Angle of Sunrise ω	Sunrise Time t	Sunrise Azimuth β	No-Shading Time t	9:00 Solar Altitude α
18	-23.45	-81.898	6:32	65.265	9:00am	29.603
20	-23.45	-80.916	6:36	64.945	9:00am	28.260
25	-23.45	-78.330	6:47	63.954	9:00am	24.819
30	-23.45	-75.496	6:58	62.644	9:00am	21.274
35	-23.45	-72.318	7:11	60.935	9:00am	17.646
40	-23.45	-68.655	7:25	58.702	9:00am	13.954
45	-23.45	-64.293	7:43	55.751	9:00am	10.213
50	-23.45	-58.872	8:05	51.750	9:00am	6.438

1. Different Latitude will have different sunrise time (maximum 1.5 hours);
2. At 9:00am, different latitude will have different solar altitude (from 6^o to 30^o);
3. So, set 9:00am to be non-shading time for all latitudes is not correct.

75% of Day-Length is more reasonable for S-N Distance (AT)

Latitude o	Tilt o	Declination o	Hour Angle	No-Shading hrs	Day-Length hrs	DL Ratio %	m^2/kW	Land increase %
10	10	-23.45	64.21	8.56	11.42	75.0	8.12	108.21
10	10	-23.45	45.00	6.00	11.42	52.6	7.50	
20	20	-23.45	60.69	8.09	10.79	75.0	10.35	114.65
20	20	-23.45	45.00	6.00	10.79	55.6	9.03	
30	30	-23.45	56.62	7.55	10.07	75.0	13.96	118.55
30	30	-23.45	45.00	6.00	10.07	59.6	11.78	
36.25	36.25	-23.45	53.59	7.15	9.53	75.0	17.60	118.54
36.25	36.25	-23.45	45.00	6.00	9.53	63.0	14.85	
40	40	-23.45	51.49	6.87	9.15	75.0	20.70	116.81
40	40	-23.45	45.00	6.00	9.15	65.5	17.72	
50	50	-23.45	44.15	5.89	7.85	75.0	36.67	96.22
50	50	-23.45	45.00	6.00	7.85	76.4	38.11	
60	60	-23.45	30.97	4.13	5.51	75.0	106.48	
60	60	-23.45	45.00	6.00	5.51	109.0	-210.72	

1. **Take 9:00am to 3:00pm as no-shading period is from GB50797-2012 (China National Standard).**
2. **Take 75% of Day-Length as no-shading period is more reasonable for S-N distance calculation since it is matched with all latitude. In this case, the shading losses will be identical and less than 3% (verified by PVSystems).**

There will be the longest E-W Distance when the sun is in the east

Latitude φ	Solar Declination δ	Date	Sunrise	SR Hour Angle	Sunrise Azimuth
0	0	Mar.21	6:00:00	90.00	90.00
10	3.5	Mar.29	5:57:28	90.62	93.55
20	6.75	Apr.7	5:50:53	92.47	97.19
30	9.75	Apr.15	5:37:47	95.69	101.28
40	12.75	Apr. 24	5:16:47	100.95	106.74
50	15.25	May. 2	4:44:50	108.96	114.15
60	17.25	May. 9	3:49:08	122.54	126.38
36.25	11.75	Apr. 20	**5:24:05**	98.77	104.63
36.25	0	Mar. 21	**6:00:00**	90.00	90.00
Latitude φ	Date	Hour Angle	Time	Solar Altitude	Solar Azimuth
0	Mar.21	70.00	7:20:00	**20.000**	**90.00**
10	Mar.29	70.30	7:18:11	**20.001**	**90.10**
20	Apr.7	71.13	7:15:30	**20.004**	**90.04**
30	Apr.15	72.45	7:10:48	**20.001**	**89.88**
40	Apr. 24	74.45	7:02:48	**20.008**	**90.06**
50	May. 2	76.90	6:52:36	**20.001**	**90.10**
60	May. 9	79.72	6:41:53	**20.001**	**90.04**
36.25	Apr. 20	73.68	**7:05:17**	**20.002**	**90.09**
36.25	Mar. 21	64.91	**7:40:22**	**20.001**	**74.52**

There must be some day when solar altitude reach to 20º (0-25º) and the sun azimuth is in the east for the places within latitude between 0 to 60 degree.

Boundary Conditions

S-N Direction

1) Winter Solstice (Sep. 21): the day has the lowest solar altitude during a year.
2) Time will be set based on 75% of day-length on winter solstice to keep shading losses identical and ≤ 3% for all latitude (verified by PVSystems).
3) Only PV array length (L) will affect S-N no-shading distance, not the width (K).

E-W Direction

1) There must be a day when solar altitude reaches to 20º and the sun is in the East for any places within 0-60º latitude. The day has the longest E-W no-shading distance.
2) Just calculate E-W distance based on 20º of solar altitude and 90º of solar azimuth without considering latitude, date and time.
3) Only PV array width (K) will affect E-W no-shading distance, not the length (L).

Formulas are very simple for all types of operation

(Thanks for sunshine is in parallel to make the calculation very easy!)

Two Formula for All-type of Operations

S-N Distance:

$D = D1+D2 = (L \times \cos Z) + (L \times \sin Z) \times \cos (\beta - r) / \tan\alpha$

Affected by the following factors:

1) Length of PV arrays (L);
2) Tilted S-N angles of PV arrays (Z);
3) Azimuth of PV arrays (r)
4) Solar azimuth (β);
5) Solar altitude (α): local latitude (φ), solar declination (δ) and solar hour angle (ω).

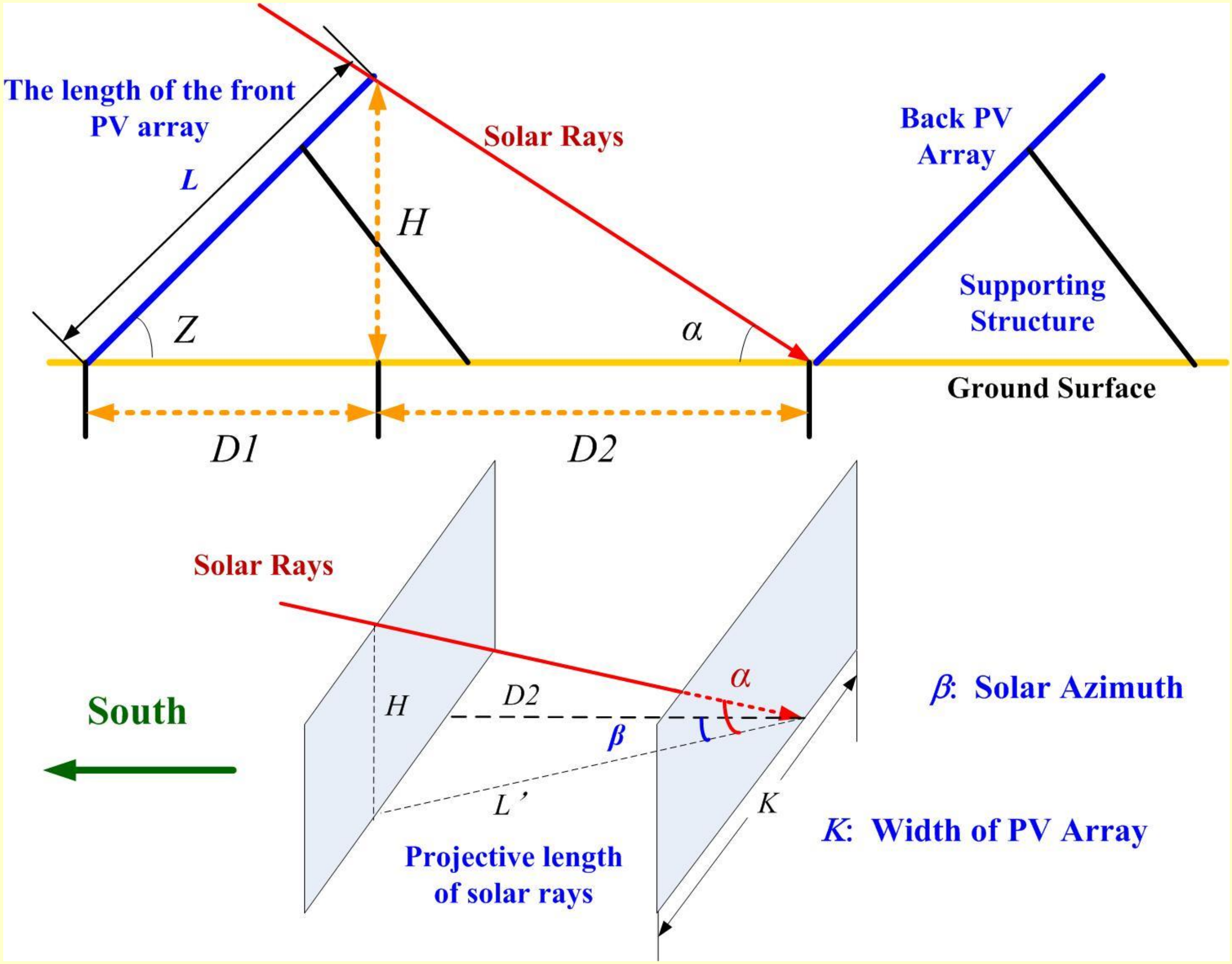
E-W Distance：

$D = D1 + D2 = K \times \cos A + (K \times \sin A) / \tan\alpha$

Affected by the following factors:

1) Width of PV arrays (K);
2) E-W tilted angle of PV arrays (A);
3) Solar altitude (α): local latitude (φ), solar declination (δ) and solar hour angle (ω).

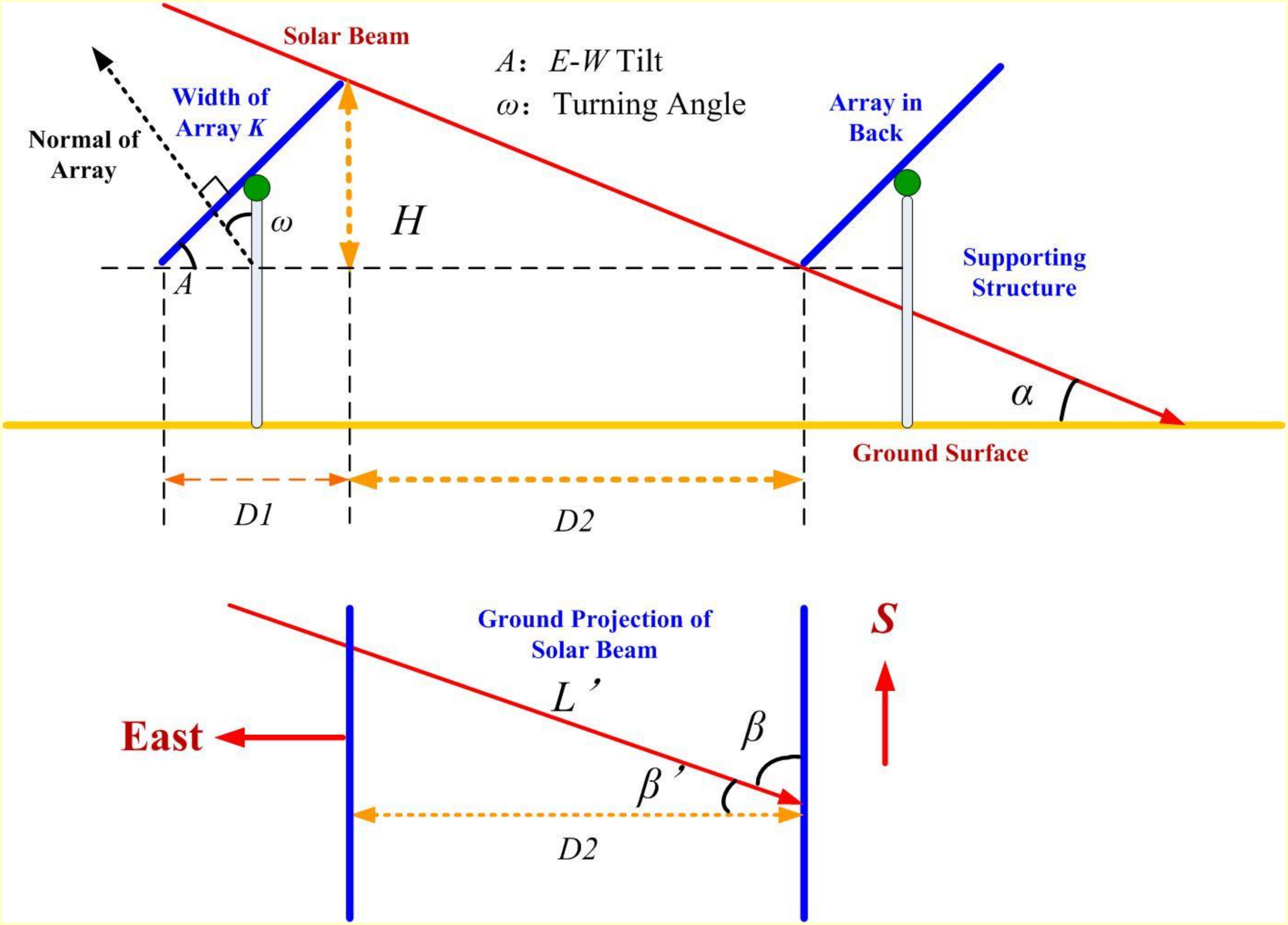
S-N Distance for Fixed PV Array



D1 = L × cos Z   H= L × sin Z

D2 = cos（β-r）×L'，L' = H/tanα

Distance D = D1+D2 =（L × cos Z）+ （L ×sin Z）×cos（β-r）/ tanα



For a Equ. Tracking system, the tilt of array A is always equal to the turning angle ω (time angle).

A = ω

E-W Distance D = D1 + D2

D1 = K×cos A

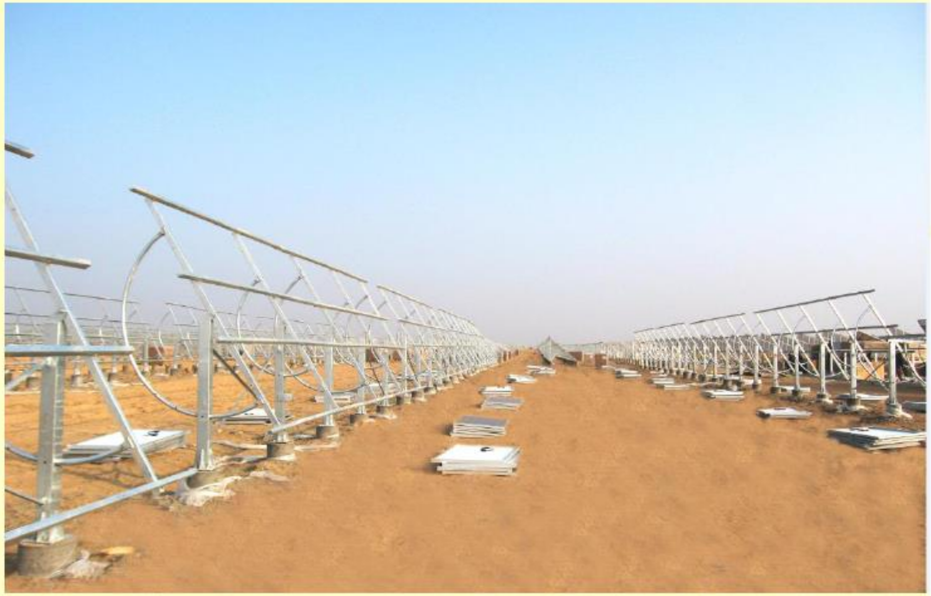
D2 = L × cosβ' = H×cosβ' / tanα

D2 = L ' = H/ tanα

East-West Distance

For E-W tracking, tilted E-W tracking and double-Axis tracking, the calculation is in the same way.

Solar Altitude Tracking with Fixed Azimuth



Regulate 2 times with 2 tilted angles : + 4.81%

1) Mar. 20th : Latitude - 12.0 degree
2) Sep. 21st : Latitude + 12.0 degree

Regulate 4 times with 3 tilted angles : + 7.12%

1) Apr. 20th : Latitude - 16.0 degree
2) Aug. 22nd : Latitude
3) Oct. 20th : Latitude + 16.0 degree
4) Feb. 19th : Latitude

Regulate 6 times with 4 tilted angles : + 8.62%

1) Mar. 20th : Latitude - 6.0 degree
2) May 4th : Latitude - 18.0 degree
3) Aug. 3rd : Latitude - 6.0 degree
4) Sep. 21st : Latitude + 6.0 degree
5) Nov. 6th : Latitude + 18 degree
6) Feb. 5th : Latitude + 6.0 degree

Verification

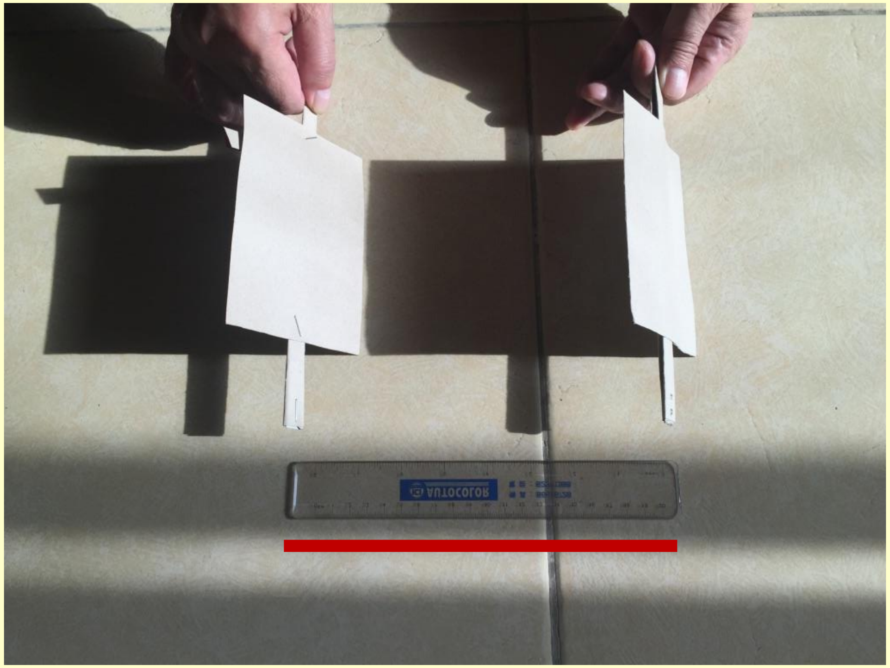
1) We can use the same formulas of Horizontal E-W trackers to calculate E-W distance for all other 3 trackers.

2) We can use the same formulas of Fixed PV Array to calculate S-N distance for all 4 equatorial trackers .

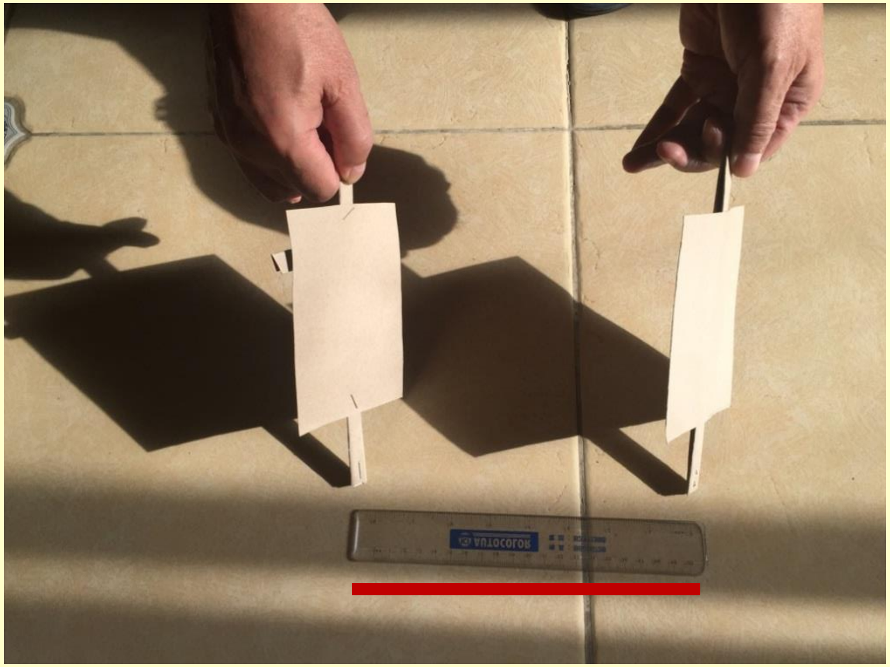
Horizontal E-W Tracking = Pole-Axis Tracking in E-W

Distance Calculation

East



Horizontal E-W Tracking



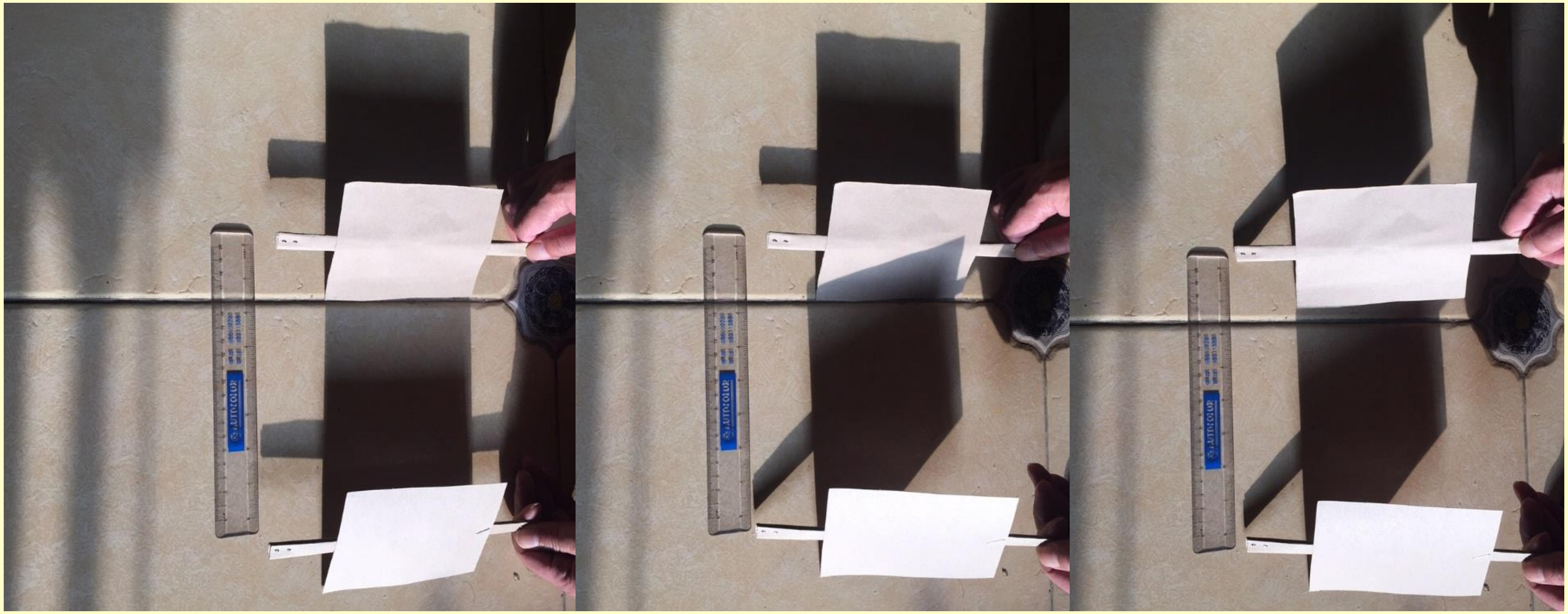
Pole-Axis Tracking

Because the solar beams are always in parallel.

The distance is the same to keep no-shading between E-W PV arrays, so the calculation must be the same.

Horizontal E-W Tracking = Pole-Axis Tracking in E-W

Distance Calculation



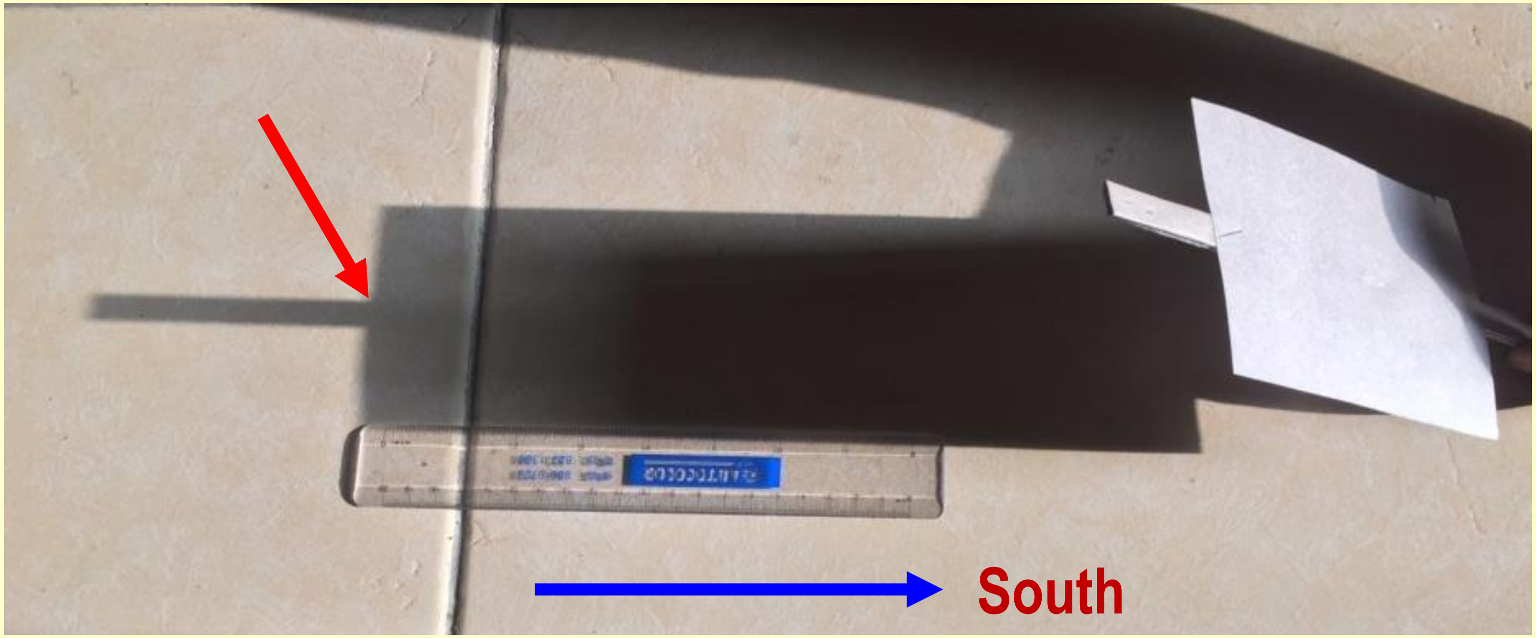
East

H- E-W Tracking | Rise One- Shaded | Rise Two- No-Shading

Because the solar beams are always in parallel.

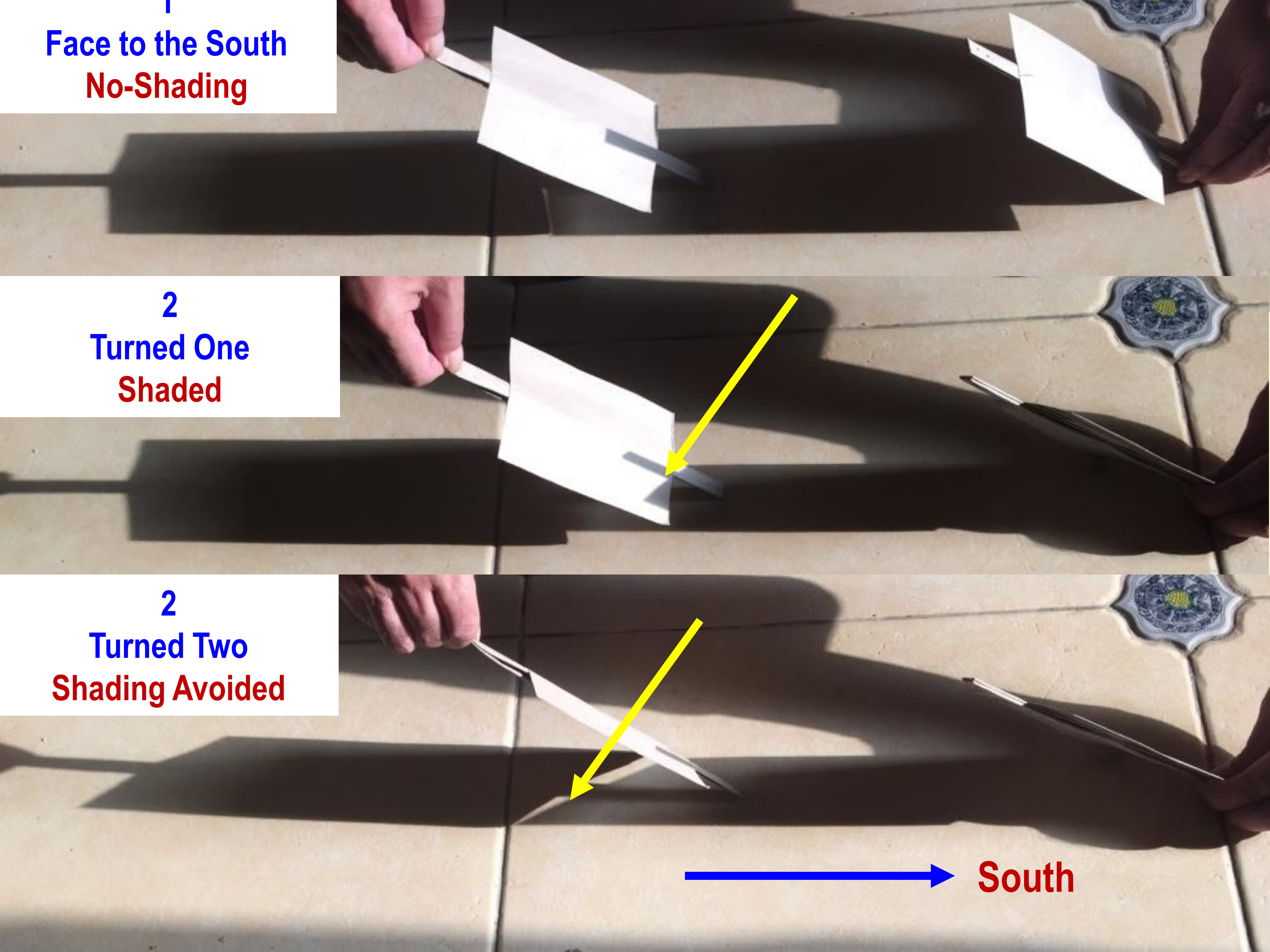
The distance is the same to keep no-shading in E-W direction, so the calculation must be the same for the two types of tracker.

Pole Tracking System: S-N Shading



1) PV Array face to south: the shading length of middle point is equal to the edge.

2) When PV array turning to the east: the shading length of middle point is different with edge.


Face to the South
No-Shading
2
Turned One
Shaded
2
Turned Two
Shading Avoided
South

Tilted East-West Tracking: E-W Shading

→ East

Horizontal E-W Shading

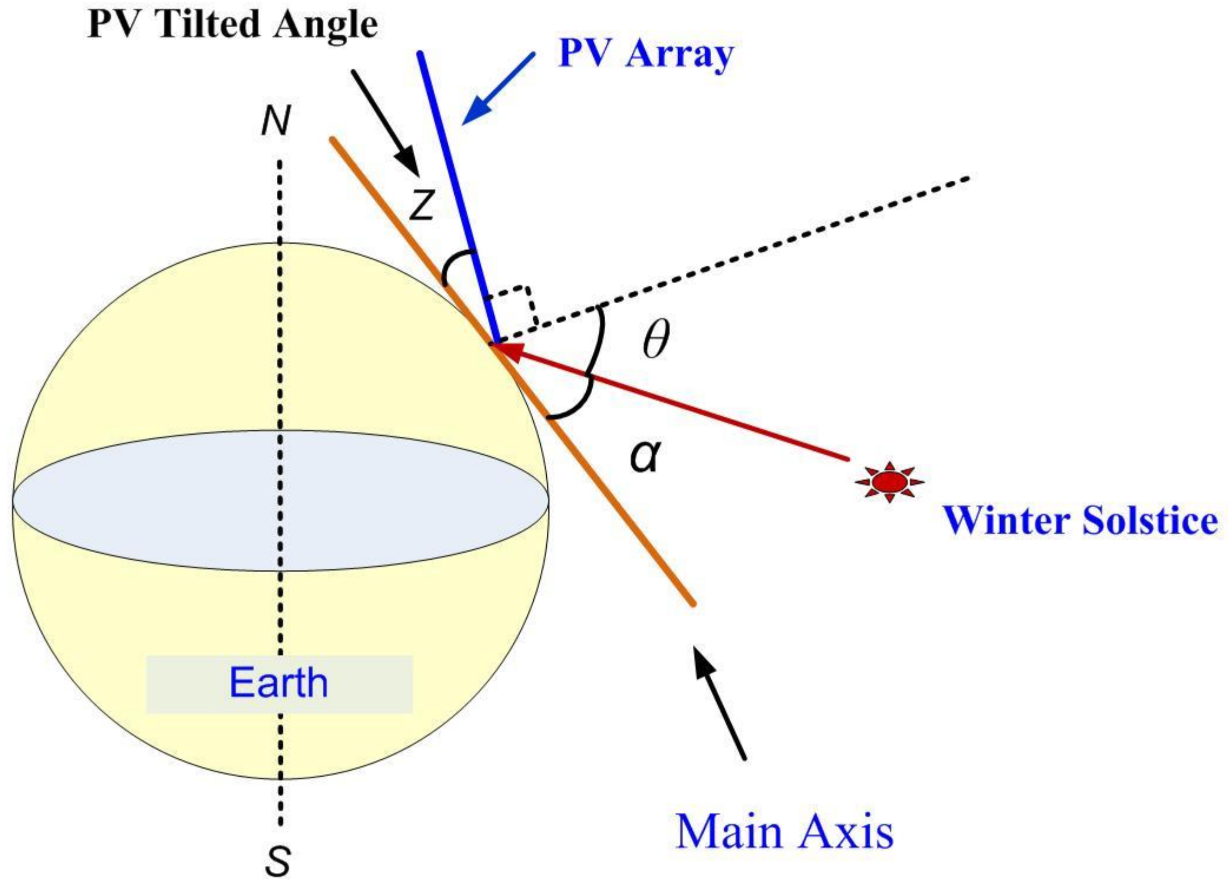
Tilted E-W Shading

1. In case the tilt and the width of PV arrays are the same for H-E-W tracking and Tilted E-W tracking, the no-shading distance is the same.
2. The above Fig. shows that no-shading distance is the same for the 2 type solar trackers.

Calculate S-N Distance for

Tilted E-W Tracking

Relationship for Tilted E-W Tracking

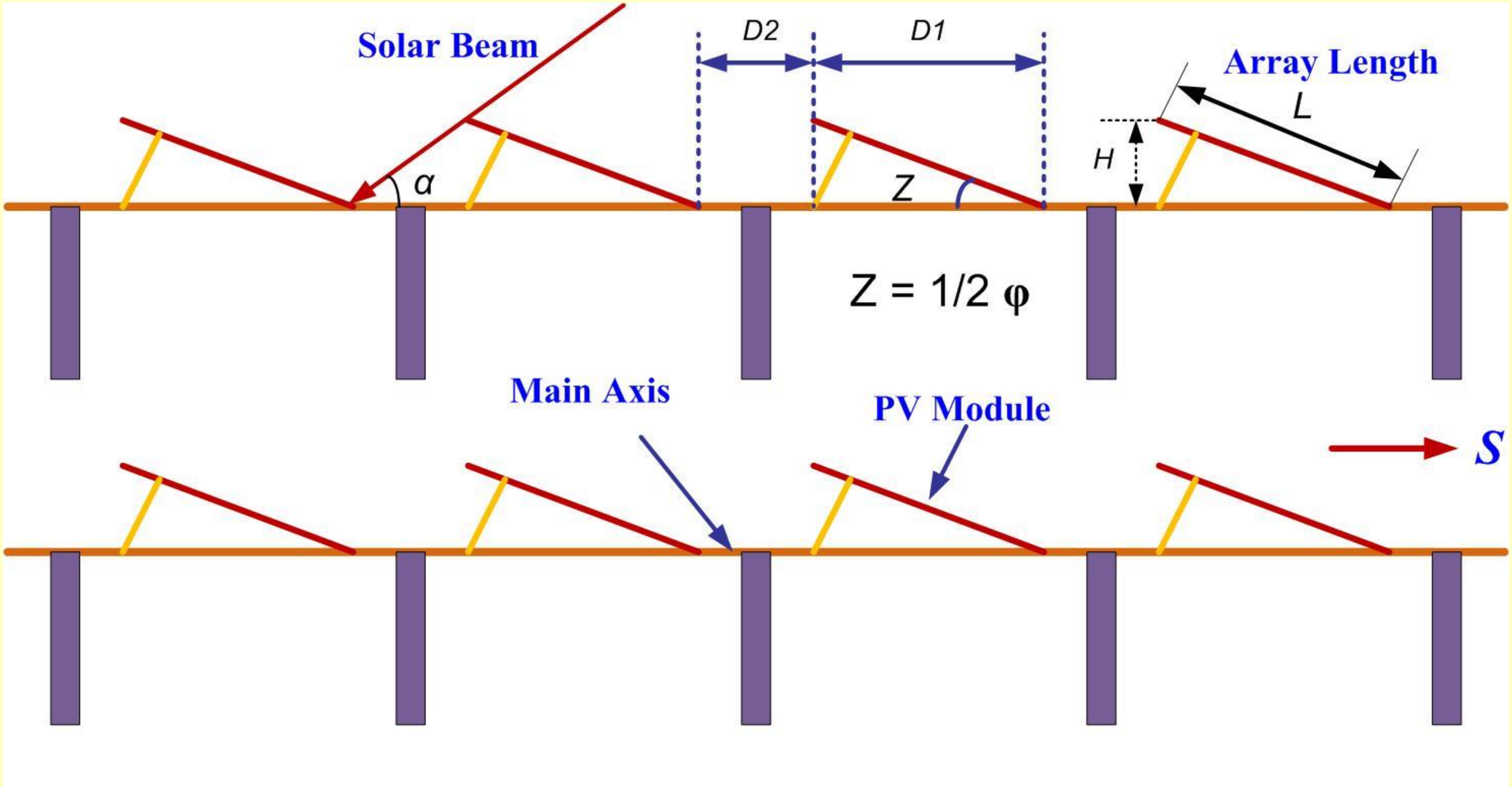


1、The tilted angle of PV modules on horizontal main axis can be any value;

2、On winter solstice, At noon time, the incident angle of solar beam is always: $\theta = 90^{o} - \alpha - Z$.

3、The south-north shading distance will be based on solar altitude α and the PV tilted angle *Z*.

S-N Distance of Tilted East-West Tracking



$D = D1+D2$ $D1 = L\times \cos Z$ $Z = 1/2\varphi$ $D2 = H/\tan\alpha$ $H = L\times\sin Z$

$\alpha = 90-\varphi-23.45$

$D = D1+D2 = L\times \cos Z + L\times\sin Z / \tan(90-\varphi-23.45)$

At noon time on winter solstice, $\omega = 0$, $\delta = -23.45$

$\sin\alpha = \sin\varphi\sin\delta + \cos\varphi\cos\delta\cos\omega = \sin\varphi\sin\delta + \cos\varphi\cos\delta = \cos(\varphi - \delta) = \sin(90- \varphi-23.45)$

So, $\alpha = 90 - \varphi - 23.45$

Tilt of PV Array = Latitude

Latitude φ	Declination δ	Sunrise β	PV Array γ	Sunrise θ	Noon θ	Aver. θ	Annual θ
30.00	-23.45	62.64	60.00	2.64	23.45	13.05	
30.00	0.00	90.00	60.00	30.00	0.00	15.00	22.82
30.00	23.45	117.36	60.00	57.36	23.45	40.41	
36.25	-23.45	60.43	53.75	6.68	23.45	15.07	
36.25	0.00	90.00	53.75	36.25	0.00	18.13	25.94
36.25	23.45	119.57	53.75	65.82	23.45	44.64	
40.00	-23.45	58.70	50.00	8.70	23.45	16.08	
40.00	0.00	90.00	50.00	40.00	0.00	20.00	27.90
40.00	23.45	121.80	50.00	71.80	23.45	47.63	

Tilt of PV Array = 1/2 Latitude

Latitude φ	Declination δ	Sunrise β	PV Array γ	Sunrise θ	Noon θ	Aver. θ	Annual θ
30.00	-23.45	62.64	75.00	22.36	48.45	35.41	
30.00	0.00	90.00	75.00	5.00	25.00	15.00	**22.45**
30.00	23.45	117.36	75.00	32.36	1.55	16.96	
36.25	-23.45	60.43	71.88	11.45	41.58	26.51	
36.25	0.00	90.00	71.88	18.13	18.13	18.13	**23.72**
36.25	23.45	119.57	71.88	47.70	5.33	26.51	
40.00	-23.45	58.70	70.00	11.30	43.45	27.38	
40.00	0.00	90.00	70.00	20.00	20.00	20.00	**25.00**
40.00	23.45	121.80	70.00	51.80	3.45	27.63	

Tilt of PV Array = 0

Latitude φ	Declination δ	Sunrise β	PV Array γ	Sunrise θ	Noon θ	Aver. θ	Annual θ
30.00	-23.45	62.64	90.00	27.36	53.45	40.41	
30.00	0.00	90.00	90.00	0.00	30.00	15.00	24.12
30.00	23.45	117.36	90.00	27.36	6.55	16.96	
36.25	-23.45	60.43	90.00	29.57	59.70	44.64	
36.25	0.00	90.00	90.00	0.00	36.25	18.13	27.98
36.25	23.45	119.57	90.00	29.57	12.80	21.19	
40.00	-23.45	58.70	90.00	31.30	63.45	47.38	
40.00	0.00	90.00	90.00	0.00	40.00	20.00	30.52
40.00	23.45	121.80	90.00	31.80	16.55	24.18	

Conclusion for Tilted E-W Tracking

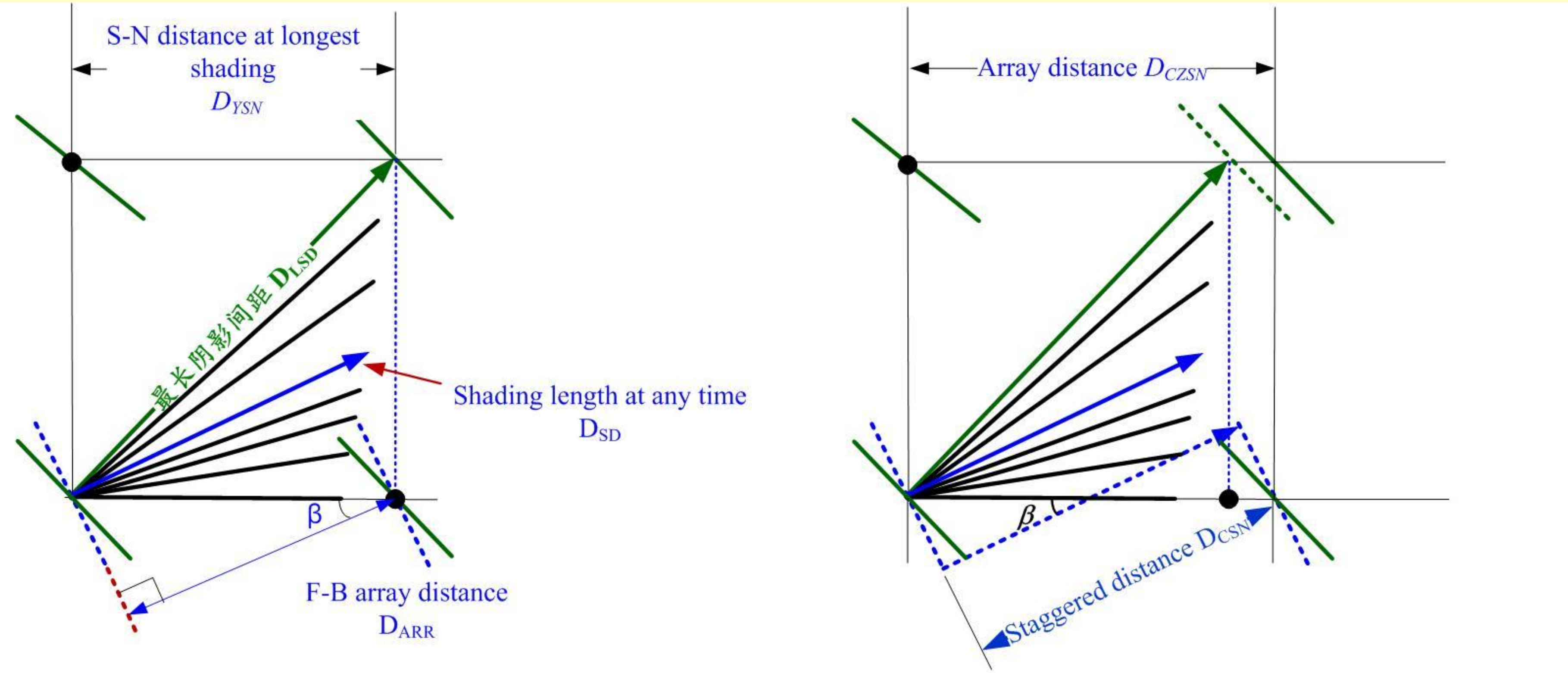
Latitude	Tilt	Annual Average Inclined Angle θ	Latitude	Tilt	Annual Average Inclined Angle θ
0	0	15.63	30	0	24.12
0	0	15.63	30	15	22.45
0	0	15.63	30	30	22.82
10	0	17.30	36.25	0	27.98
10	5	17.30	36.25	18.125	23.72
10	10	17.30	36.25	36.25	25.94
20	0	18.99	40	0	30.52
20	10	18.99	40	20	25.00
20	20	18.99	40	40	27.90

- **For the places within tropic line, just putting PV arrays horizontally (no tilt), since the Cosine losses is the same (< 5%) whatever PV array has tilt or not;**

- **For the places outside of tropic line, the optimized tilt of PV array is 1/2 latitude to get lowest Cosine losses during a year.**

Calculate S-N Distance for Horizontal Double Axis and Azimuth Tracking

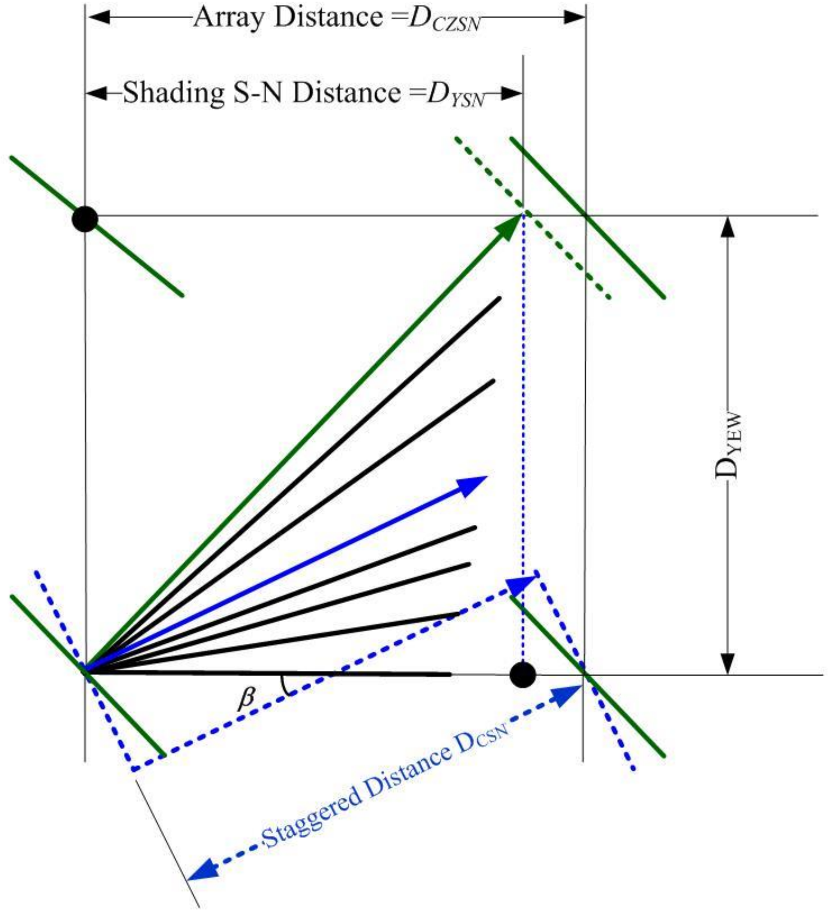
6 Distances need to be Considered



1. Front and back (F-B) array distance at longest shading D_{LSD}: $D_{LSD} = D1+D2$ at 9:00, winter solstice;
2. S-N distance at longest shading: $D_{YSN} = D_{LSD} \times \cos\beta$ depends on D_{LSD} and β ;
3. F-B distance at any time D_{ARR}: $D_{ARR} = D_{YSN} \times \cos\beta$ from small to large till D_{YSN};
4. Front array shading length at any time D_{SD}: $D_{SD} = D1 + D2$ from large to small（smallest at noon time）。
5. S-N staggered distance is from small to large till ∞， when $D_{SN} = D_{CSN}$， it is required D_{CSN};
   $D_{CSN} = K/\tan\beta$;
6. The set S-N distance of arrays D_{CZSN} can be derived from D_{CSN}: $D_{CZSN} = D_{CSN}/\cos\beta$.

S-N Distance for Horizontal Double-Axis Tracking

How to set S-N Distance for Horizontal Double Tracking Systems



a) Calculate the longest no-shading distance between PV arrays;

b) Set shading S-N distance and E-W distance (D_{YEW} and D_{YSN});

c) Calculate The shading distance and the staggered distance between arrays step by step and to find the point when the shading distance equal to the staggered distance ($D_{YSN} = D_{CEW}$). Record the staggered distance;

d) Calculate the PV array S-N distance D_{CZSN};

e) Compare D_{CZSN} and D_{YSN}, take the larger as the final S-N distance;

f) Also compare D_{YEW} and E-W distance calculated separately, take the larger as the final E-W distance.

S-N Distance for Horizontal Double-Axis Tracking

Lat φ	Tilt Z	Dec δ	HA ω	Alt α	Azi β	Length (m)	Width (K)
36.25	60	-23.45	45	16.73	42.64	3.988	8.425
36.25	60	-23.45	40	19.36	38.68	3.988	8.425
36.25	60	-23.45	37.6	20.54	36.71	3.988	8.425
36.25	60	-23.45	30	23.92	30.12	3.988	8.425
36.25	60	-23.45	27	25.08	27.38	3.988	8.425
36.25	60	-23.45	23	26.47	23.61	3.988	8.425
36.25	60	-23.45	15	28.64	15.70	3.988	8.425
36.25	60	-23.45	10	29.56	10.55	3.988	8.425
36.25	60	-23.45	5	30.11	5.30	3.988	8.425
36.25	60	-23.45	0	30.30	0.00	3.988	8.425

H （m）	D2 (m）	D1 (m）	D_{SD} (m) (D1+D2)	D_{YSN} (m)	D_{ARR} (m) (F-B)	D_{CSN} (m)	D_{ZSN} (m)
3.45	11.49	1.99	13.49	9.92	7.30	9.15	12.44
3.45	9.83	1.99	11.83	9.23	7.74	10.52	13.48
3.45	9.22	1.99	11.21	8.99	7.95	11.30	14.09
3.45	7.79	1.99	9.78	8.46	8.58	14.52	16.79
3.45	7.38	1.99	9.37	8.32	8.81	16.27	18.32
3.45	6.94	1.99	8.93	8.18	9.09	19.28	21.04
3.45	6.32	1.99	8.32	8.01	9.55	29.98	31.14
3.45	6.09	1.99	8.08	7.95	9.75	45.23	46.00
3.45	5.95	1.99	7.95	7.91	9.88	90.76	91.15
3.45	5.91	1.99	7.90	7.90	9.92	∞	∞

Land-Usage Affection by

L:K Ratio

Land Usage affected by Length-Width Ratio

The operations not affected by length-width ratio :

- Fixed PV arrays ;
- Manual regulated PV arrays (solar altitude manually tracking) ;
- Horizontal E-W tracking ;
- Tilted E-W tracking ;
- Pole-Axis tracking ;
- Equatorial Double-Axis tracking.

The operations will be affected by length-width ratio :

- **Azimuth tracking in ground horizontal coordinates ;**
- **Double axis tracking in ground horizontal coordinates.**

L:K Ratio for Horizontal Double Axis

L:K = 1:1

L:K = 1:2

I have never seen the array with L:K ratio equal to 2:1.

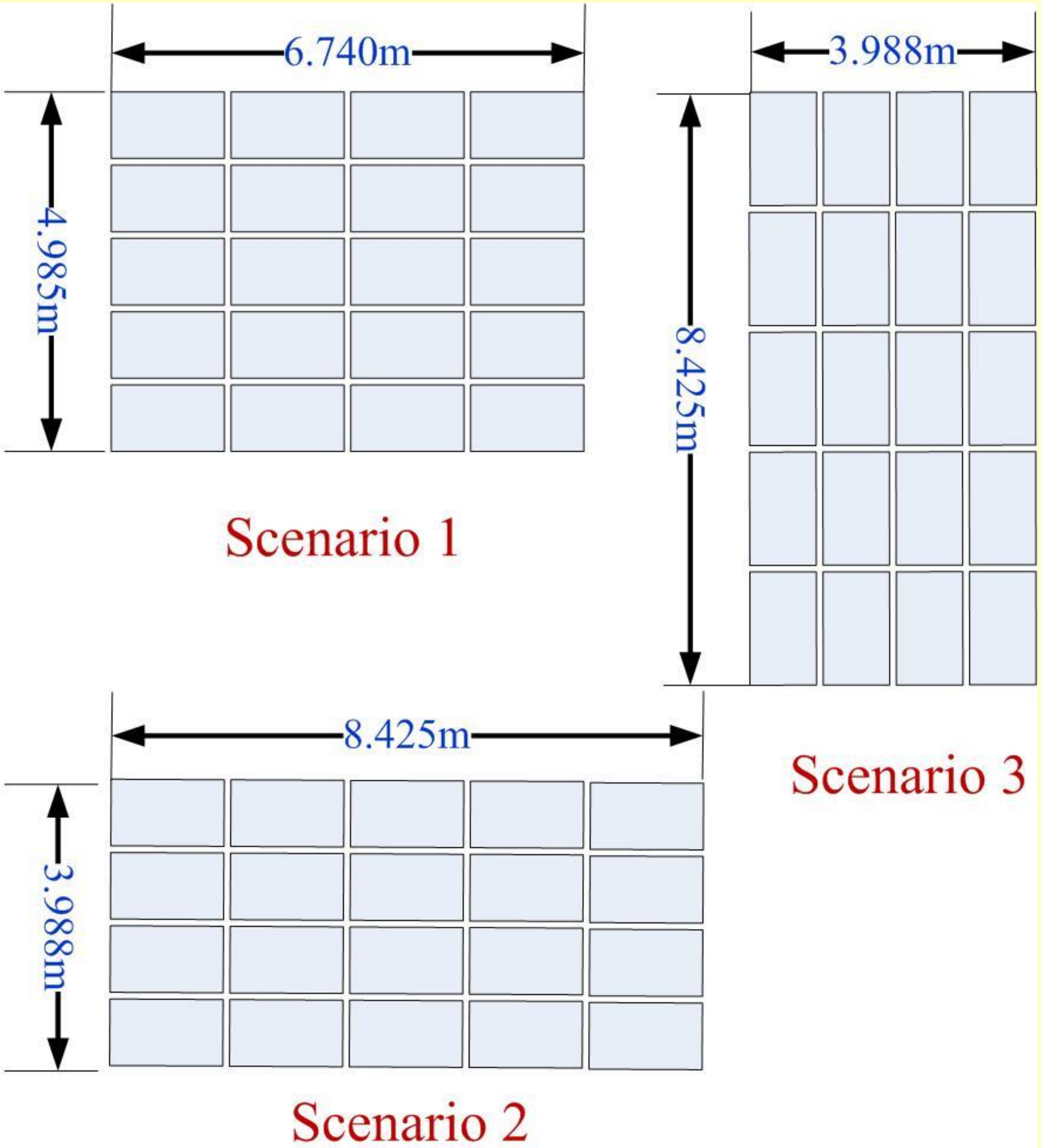
Solar Azimuth = Array Azimuth

The length (L) of the PV array is the key factor to calculate distance between arrays, all E-W distance and S-N distance based on L.
The width (K) of array is used to get staggered distance and to compare. K is also considered to avoid collision by adjacent arrays.

Calculation for 3 Scenarios

PV Module Data:
Module Length: 1.685m
Module Width: 0.997m
Module Power: 255Wp

PV Array Data:
Scenario 1:
L= 5MW=4.985m
K=4ML = 6.74m
Scenario 2:
L= 4MW=3.988m
K=5ML = 8.425m
Scenario 3:
L= 5ML=8.425m
K=4MW = 3.988m

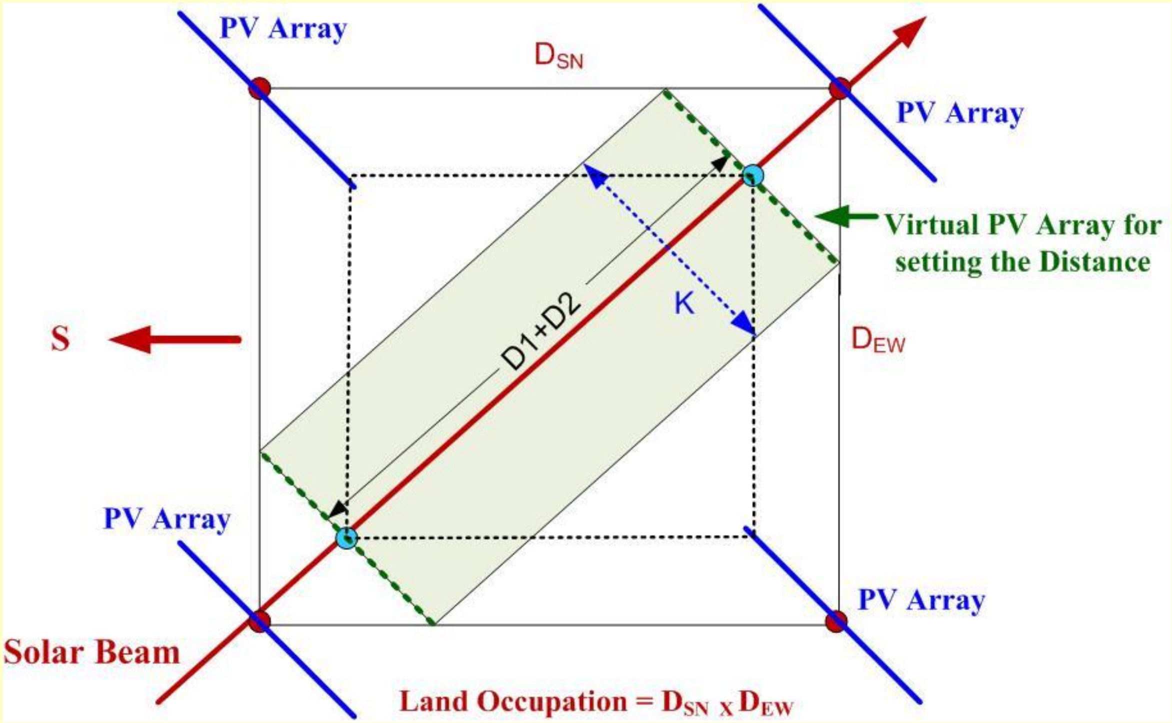


DTR gives examples of land usage for different L:K ratio and different latitude

Scenarios	1		2		3		Remarks
PV Array (m)	L	K	L	K	L	K	
	4.985	6.740	3.988	8.425	8.425	3.988	
Latitude ^{o}N	Unit Land Use (m^2/kW)		Unit Land Use (m^2/kW)		Unit Land Use (m^2/kW)		
20.00	30.56		22.49		67.86		L:K = 1:2 use less land.
36.25	38.86		32.18		99.69		
40.00	42.11		29.73		118.79		

How PV Companies doing Calculations for Double Tracking Systems?

Original Design for Horizontal Double-Axis Tracking-1

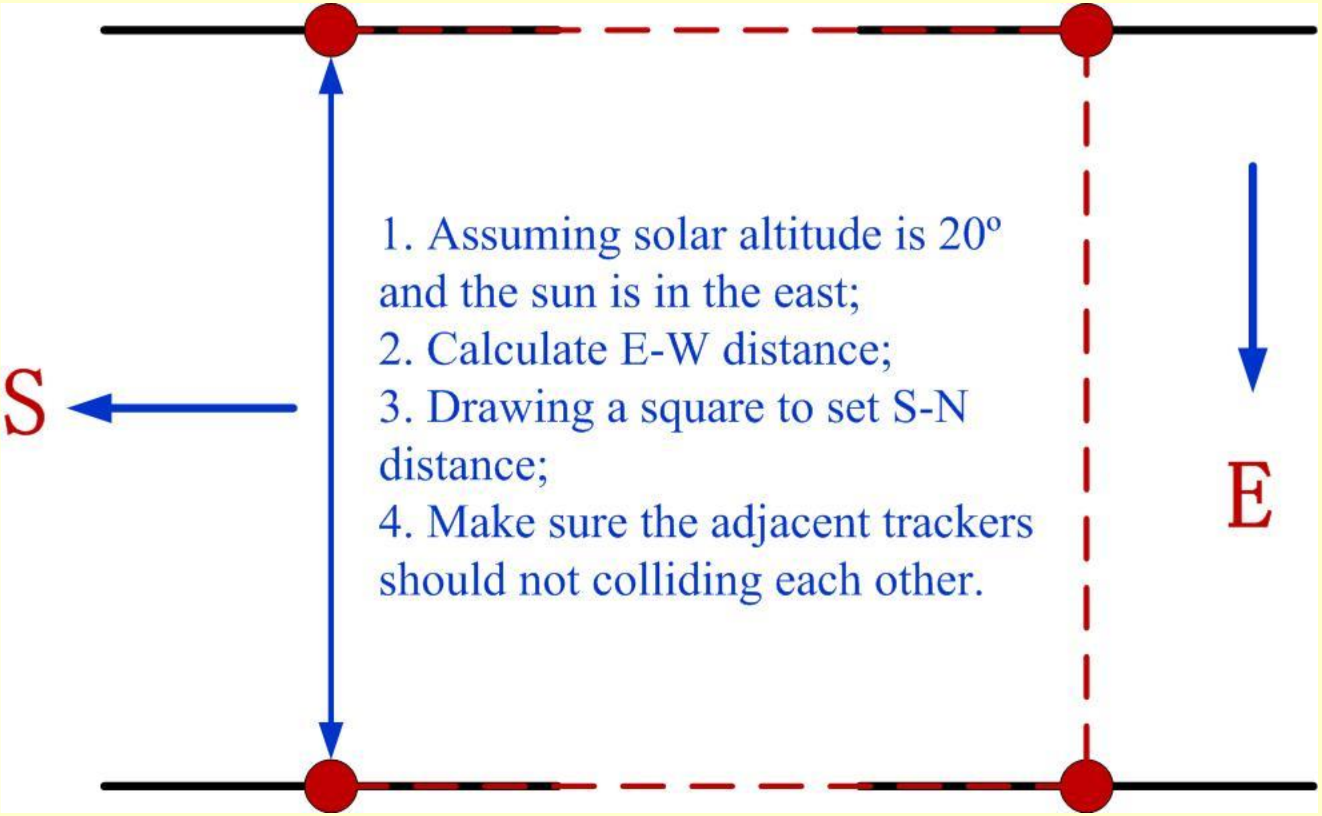


Latitude: 36.25º
Date: winter solstice (Dec. 21st)
Time: 9:00am
Solar altitude: 16.73º
Solar azimuth: 42.64º

1. Array length L: 4.985 m
2. Array width K: 6.74 m
3. Total power: 5.1 kW
4. Array Tilt: 60º
5. D_{SN} = (D1+ D2) x cosβ + K x sinβ
6. D_{EW} = (D1+ D2) x sinβ + K x cosβ
7. D1 + D2 = 16.856 m
8. DSN = 16.965m DEW = 16.376m Total: 277.83m²

Unit Land: 54.48 m²
TR Unit Land: 38.86 m²

Original Design for Horizontal Double-Axis Tracking-2



1. **Array length L: 4.985 m**
2. **Array width K: 6.74 m**
3. **Total power: 5.1 kW**
4. **Array Tilt: 60º**
5. **Solar altitude 20º, solar azimuth 90º**
6. **D_{EW} = D1+ D2 = 14.354 m**
7. **D_{SN} = 14.354 m**
8. **Total: 206.03m^2**

Unit Land Usage: 40.40 m^2

TR Unit Land Usage: 38.86 m^2

Comparing 3 Models and 3 Scenarios at Different Latitude

Scenario		1		2		3		Remarks
PV Array (m)		L	K	L	K	L	K	(Shorter and wider arrays will have less land usage)
		4.985	6.740	3.988	8.425	8.425	3.988	
Models	Latitude ºN	Unit Land Usage (m^2/kW)		Unit Land Usage (m^2/kW)		Unit Land Usage (m^2/kW)		
TM-1	20.00	29.16		**27.77**		46.36		1) L:K=1:2 is the best; 2) Too much land used.
	36.25	54.48		**46.98**		103.13		
	40.00	69.16		**57.80**		137.71		
TM-2	20.00	40.40		**25.85**		115.39		1) Not consider width; 2) Only for L/K Ratio ≥ 1; 3) More land usage than DTR; 4) L:K=1:2 is the best.
	36.25	40.40		**25.85**		115.39		
	40.00	40.40		**25.85**		115.39		
DTR	20.00	30.56		22.49		67.86		1) More efficient land usage; 2) L/K Ratio = 1:2 is the best.
	36.25	38.86		32.18		99.69		
	40.00	42.11		29.73		118.79		

Conclusion: 1) DTR is the best way to calculate the land usage;
2) Least land usage for 1:2 length and width ratio.

Comparing the results with PVSystems

(100% identical for no-shading distance on designed date and time)

Comparing the Results with PVSyst

Type of Installation	PVSyst	
	Shading Losses	Back-tracking
Fixed PV Arrays	√	X
Manual Regulation	√	X
Horizontal E-W Tracking	√	√
Pole-Tracking	√	NA
Tilted E-W Tracking	NA	NA
Double Tracking Equatorial Coordinates	NA	NA
Azimuth Tracking Horizontal Coordinates	√	X
Double Tracking Horizontal Coordinates	√	NA

For Geometry Method:
The designed distance between PV arrays of DTR is based on direct-irradiance.

For PVSyst:

1) **Irradiance shading losses at certain time and certain day is based on direct-irradiance. So it can be compared with DTR;**
2) **The annual shading losses is based on total annual irradiation and direct and diffuse irradiation ratio. So this data is only for reference.**

Comparing the results between DTR and PVSyst

The number one PVSyst expert in China, Mr. Jiang Huaqing helped me to do the comparison.

Bruce's colleague, Miss Zhou Dan also spend a lot of time to helped me to do the comparison and data analysis.

Comparing the results between DTR and PVSyst

Type of Installation	Fixed PV Arrays (9:00am)	Fixed PV Arrays (75%)	Fixed PV Arrays (9:00am)	Fixed PV Arrays (75%)
Boundary Condition	Latitude φ: 36.25 N Date and Time: Dec.21, 9:00am Solar Altitude α: 16.73º Solar Azimuth: 42.64º PV S-N Tilte Z: 36.25º Array Length L: 3.988 m Array Width K: 37.07 m Array Number: 5 Total Power: 112.2 kWp	Latitude φ: 36.25 N Date and Time: Dec.21,8:25:22am Solar Altitude α: 11.33º Solar Azimuth: 48.95º PV S-N Tilte Z: 36.25º Array Length L: 3.988 m Array Width K: 37.07 m Array Number: 5 Total Power: 112.2 kWp	Latitude φ: 20.00 N Date and Time: Dec.21, 9:00am Solar Altitude α: 28.26º Solar Azimuth: 47.43º PV S-N Tilte Z: 20.00º Array Length L: 3.988 m Array Width K: 37.07 m Array Number: 5 Total Power: 112.2 kWp	Latitude φ: 20.00 N Date and Time: Dec.21,7:57:45am Solar Altitude α: 16.62º Solar Azimuth: 59.59º PV S-N Tilte Z: 20.00º Array Length L: 3.988 m Array Width K: 37.07 m Array Number: 5 Total Power: 112.2 kWp
DTR Results **No-Shading Distance** between PV Arrays	S-N Direction: 8.988 m Unit Land Usage: 14.85 m^2/kW	S-N Direction: 10.654 m Unit Land Usage: 17.60 m^2/kW	S-N Direction: 5.464 m Unit Land Usage: 9.026 m^2/kW	S-N Direction: 6.264 m Unit Land Usage: 10.348 m^2/kW
PVSyst Shading loss at same time	At 9:00am, Dec.21 S-N Shading: 0.3%	At 8:25:22am, Dec.21 S-N Shading: 0.0%	At 9:00am, Dec.21 S-N Shading: 0.1%	At 7:57:45am, Dec.21 S-N Shading: 0.0%
PVSyst Annual Irradiation Loss	3.50%	2.80%	2.90%	2.10%

Comparing the results between DTR and PVSyst

Type of Installation	**Horizontal E-W Tracking (Spring Equinox)**	**Horizontal E-W Tracking (20º and East)**
Boundary Condition	Latitude φ: 36.25 N Date and Time: Mar.21, 7:40am Solar Altitude α: 20.00º Solar Azimuth: 74.52º PV E-W Tilt A: 60.00º Array Length L: 19.94 m Array Width K: 1.68 m Array Number: 20 Total Power: 102.0 kWp	Latitude φ: 36.25 N Date and Time: Apr.20, 7:05:48am Solar Altitude α: 20.00º Solar Azimuth: 90.00º PV E-W Tilt A: 60.00º Array Length L: 19.94 m Array Width K: 1.68 m Array Number: 20 Total Power: 102.0 kWp
DTR Results **No-Shading Distance** between PV Arrays	E-W Direction: 4.692 m Unit Land Usage: 18.346 m^2/kW	E-W Direction: 4.837 m Unit Land Usage: 18.912 m^2/kW
PVSyst Shading loss at same time	At 7:40am, Mar.21 E-W Shading: 0.7%	At 7:05:17am, Apr.20 (At 7:05:00am, Apr. 19) PVSyst E-W Shading: 0.0%
PVSyst Annual Irradiation Loss	4.80%	4.60%

Type of Installation	**Pole-Tracking (Spring Equinox)**	**Pole-Tracking (20º and East)**
Boundary Condition	Latitude φ: 36.25 N For E-W Distance: Date and Time: Mar.21, 7:40am Solar Altitude α: 20.00º Solar Azimuth: 74.52º PV E-W Tilt A: 60.00º For S-N Distance: Date and Time: Dec.21, 9:00am Solar Altitude α: 16.73º Solar Azimuth: 42.64º PV S-N Tilt Z: 36.25º Array Length L: 6.72 m Array Width K: 0.997 m Array Number: 100 (20 x 5) Total Power: 102.0 kWp	Latitude φ: 36.25 N For E-W Distance: Date and Time: May.6, 7:17:37am Solar Altitude α: 20.00º Solar Azimuth: 90.00º PV E-W Tilt A: 60.00º For S-N Distance: Date and Time: Dec.21, 9:00am Solar Altitude α: 16.73º Solar Azimuth: 42.64º PV S-N Tilt Z: 36.25º Array Length L: 6.72 m Array Width K: 0.997 m Array Number: 100 (20 x 5) Total Power: 102.0 kWp
DTR Results **No-Shading Distance** between PV Arrays	S-N Direction: 15.145 E-W Direction: 2.785 m Unit Land Usage: 41.35 m2/kW	S-N Direction: 15.145 E-W Direction: 2.871 m Unit Land Usage: 42.63 m2/kW
PVSyst Shading loss at same time	At 7:40am, Mar.21 E-W Shading: 0.00% At 9:00am, Dec.21 S-N Shading: 0.00%	At 7:05:17am, Apr.20 (At 7:05:00am, Apr. 19) PVSyst E-W Shading: 0.00% At 9:00am, Dec.21 S-N Shading:0.00%
PVSyst Annual Irradiation Loss	6.00%	5.80%

Comparing the results between DTR and PVSyst

Type of Installation	Double Tracking Horizontal Coordinates (Dec.21 for both direction)	Double Tracking Horizontal Coordinates (de-coupled)
Boundary Condition	Latitude φ: 36.25 N Date and Time: Dec.21, 9:00am Solar Altitude α: 16.73º Solar Azimuth: 42.64º PV Array Tilt Z: 60.00º Array Length L: 4.985 m Array Width K: 6.74 m Array Number: 20 (4 x 5) Total Power: 102.0 kWp	Latitude φ: 36.25 N For E-W Distance: Date and Time: May.6, 7:17:37am Solar Altitude α: 20.00º Solar Azimuth: 90.00º PV Array Tilt Z: 60.00º For S-N Distance: Date and Time: Dec.21, 9:00am Solar Altitude α: 16.73º Solar Azimuth: 42.64º PV Array Tilt Z: 60.00º Array Length L: 4.985 m, Array Width K: 6.74 m Array Number: 20 Total Power: 102.0 kWp
DTR Results **No-Shading Distance** between PV Arrays	S-N Direction: 13.806 E-W Direction: 11.418 m Unit Land Usage: 30.91 m2/kW	S-N Direction: 13.806 E-W Direction: 14.353 m Unit Land Usage: 38.85 m2/kW
PVSyst Shading loss at same time	At 7:40am, Mar.21 E-W Shading: 10.5% At 9:00am, Dec.21 S-N Shading: 0.00	At 7:05:17am, Apr.20 (At 7:05:00am, Apr. 19) PVSyst E-W Shading: 0.00% At 9:00am, Dec.21 S-N Shading: 0.00%
PVSyst Annual Irradiation Loss	4.40%	2.90%

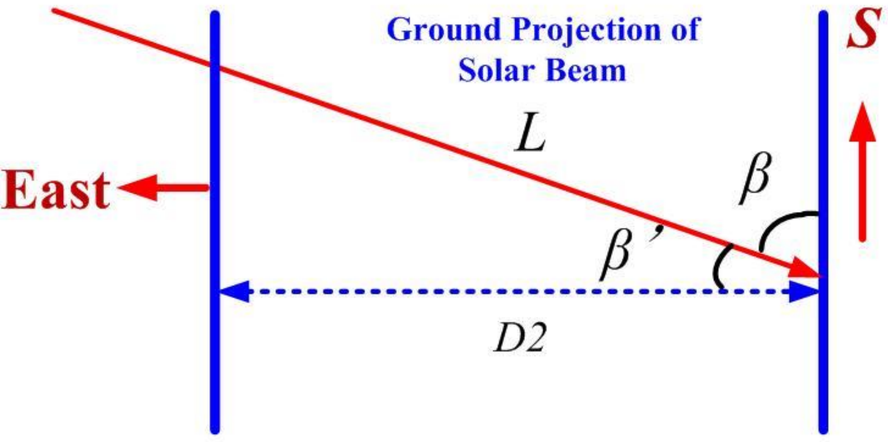
Type of Installation	Double Tracking Horizontal Coordinates (L:K = 1.0:1.3)	Double Tracking Horizontal Coordinates (L:K = 1.0:2.0)	Double Tracking Horizontal Coordinates (L:K = 1.0:2.0)
Boundary Condition	Latitude φ: 36.25 N For E-W Distance: Date and Time: May.6, 7:17:37am Solar Altitude α: 20.00º Solar Azimuth: 90.00º PV Array Tilt Z: 60.00º For S-N Distance: Date and Time: Dec.21, 9:00am Solar Altitude α: 16.73º Solar Azimuth: 42.64º PV Array Tilt Z: 60.00º Array Length L: 4.985 m Array Width K: 6.74 m Array Number: 20 Total Power: 102.0 kWp	Latitude φ: 36.25 N For E-W Distance: Date and Time: May.6, 7:17:37am Solar Altitude α: 20.00º Solar Azimuth: 90.00º PV Array Tilt Z: 60.00º For S-N Distance: Date and Time: Dec.21, 9:00am Solar Altitude α: 16.73º Solar Azimuth: 42.64º PV Array Tilt Z: 60.00º Array Length L: 3.988 m Array Width K: 8.425 m Array Number: 20 Total Power: 102.0 kWp	Latitude φ: 36.25 N For E-W Distance: Date and Time: May.6, 7:17:37am Solar Altitude α: 20.00º Solar Azimuth: 90.00º PV Array Tilt Z: 60.00º For S-N Distance: Date and Time: Dec.21, 9:00am Solar Altitude α: 16.73º Solar Azimuth: 42.64º PV Array Tilt Z: 60.00º Array Length L: 3.988 m Array Width K: 8.425 m Array Number: 20 Total Power: 102.0 kWp
DTR Results No-Shading Distance between PV Arrays	S-N Direction: 13.806 m E-W Direction: 14.353 m Unit Land Usage: **38.85 m2/kW**	S-N Direction: 14.29 m E-W Direction: 11.48 m Unit Land Usage: 32.18 m2/kW	S-N Direction: 14.29 m E-W Direction: 13.87 m Unit Land Usage: **38.85 m2/kW**
PVSyst Shading loss at same time	At 7:05:17am, Apr.20 (At 7:05:00am, Apr. 19) PVSyst E-W Shading: 0.00% At 9:00am, Dec.21 S-N Shading: 0.00%	At 7:05:17am, Apr.20 (At 7:05:00am, Apr. 19) PVSyst E-W Shading: 0.00% At 9:00am, Dec.21 S-N Shading: 0.00%	At 7:05:17am, Apr.20 (At 7:05:00am, Apr. 19) PVSyst E-W Shading: 0.00% At 9:00am, Dec.21 S-N Shading: 0.00%
PVSyst Annual Irradiation Loss	2.90%	3.90%	3.00%

Comparing Results

1. PVSyst has no models for tilted E-W tracking and equatorial double-axis tracking.
2. For the no-shading distance at designed time and date, the results are 100% identical between DTR and PVSyst.
3. Annual irradiation losses for Pole-axis tracking is larger than horizontal E-W tracking at same conditions;
4. For horizontal double tracking system: PVSyst shows: length and width ratio (L:K) does not affect land usage; but DTR shows: length and width ratio (L:K) definitely affect land usage. (This issue needs to be discussed)

Back-Tracking Technology

"Backtracking" Principle of Equatorial Sun-Trackers

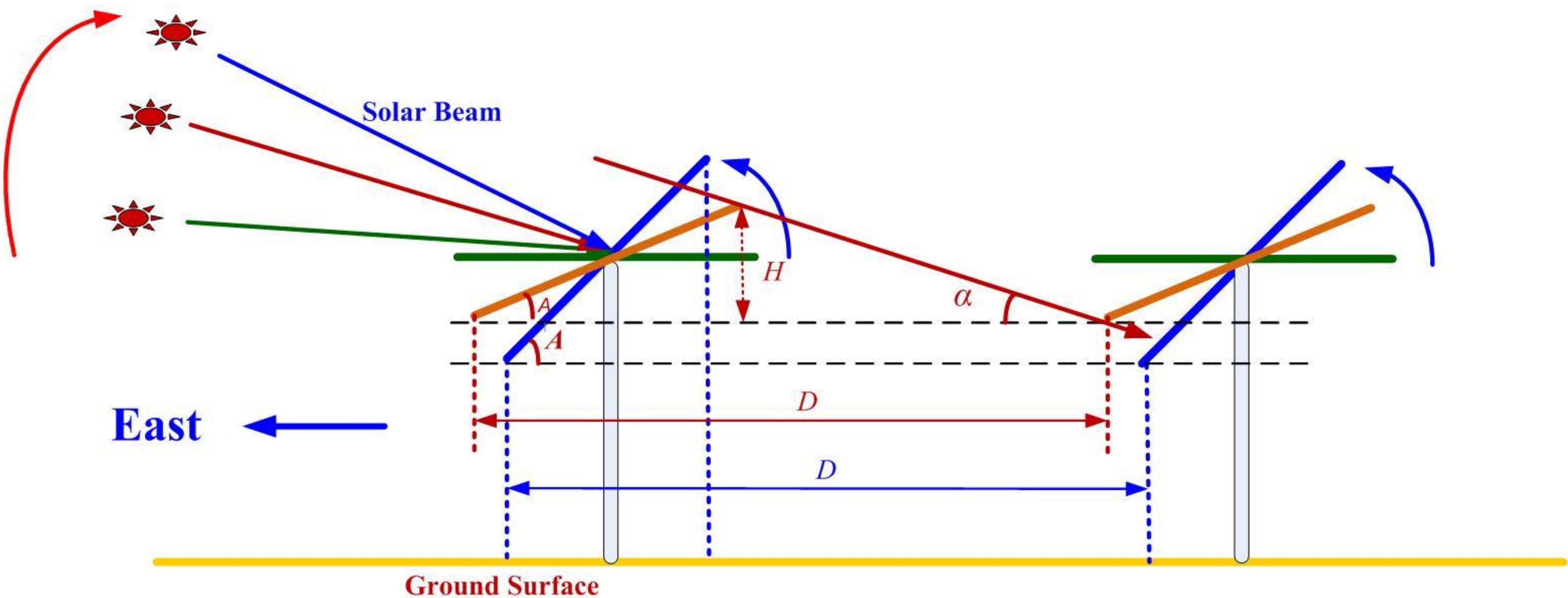


$$D = D$$

$$K\cos A + K\sin A\cos\beta' / \tan\alpha = D$$

D is known, Z is to be calculated

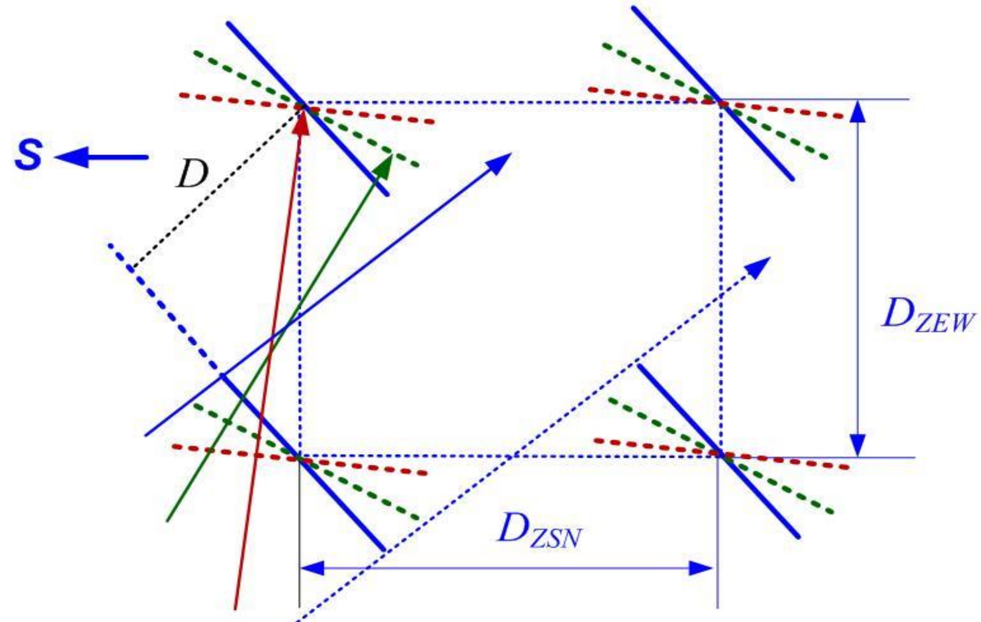
D: distance between PV arrays
K: width of PV array
A: the designed E-W tilted angle
β' : 90-β (β: Solar azimuth)
α: solar altitude



Back tracking tilt calculation for *E-W* tracking on winter solstice (365 days Calculation is Required)

Latitude φ	Sun declination δ	Hour angle ω	Solar time h	Solar altitude α	Array distance D	Shading distance D’	PV E-W tilt A
°	°	°	°	°	m	m	°
36,25	-23,45	-71,455	7:14	0,00	4,674	0	0
36,25	-23,45	-70	7:20	1,02	4,674	4,674	2,10
36,25	-23,45	-68	7:28	2,40	4,674	4,674	5,04
36,25	-23,45	-66	7:36	3,76	4,674	4,674	8,06
36,25	-23,45	-64	7:44	5,11	4,674	4,674	11,21
36,25	-23,45	-62	7:52	6,43	4,674	4,674	14,53
36,25	-23,45	-60	8:00	7,74	4,674	4,674	18,08
36,25	-23,45	-58	8:08	9,02	4,674	4,674	21,94
36,25	-23,45	-56	8:16	10,28	4,674	4,674	26,24
36,25	-23,45	-54	8:24	11,51	4,674	4,674	31,20
36,25	-23,45	-52	8:32	12,72	4,674	4,674	37,22
36,25	-23,45	-50	8:40	13,90	4,674	4,674	45,28
36,25	-23,45	-48	8:48	15,05	4,674	4,659	60,00

"Backtracking" Principle of Horizontal Sun-Trackers



$$\beta = r$$

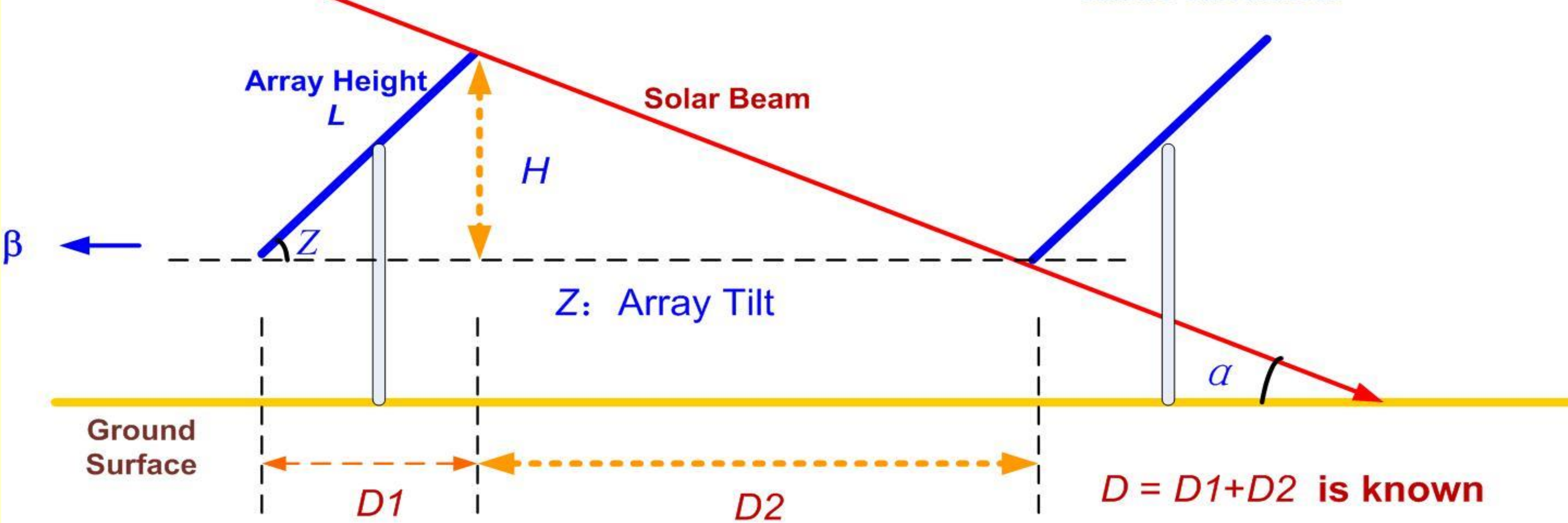
$$L \times \cos Z + (L \times \sin Z) / \tan\alpha = D$$

D is known, Z is to be calculated

$$D = D_{ZEW} \times \sin\beta$$

- **D: distance of E-W array (known)**
- **L: length (height) of array (known)**
- **Z: tilt of PV array**
- **β: solar azimuth**
- **r: array azimuth**
- **α: solar altitude**

Taking time angle or solar altitude into the formula, the backtracking array tilt can be calculated.



Back tracking tilt calculation for *H-Double Axis* on winter solstice (365 days Calculation is Required)

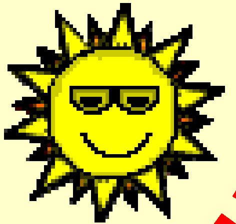
Latitude	Solar declination	Solar time	Hour angle	Solar altitude	D	shading	Tilt
φ	δ	h	ω	α		D’	Z
º	º		º	º	m	m	°
39,8	-23,45	7:25:00	-68,813	0,00	13,161	-	0,00
39,8	-23,45	7:32:00	-67,0	1,18	13,161	13,161	2,52
39,8	-23,45	7:40:00	-65,0	2,47	13,161	13,161	5,39
39,8	-23,45	7:48:00	-63,0	3,74	13,161	13,161	8,40
39,8	-23,45	7:56:00	-61,0	4,99	13,161	13,161	11,58
39,8	-23,45	8:04:00	-59,0	6,22	13,161	13,161	14,97
39,8	-23,45	8:12:00	-57,0	7,42	13,161	13,161	18,65
39,8	-23,45	8:20:00	-55,0	8,60	13,161	13,161	22,70
39,8	-23,45	8:28:00	-53,0	9,76	13,161	13,161	27,24
39,8	-23,45	8:36:00	-51,0	10,89	13,161	13,161	32,48
39,8	-23,45	8:44:00	-49,0	11,99	13,161	13,161	38,78
39,8	-23,45	9:00:00	-45,0	14,10	13,161	13,161	60,00
39,8	-23,45	10:00:00	-30,0	20,83	13,161	6,791	69,17
39,8	-23,45	11:00:00	-15,0	25,22	13,161	3,060	64,78
39,8	-23,45	12:00:00	0,0	26,75	13,161	0,000	63,25

The Proposed Boundary Conditions

Ground-Horizontal Coordinates					
Type of Operation	S-N Distance	Array Tilt (Z)	E-W Distance	Array Azimuth	Remarks
Fixed PV Arrays	75% day length, on winter solstice	φ	NA	0º	
Manual-Regulated Arrays	75% day length, on winter solstice	2 times or 4 times (provide tables)	NA	0º	No more than 4 times
Azimuth Tracking	75% day length, on winter solstice	φ	Solar altitude 18º-20º Solar azimuth 90º	= solar azimuth	L:K Ratio 1:1 ~ 1:2
Double Axis Tracking (for flat-plate panels)	75% day length, on winter solstice	60º	Solar altitude 18º-20º Solar azimuth 90º	= solar azimuth	L:K Ratio 1:1 ~ 1:2
Double Axis Tracking (for HCPV and LCPV)	Solar altitude reach to 20º, on winter solstice	70º	Solar altitude 20º Solar azimuth 90º	= solar azimuth	L:K Ratio 1:1 ~ 1:2
Equatorial Coordinates					
Type of Operation	S-N Distance	Array Tilt (Z)	E-W Distance	Array Tilt (A)	Remarks
Horizontal E-W Tracking	NA		Solar altitude 18º-20º Solar azimuth 90º	60º	
Tilted E-W Tracking	75% day length, on winter solstice	1/2 φ	Solar altitude 18º-20º Solar azimuth 90º	60º	
Pole-Axis Tracking (for flat-plate panels)	75% day length, on winter solstice	φ	Solar altitude 18º-20º Solar azimuth 90º	60º	
Pole-Axis Tracking (for line-focus LCPV)	75% day length, on winter solstice	φ	Solar altitude 20º Solar azimuth 90º	70º	
Double Axis Tracking (for flat-plate panels)	75% day length, on winter solstice	φ+23.45	Solar altitude 18º-20º Solar azimuth 90º	60º	
Double Axis Tracking (for HCPV & LCPV)	Solar altitude reach to 20º, on winter solstice	φ+23.45	Solar altitude 20º Solar azimuth 90º	70º	

Some Calculation Results

Latitude : 36.25N Module Efficiency : 15.18%							
Array Type	Boundary Conditions		Unit Land (m2/kW)	Array Type	Boundary Conditions		Unit Land (m2/kW)
Fixed to South	Date & Time: 75% Day Length Dec. 21, 8:34:23am Solar Alt: 11.76º Solar Azim : 48.95º S-N Tilt : 36.25º		17.6 (-2.8% PVSyst)	Pole-Tracking	E-W Distance: Apr. 20, 7:05:43am Solar Alt: 20.00º Solar Azim: 90.00º E-W Tilt: 60.00º	S-N Distance: Dec. 21, 9:00am Solar Alt: 16.73º Solar Azim : 42.64º S-N Tilt: 36.25º	42.63 (-5.6% PVS)
Mannual Regul.	Date & Time: 75% Day Length Dec. 21, 8:34:23am Solar Alt: 11.76º Solar Azim : 48.95º S-N Tilt: 36.25º+16º		20.46	Equatorial Double	E-W Distance: Apr. 20, 7:05:43am Solar Alt: 20.00º Solar Azim: 90.00º E-W Tilt: 60.00º	S-N Distance: Dec. 21, 9:00am Solar Alt: 16.73º Solar Azim : 42.64º S-N Tilt: 36.25º + 23.45º	49.51
Hor. E-W	Date & Time: Apr. 20, 7:05:43am Solar Alt: 20.00º Solar Azim: 90.00º E-W Tilt: 60.00º		18.91 (-4.6% PVS)	Azimuth Track	E-W Distance: Apr. 20, 7:05:43am Solar Alt: 20.00º Solar Azim: 90.00º Array Tilt: 36.25º	S-N Distance: Dec. 21, 9:00am Solar Alt: 16.73º Solar Azim : 42.64º Array Tilt: 36.25º	30.46
Tilted E-W	E-W Distance : Apr. 20, 7:05:43am Solar Alt: 20.00º Solar Azim: 90.00º E-W Tilt: 60.00º	S-N Distance : Dec. 21, 12:00 Solar Alt : 30.3º Solar Azim : 0º S-N Tilt : 18.125º	28.04	Horizontal Double	E-W Distance: Apr. 20, 7:05:43am Solar Alt: 20.00º Solar Azim: 90.00º E-W Tilt: 60.00º	S-N Distance: Dec. 21, 9:00am Solar Alt: 16.73º Solar Azim : 42.64º Array Tilt: 60.00º	38.85 (-2.9% PVS)



Thank You for Your Attention!