The Ravina Project

Solar Array Aperture Analysis 21

Calculating the -3.0 dB Beam Width

Gordon Fraser B.A.
Director - The Ravina Project
Toronto, Canada

2008/09/04

Blank Page

Solar Array Aperture Analysis

Calculating the minus 3.0 dB beam width

Introduction

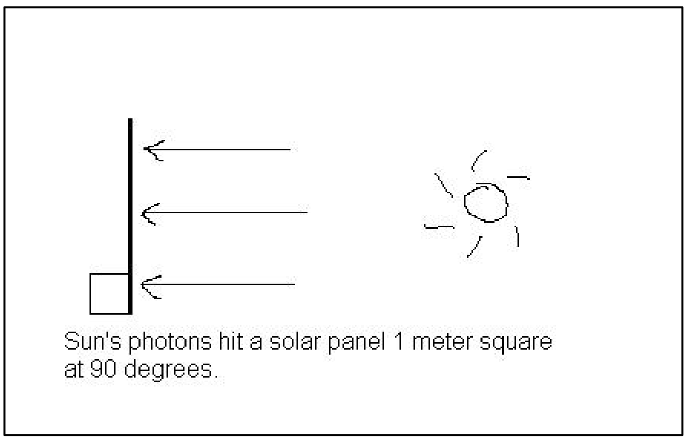
As we discussed in our paper, "Solar Project Theory and Practice 14" we, in theory, view our solar array as a radio antenna. The sun is a transmitter of electromagnetic radiation or photons and our solar array is a giant receiving antenna. We have built models based upon that theory and have been actively using them to aim our array.

Now this is all well and good in theory. Just recently we have taken data readings to try and push past the theoretical stage and calculate the minus 3.0 dB (half power) beam width on one axis of the array's aperture, a standard calculation for all radio antennae. We discuss this experiment, produce the data in graphic and tabular forms, and include a copy of the original worksheet.

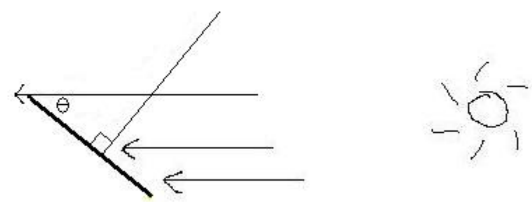
We discuss the design implications for dynamic arrays in light of both the radio antenna paradigm and the data we have collected. And finally, we discuss an inexpensive hypothetical sun tracker using our theoretical model that will lose a daily worst case maximum of 10% or 0.45 dB of the sun's energy due to poor sun angles upon the collecting surface of the array.

Theoretical Analysis - Effective Aperture of a Solar Array

Consider the following diagram.



The point of view is from the end of the array. The sun's rays (photons) hit the array in parallel lines. One of our assumptions in the paper mentioned above is that when solar radiation hits the aperture of the array at 90 degrees, or Normal, the number of photons intercepted is at a maximum. The signal power received is at a maximum. The solar array will generate maximum power in this orientation to the sun.



Sun's photons hit a solar panel 1 meter square at Theta degrees.

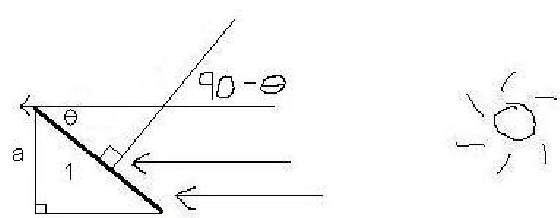
Consider the next diagram above.

Here's the same array but this time the sun's rays are hitting it at **theta** degrees. Note the following. The incident ray is offset from array Normal, the maximum power angle for the array, by (90 – theta) degrees. Note that at the latitude of The Ravina Project (43 degrees North) the sun will never be at the zenith or 90 degrees overhead. The best we can do here is about 70 degrees of elevation on the 21st of June at noon sun time.

This diagram also gives insight into the solar designer's dilemma for the proper angle to set a non-dynamic solar array with respect to the sun's seasonal angles and time of day. Traditionally we are always dealing with compromises with respect to the proper orientation of the non-dynamic solar arrays we put up.

Consider this next diagram.

The effective size of an array dimension shrinks when the photons hit the array at any angle other than 90 degrees. In fact the effective size of the array is proportional to the sine of the angle of incidence, **theta**. Note as well that the length 'a' expressed in proportion to the offset of the incident angle from normal, (90 minus theta), is COSINE (90-theta).



Effective size of array 1 meter in length is "a" when angle of sun's rays hit the array at theta degrees. Effective length "a" is calculated as Sin (theta).

The angle theta approaches zero as the dimension 'a' approaches zero. As the angle theta approaches 90 degrees, the dimension 'a' approaches unity which is the physical length of the array. This approach to calculating an effective dimension of the array can work for both the array's effective width and its effective height. This allows for the calculation of the array's effective aperture.

Calculating Effective Array Aperture

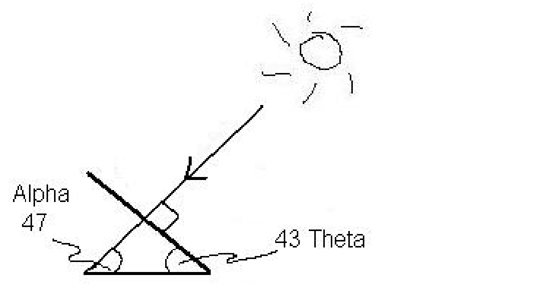
As we have seen above the array's effective collecting dimensions are affected greatly by the photon's angle of incidence upon the plane of the array.

Since the sun's altitude starts at the horizon, zero degrees and increases to some maximum before decreasing during the afternoon, the sun's daily motion can be understood, on the vertical axis, as an up and down motion. The effective array height can be calculated using the methods described above using the sun's altitude and array angle from horizontal.

Consider an array 1 meter square that is fixed at a tilt of 43 degrees from horizontal and its centerline is 30 degrees east of south at 150 degrees … exactly like the array at The Ravina Project.

If the sun is at an azimuth of 150 degrees and at an altitude of 47 degrees the sun's rays will hit the array surface at an angle of 90 degrees in both the horizontal and vertical axes.

Keeping the same azimuth, let's say that the altitude of the sun is 30 degrees. As we can see from the diagram alpha and theta must add up to 90 degrees if the 90 degree incident angle is to be maintained. However, the array angle theta is fixed at 43 degrees and alpha has decreased to 30 degrees. Since the triangle must contain 180 degrees the remaining angle once normal at 90 degrees now must now become obtuse. When



Array raised to an angle of 43 degrees from horizontal. Sun's rays hit the array at 90 degrees when sun is at 47 degrees altitude.

alpha decreases by 17 degrees to become 30, the right angle must increase by 17 degrees to compensate. The sun's ray hits at an offset of 17 degrees from normal on the vertical axis. From the argument above we know that the effective vertical dimension of the array varies as the cosine of the offset. The vertical dimension becomes COS (17) or .96m.

We now have a theoretical method for calculating the -3.0 dB (half) power point on one axis of the array. By definition, a change in power of 3.0 dB varies the power by a factor of two. Minus 3 dB is therefore the half power point. What offset from normal on the surface of the array will theoretically drop the aperture available for harvesting energy by a factor of two?

One of our assumptions made in the paper cited above is that the maximum number of photons intercepted by the array on an axis occurs when that axis is normal to the sun's rays. As we see above when the photons strike the array axis at some angle other than Normal the virtual size of the array's collector decreases as the COSINE of the offset angle from Normal. What COSINE angle value gives us half power? COS (60 degrees) equals .5. Therefore in theory, when the sun's offset is 60 degrees from Normal the power generated on that axis is reduced by 50% or half power. This offset angle is the half power point for that axis.

For the purposes of this paper we are going to treat both the vertical and horizontal axes identically in this regard. To calculate the total aperture of the array we can multiply together the effective aperture on both axes since the surface of the array is two dimensional, that is, can only be resolved into vertical and horizontal components. Unlike some radio antennae designs which are axis asymmetric, solar array offset angles on either axis are treated the same because they are the same. We can therefore take a set of measurements of the power generation characteristics on one plane and generalize it to the characteristics of the other without taking any further data.

Method

Our data collection followed very specific procedures in order to ensure that the data collected was unaffected by elements that are not part of the measurement process. The user of solar arrays can only control the number of panels, their total power generation capacity and their angle to the sun. Other effects like: dust, pollution, sun conditions, length of day, weather, haze, and clouds are beyond the user's control.

In anticipation of the data run, the array's pre-programmed angles were verified by an angle meter just weeks before the data run.

We waited several weeks for the proper conditions in order to take our data. We wanted pristine sun with no cloud or haze. The sun had to exhibit a short term power stability of about plus or minus .5%. That is, for a reading of 1000 watts on our MX-60 solar charge controller the variation in the sun's power could not vary by about 5 watts either side of 1000. We needed the high quality sun in the morning preferably before noon because we were looking at angles on the order of 60 degrees or more offset from normal. This would require that the sun be below 30 degrees in altitude.

Winter time here is really the only time that good, stable sun is off the horizon by at least 10 degrees, to clear out any atmospheric and Fresnel effects that may occur, and be settled, powerful enough to get good data and the sky clear, free from haze and smog.

Each reading was taken after watching the solar charge controller working under MPPT (Maximum Power Point Tracking) for 5 seconds and taking the average. Since the sun's short term power did not vary by much, each data point was easily computed.

The method consisted of the following for each set of data.

- The sun time was noted.
- The power levels at each angle from +70 to 0 degrees inclusive in 10 degree intervals was taken for a total of eight data points per run.

We executed 3 data runs for a total of 24 points of data.

Each data run took less than three minutes to complete due to the programmed nature of the array aiming technology. Basically, the experimenter keys in the angle and the array moves to that angle within seconds.

Data

The goal of the project is to determine how closely the predicted characteristics of the array aperture correspond with its actual characteristics. With any kind of luck, we thought we would be able to calculate the –3.0 dB power points on one axis of the aperture and thereby describe its receiving characteristics solely in terms of a radio antenna aperture.

We were not prepared for the virtual match between the predicted data and the actual data. Our model for analysis turns out to be very powerful.

In our paper, "*The Ravina Project – Solar Theory and Practice 14*" we describe a theoretical model to evaluate the efficiency of a solar array when the sun is shining upon it at various angles throughout the day. We developed a dimensionless factor, the aperture-hour, that allowed us in theory to analyze the power generation capability of an array. There are no actual Watt-hour predictions because the aperture-hour analysis only predicts a drop off from maximum power as the sun's angle on the array changes on both axes as the day progresses. Since the maximum power generated by the array occurs when the sun is at Normal angle on both axes the best the array could do in an hour would be one (1) aperture-hour.

Given the comparative and theoretical nature of the analysis, taking data to try to anchor the theoretical analysis to actual Watts generated was the next step.

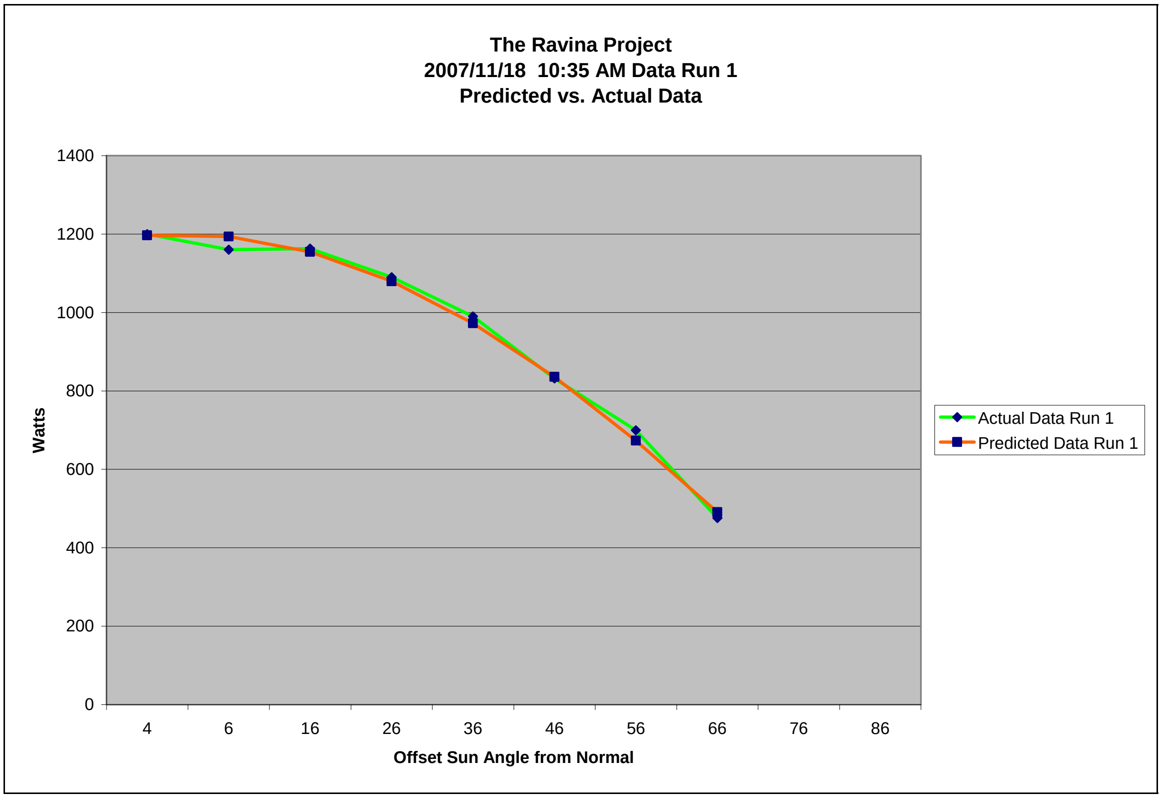
We used the data in the following way. Since the aperture-hour analysis predicted the fall off we plugged in the maximum sustained power in Watts generated by the array when the vertical axis was near normal. We then applied the fall off from our theoretical calculations to each of the 10 degree marginal offsets the array assumed during the data run. We then compared the predicted data to the actual data recorded for each data point / array angle.

Our array and its associated equipment at The Ravina Project has a power generating dynamic range of about 17.3 dB, (25 to 1300 Watts sustained power) and about 18.5 dB when the power peak (for this year) of 1787 Watts is used for the dB calculation. It has more than enough sensitivity to be used as an instrument in this investigation because the power Delta we are trying to measure maxes out at only 5 dB.

Data Run 1

Consider the graph below. As the array tilted in 10 degree increments, the sun's offset angle changed on the vertical axis of the array. As the angle offset increased, the power generated by the array changed. The change is plotted below. The theoretical calculations used the maximum power generated by the array for calibration purposes. The theoretical calculations do not specify how much power an array can generate. They only specify what happens to that power when the offset diverges from normal. The theoretical calculations focus on the size of aperture available to collect the sun's signal not the size of the collecting surface.

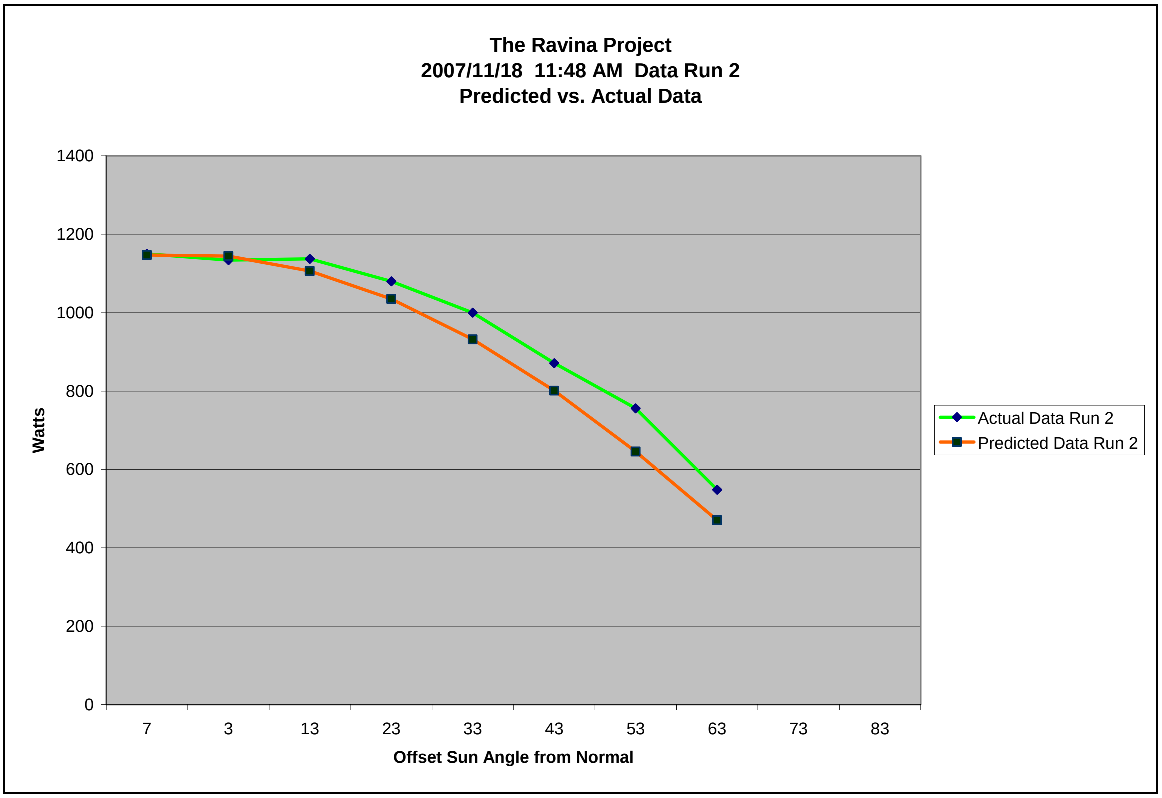
As can be seen, the calculated data based upon the maximum power generated when the sun was virtually at normal for the array on the vertical axis, started at about 1200 watts.



Sun power changes as a result of azimuth changes are not involved. The measurements were taken in such a short period of time that sun movement on the azimuth is minimal. This data reflects only power changes that are the result of changes in the angle of the sun upon the collecting surface.

Data Run 2

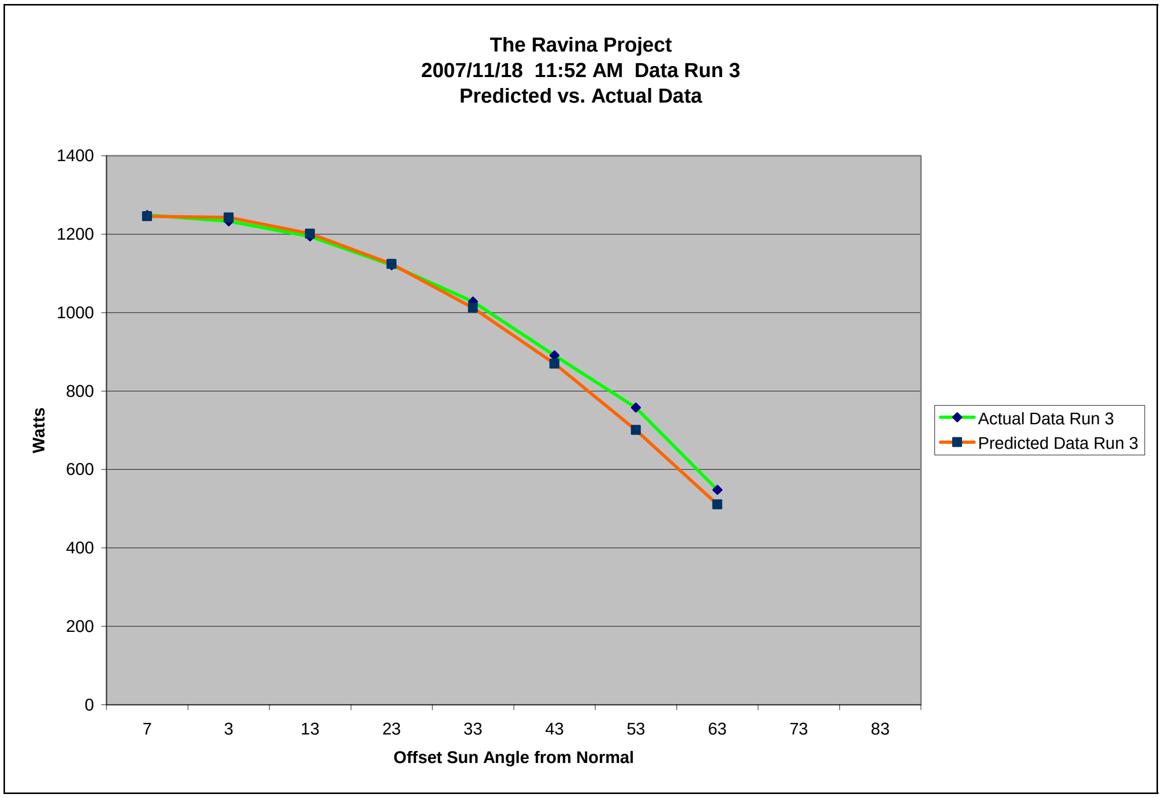
The second data run took place a little more than an hour after the first. The maximum power recorded at that time calibrated the theoretical prediction of power roll off. Again we see that the – 3.0 dB power point seems to be in the area of 60 degrees of offset on the array's vertical axis.



Data Run 3

Data run 3 occurred just a few minutes after the second data run. Clouds were gathering and were soon to overwhelm the experiment but the sun's power was still surprisingly steady. We gathered data at that time rather than putting it off.

The calibration procedure followed the same method. The predicted roll off seems to agree with the real data. The minus 3.0 dB power point on the vertical axis occurs in the area of about 60 degrees.



Offset Angle to the Sun vs Power

Array Angle From Horizontal	Data run 1 in Watts	Data run 2 in Watts	Data run 3 in Watts	Data run 1 Angle Offset from Normal	Data Run 2/3 Angle Offset from Normal
70	1200	1150	1249	4	7
60	1160	1134	1233	6	3
50	1163	1137	1194	16	13
40	1090	1080	1121	26	23
30	990	1000	1028	36	33
20	832	871	891	46	43
10	700	756	758	56	53
0	476	548	548	66	63

Predicted Vertical Aperture Size from Unity	Power Roll Off in dB Run 1	Power Roll Off in dB Run 2	Power Roll Off in dB Run 3
0.997390625	0.00	0.00	0.00
0.994774337	-0.15	-0.06	-0.06
0.961932335	-0.14	-0.05	-0.20
0.899862505	-0.42	-0.27	-0.47
0.810450808	-0.84	-0.61	-0.85
0.696413974	-1.59	-1.21	-1.47
0.561216953	-2.34	-1.82	-2.17
0.408967639	-4.02	-3.22	-3.58

Predicted Power Gen Data Run 1	Predicted Power Gen Data Run 2	Predicted Power Gen Data Run 3
1197	1147	1246
1194	1144	1242
1154	1106	1201
1080	1035	1124
973	932	1012
836	801	870
673	645	701
491	470	511

Correlation	0.9973521	0.9950077	0.999096

11/18/2007		**Sun Alt**
Time 1	**10:35**	**24.14**
Time 2	**11:48**	**27.02**
Time 3	**11:52**	**27.05**

lat 43.68 N
long 79.34 W

MPPT on.
5 second reading
5 readings

Daily Maximum Power Flapp

Date: 2007/11/18

REV: 02 2007/08/13

Start Time / End Time	A0	A1	A2	B2	A3	A4	B4	A5	B5	A6	A7
10:21 / 10:27	454 / 460										1162 / 1194
10:35	476	700	832		990	1090		1163		1160	1200
11:40	607										1312
11:48	548	756	871		1000	1080		1137		1134	1150
11:52	548	758	841		1028	1121		1194		1233	1249
14:12		160	196		213	213		246		252	230 / 196

Analysis

Note that the time is expressed in Eastern Standard Time calibrated to WWV.

The actual data strongly suggests that the single axis -3.0 dB power points are 120 degrees apart. This would imply that the 2-axis half power point would be in the range of 45 degrees offset on both axes or 90 degrees apart. The data above expressed on the decibel (dB) scale shows -1.59 dB when the array has a sun offset of 46 degrees. If we calculate the array aperture based upon the offset of 46 degrees on both axes, the total power generation capacity for the array is -1.59 plus -1.59 dB or -3.18 dB. This stands to reason. Each axis is down by so many dB. Simple addition calculates the total roll off amount for the array.

Similarly, in data run two the roll off reaches 1.21 dB when the array has a sun offset of 43 degrees. The roll off for the array as a whole if the offset is 43 degrees on both axes is 2.42 dB.

And finally in data run three the roll off reaches 1.47 dB when the sun has an offset on the axis of 43 degrees. If both axes have the same offset then the power generated will be down a total of 2.94 dB.

In theory and for the array as a whole the .500 aperture power lobe is bounded by an offset of the following form:

Array aperture equals COSINE(offset vertical) times COSINE(offset horizontal) equals .500.

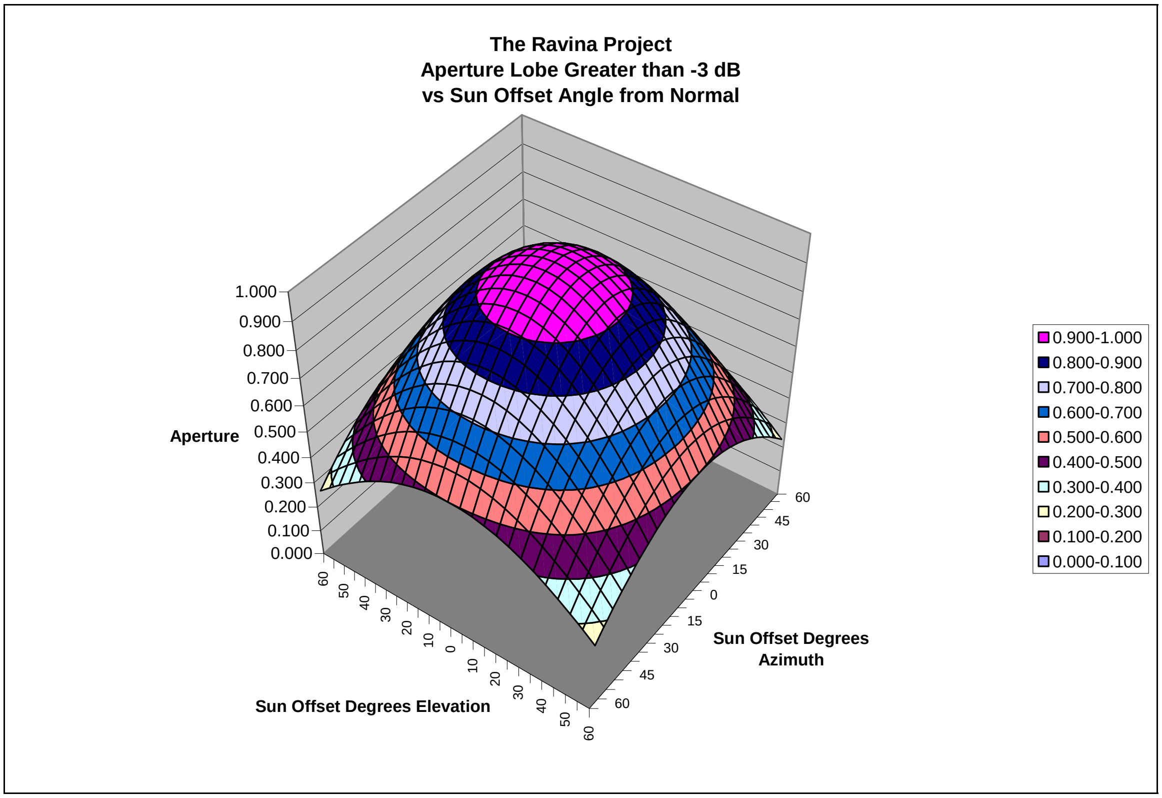
However, the more profound outcome of this exercise is that the theoretical data predictions and the actual data correspond very, very closely. Correlation coefficients of .99 are the norm for these data. It is possible now to use this theoretical model to predict the behaviour of solar arrays.

The main receiving lobe of the array is huge on both axes. From the data the 98% power lobe is bounded by an offset of plus or minus 8 degrees on both axes from Normal. If the offset is relaxed to plus or minus 10 degrees from Normal the resulting lobe contains 96% of the power.

This analysis suggests that the sun could move up to square root (800) or 28.3 degrees in the sky and still be inside the 96% power lobe.

These data should have a huge impact upon the future of dynamic array design.

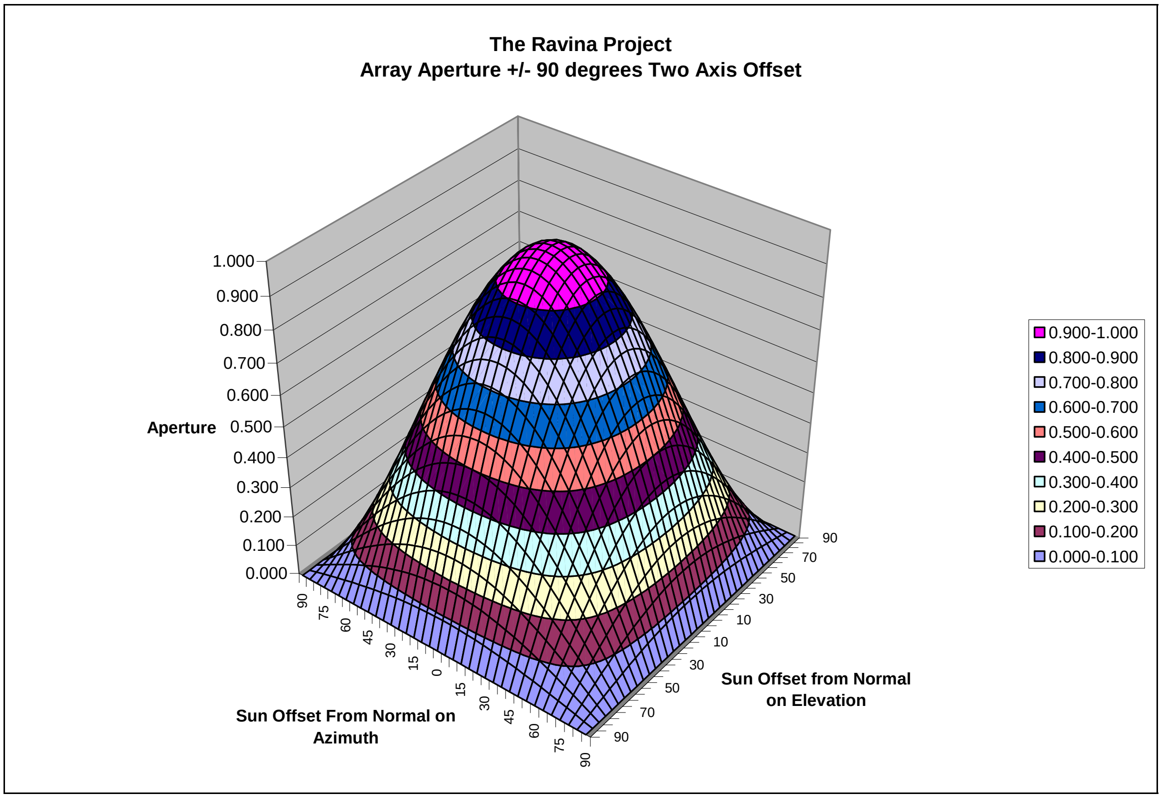
Here is a graphic depicting the -3 dB power lobe for the whole array.



Each plotted point on this graph represents the aperture available given the offset values on two axes. In theory the array's power is down 3.0 dB when the sun on both axes has an offset from normal of 45 degrees. The power reduction of a per axis offset of about 45 degrees averages 1.42 dB taken from the data above. For the array, including both axes offset at 45 degrees, the total roll off in dB will be 1.42 plus 1.42 (one roll off per axis) for a total of 2.84 dB. This average value is .16 dB away from the theoretical prediction of a roll off of 3 dB and can be accounted for by the approximation of our angle measurements taken during the experimental test run, slight modifications in the sun's intensity from changes in the atmosphere and air quality. One run had one data point at 46 degrees offset and the other two had points taken at 43 degrees offset. In any case our theoretical predictions for the array's main power lobe are very close to the actual data recorded. We believe that the data is so close to the theoretical predictions that we can, with a degree of confidence, use our theoretical model to evaluate the performance of many kinds of arrays. We will explore that theme in upcoming papers.

If the array surface was reduced to a point, from the point of view of the array, how big a rectangle one meter away from the array center point would represent a +/- 45 degree two axis offset? The rectangle would be 2 meters square. In order to guarantee that the array aperture stays above -3.0 dB or .500 aperture, the sun's rays must pass through the surface of the square and hit the point sized array. This gives one a good understanding of how far from normal the sun's rays have to be in order for the aperture to drop below .500. If I was laying on my back looking up at the sky with a 4 square meter sheet one meter away above my head, there would be little I could see except for sky on the horizons.

Consider the following graphic.

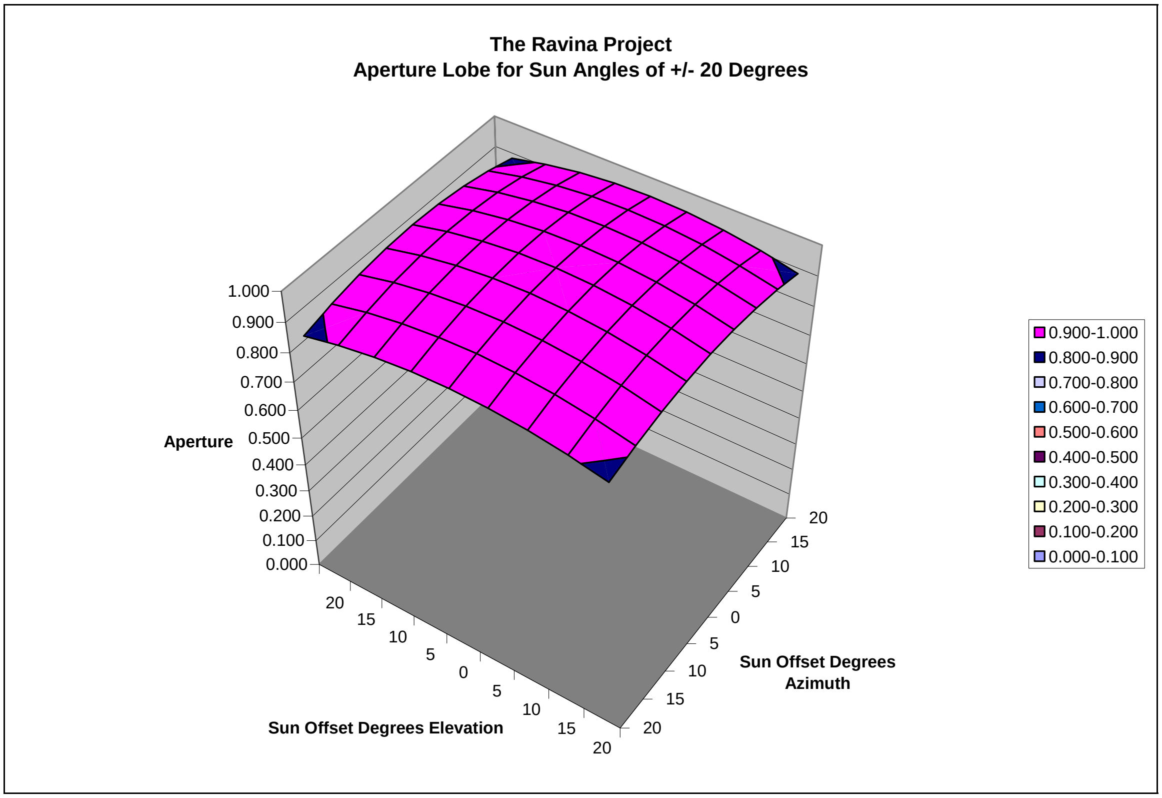


This graph represents the power receiving lobe of our array constructed according to our model of array evaluation.

In order to construct this graphic we took the array offset on both axes and ran their values through 180 degrees. More precisely, we ran them both through +/- 90 degrees in 5 degree increments. This is a graph of the two axis power generation roll off when the sun hits the array at some offset angle other than normal. For each two dimensional point across both axes there exists a usable aperture available for power generation. As the sun's dual axis offset changes the aperture changes.

When we first saw this graph we noticed how closely this resembled an analog RF filter roll off diagram showing the Q of the filter. Since the paradigm for our model is right out of RF antenna design, it stands to reason that the shape, if our hypothesis is correct, resembles the rejection skirts of the filter. Actually, it would only look this way if the array operated like a directional radio antenna. For those who are not familiar with radio antennae, directional antennae are designed as much for their ability to reject signals that are offset from their apertures as their ability to amplify signals that have little aperture offset. They operate as an RF filter both in the physical way as described above but in the frequency domain as well. That is, they reject bands of radio signals that lie external to their resonant frequencies. Here in this diagram we see the decrease in aperture available or an increase in signal rejection, like any filter, as the sun moves offset from a two axis Normal.

Consider the following graphic.



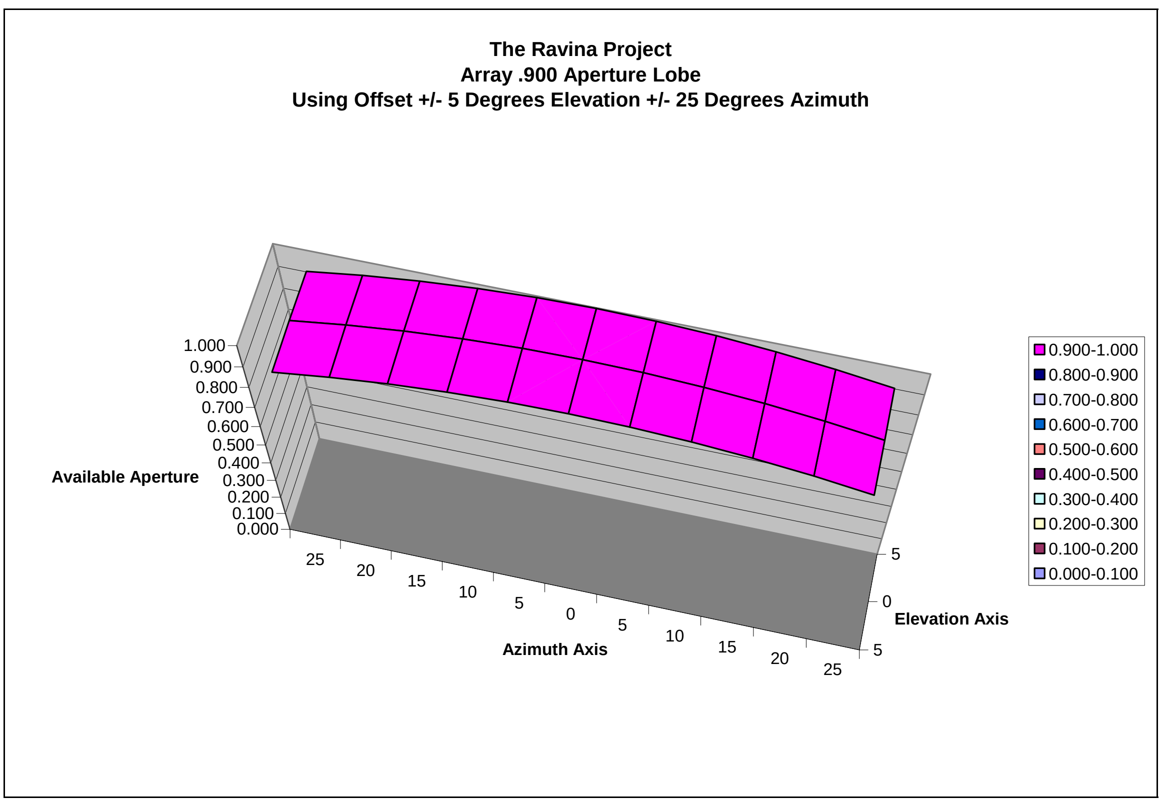
This graphic shows the two axis offset of +/- 20 degrees from Normal. The aperture is at least .900 for the vast majority of the offset angles. This is a large rectangle in the sky for the sun to be inside of all day long. The sun can move square root (3200) or 56 degrees across the sky and still be within the .900 aperture for the overwhelming majority of that trip.

If the array surface were reduced to a point, from the point of view from the center point of the array, the rectangle would be square with about 72.8 cm on a side. For the aperture to stay above .900 the sun's rays would have to pass through the surface of the square and hit the point sized array. One meter away from a rectangle that covers 5,299.8 square centimeters is a big patch of sky.

Consider the following data.

		Horizontal Sun Angle Offset on Array										
V	**Degrees**	**25**	**20**	**15**	**10**	**5**	**0**	**5**	**10**	**15**	**20**	**25**
E	**Offset**											
R	**30**	0.785	0.814	0.837	0.853	0.863	0.866	0.863	0.853	0.837	0.814	0.785
T	**25**	0.821	0.852	0.875	0.893	**0.903**	**0.906**	**0.903**	0.893	0.875	0.852	0.821
I	**20**	0.852	0.883	**0.908**	**0.925**	**0.936**	**0.940**	**0.936**	**0.925**	**0.908**	0.883	0.852
C	**15**	0.875	**0.908**	**0.933**	**0.951**	**0.962**	**0.966**	**0.962**	**0.951**	**0.933**	**0.908**	0.875
A	**10**	0.893	**0.925**	**0.951**	**0.970**	**0.981**	**0.985**	**0.981**	**0.970**	**0.951**	**0.925**	0.893
L	**5**	**0.903**	**0.936**	**0.962**	**0.981**	**0.992**	**0.996**	**0.992**	**0.981**	**0.962**	**0.936**	**0.903**
	0	**0.906**	**0.940**	**0.966**	**0.985**	**0.996**	**1.000**	**0.996**	**0.985**	**0.966**	**0.940**	**0.906**
O	**5**	**0.903**	**0.936**	**0.962**	**0.981**	**0.992**	**0.996**	**0.992**	**0.981**	**0.962**	**0.936**	**0.903**
F	**10**	0.893	**0.925**	**0.951**	**0.970**	**0.981**	**0.985**	**0.981**	**0.970**	**0.951**	**0.925**	0.893
F	**15**	0.875	**0.908**	**0.933**	**0.951**	**0.962**	**0.966**	**0.962**	**0.951**	**0.933**	**0.908**	0.875
S	**20**	0.852	0.883	**0.908**	**0.925**	**0.936**	**0.940**	**0.936**	**0.925**	**0.908**	0.883	0.852
E	**25**	0.821	0.852	0.875	0.893	**0.903**	**0.906**	**0.903**	0.893	0.875	0.852	0.821
T	**30**	0.785	0.814	0.837	0.853	0.863	0.866	0.863	0.853	0.837	0.814	0.785

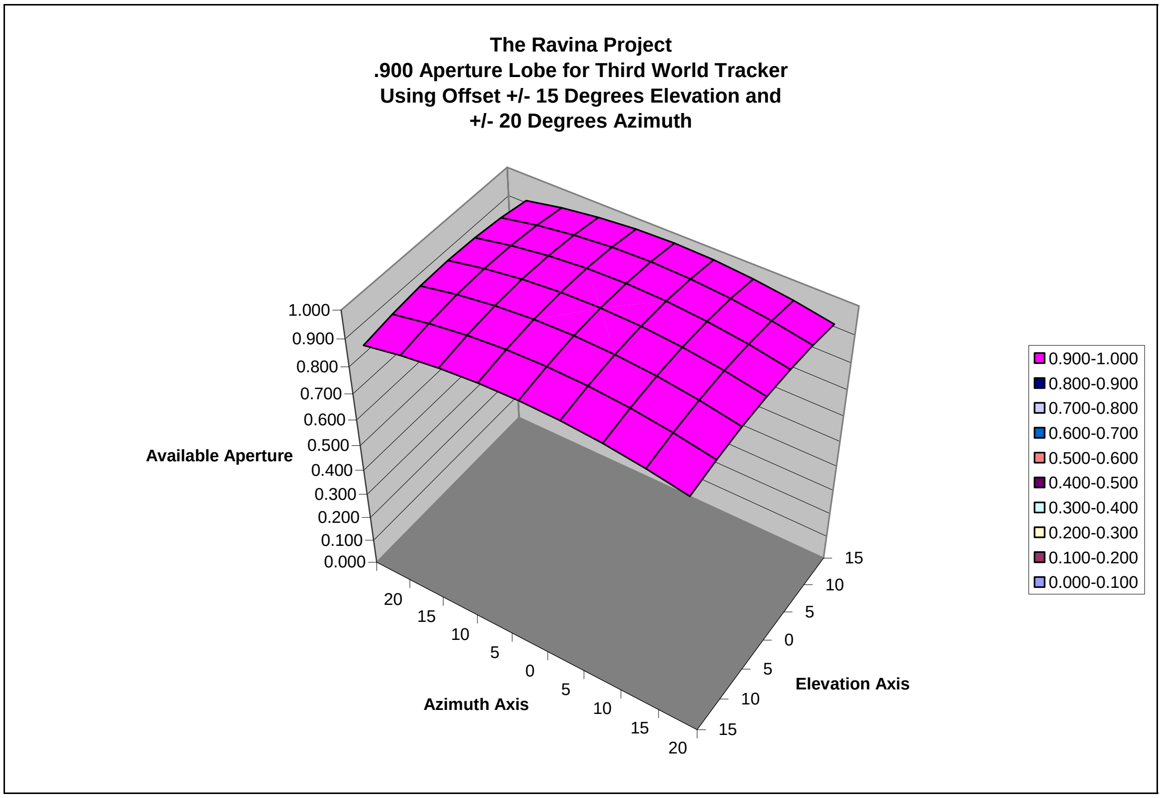
The data shown here represent the aperture available on both axes in terms of a roll off from the best signal strength which is unity (1). If any two offset values are used, one on the vertical axis and one on the horizontal axis, and if they both point to an aperture value that is listed in red, the array will be within the .900 aperture. From the sheet of values above the horizontal offset values can be set at +/- 25 degrees. However, if we examine the red values for the corresponding vertical offset we are limited to +/- 5 degrees.



If the array surface were reduced to a point, a rectangle one meter away would have 17.5 cm on one axis and 93.3 cm on the other. This patch in the sky would have a surface area of about 1,632.8 square cm.

If we relax our horizontal range from +/- 25 degrees to +/- 20 degrees we get a huge bonus on the elevation. Our window on the elevation increases from +/- 5 degrees to +/- 15 degrees.

Consider the following graphic.

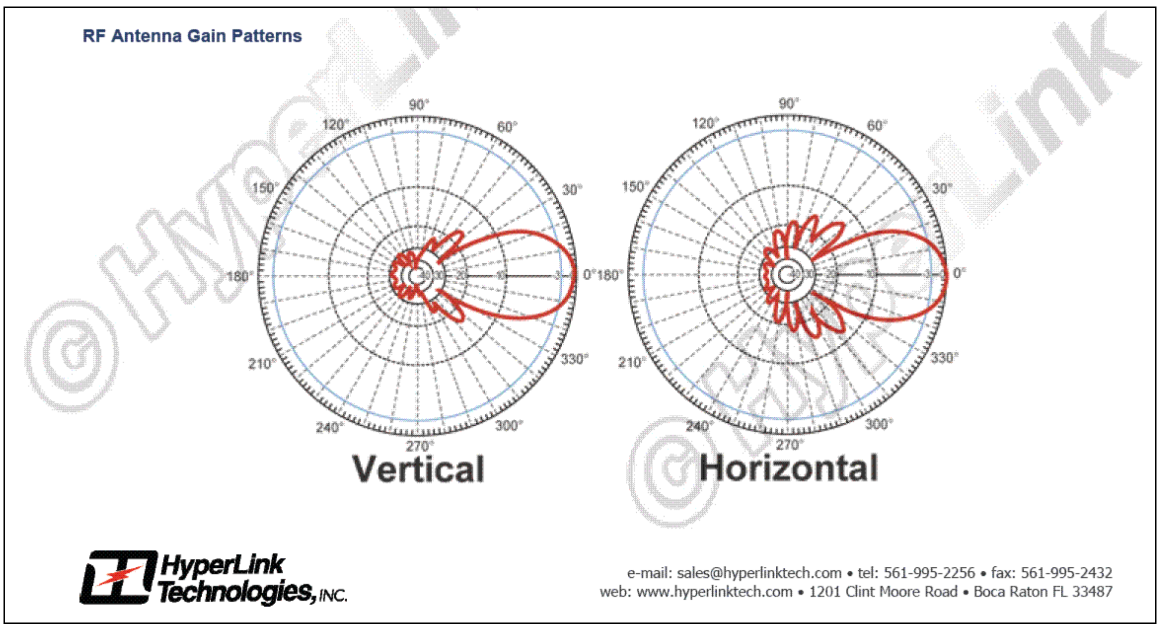


The rectangle in the sky increases in square cm area from 1,632.8 (17.5 cm by 93.3 cm) to 4,438 (72.8 cm by 53.6 cm).

The Solar Array as a Radio Antenna

With all the analysis above we now have the data to view the performance of the solar array using graphs that are used to evaluate the performance of radio antennae. In the radio paradigm it is important to know when aiming the antenna the maximum offset angle permitted before the received power drops to half or minus 3.0 dB. The calculation is done for each antenna axis … vertical and horizontal. The minus 3.0 dB power point is associated with some offset angle from Normal for each antenna. Since the angle can be calculated as Normal plus and minus an offset angle, the result is a range of angles over which the antenna has a power greater or equal to -3.0 dB. Let's say that an antenna has a receiving characteristic such that when the received signal moves to a one axis offset of 30 degrees from Normal the power of the received signal is reduced to half or -3.0 dB. On the axis there is an angular distance between Normal plus and Normal minus of 30 degrees. The total distance is 60 degrees. This distance is called the -3.0 dB Beam Width of the antenna. Note that the receiving and transmitting characteristics of a radio antenna are identical. The beam width is identical for both functions.

Observe the following specification for a commercial 900 MHz Yagi antenna.



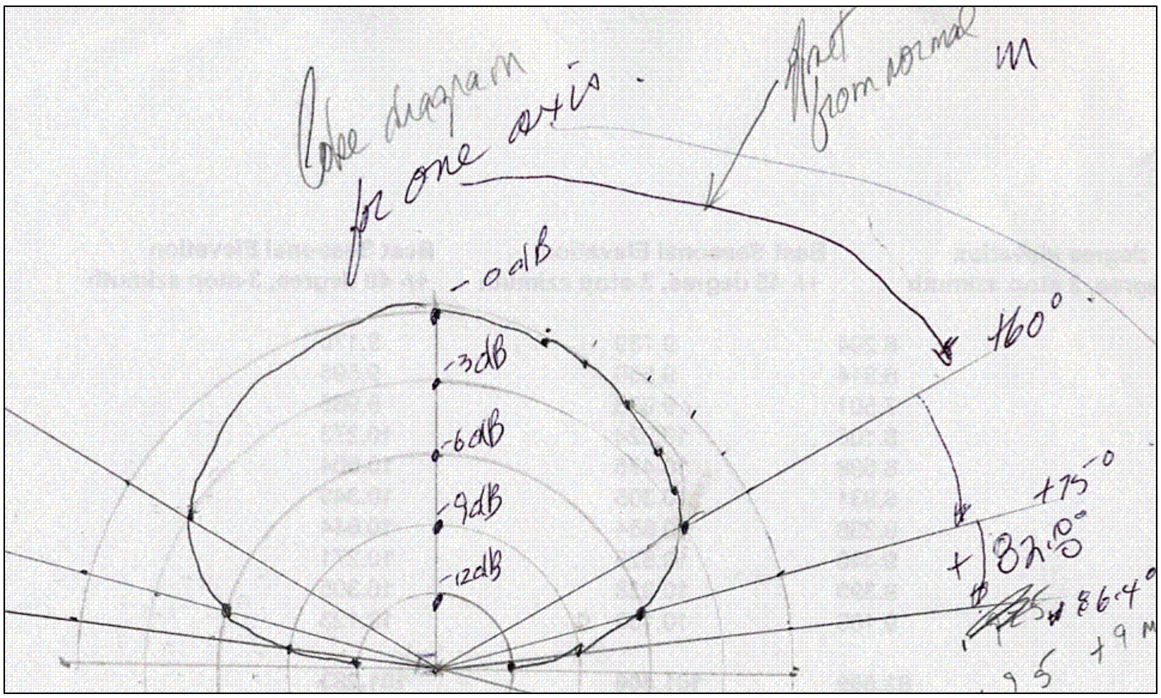
Notice the chart is polar. The length of the line between the centre of the circle and the red line at any point represents the power being received at that angle. The line is a vector describing power amount and the direction from which it is received. At zero degrees offset the power is at a maximum and as the received power offset angle increases the received power decreases. The inner circles are measured in decibels and are negative in value. The plotted power rolls off from 0.0 dB at Normal to some negative number as the received signal's offset angle increases. The blue line represents a 3.0 dB roll off which helps in finding the half power points. This antenna gain pattern indicates that the -3.0 dB beam width is about +/- 12 degrees offset from Normal on both the vertical and horizontal axes for this antenna. Nice symmetrical design …

Why two axes? Radio antennas must deal with both the electric and magnetic components of radio waves. These two components have power curves at right angles to each other … horizontal and vertical. The antenna exhibits different properties when evaluated magnetically or electrically. Hence there are typically two plots included in an antenna's specification. Solar arrays do not have these characteristics.

The aim here by using this diagram above is to show a typical beam width specification for a commercial antenna.

What we want to do is restate our findings above in a way that is compatible with a RF antenna beam width specification.

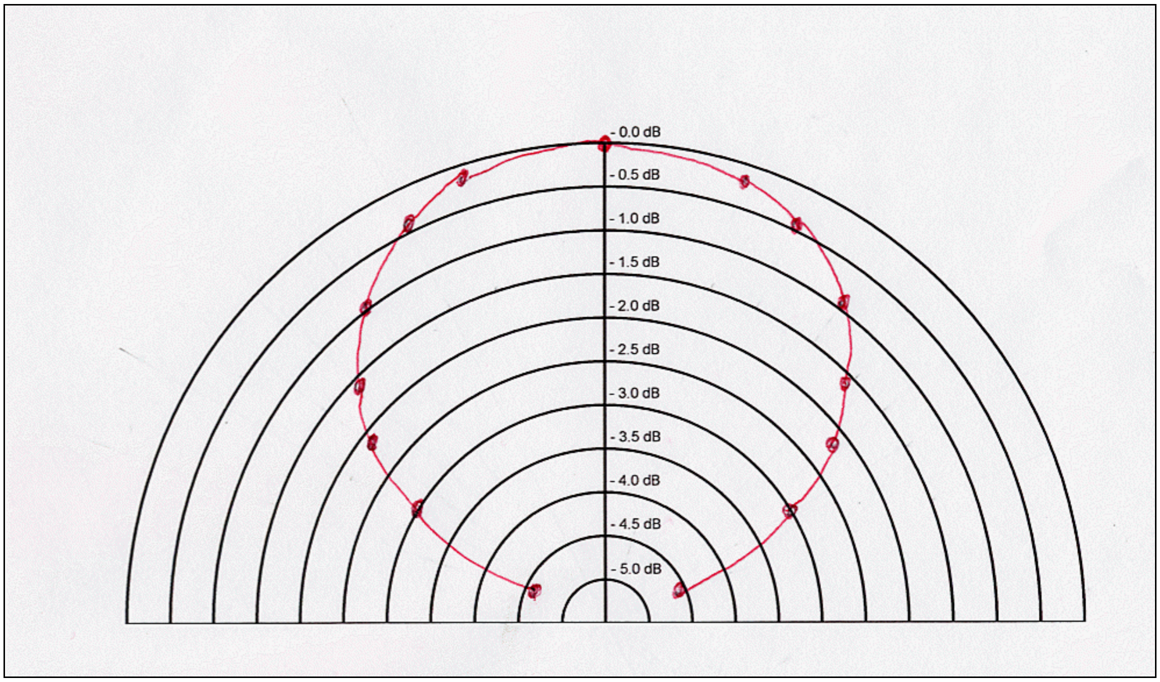
From our data we know that the per axis beam width specification for our solar array is plus or minus 60 degrees or 120 degrees. What does it look like?



The concentric circles are measured in 3.0 dB intervals. We can see that at an offset of 60 degrees the power has fallen by half or minus 3.0 dB. This is the power plot of our array of solar panels. From my point of view it sure looks like the plot of a radio antenna. Maybe this paradigm, that of treating the receiving characteristics of an array of solar panels as a radio antenna, is not too far from being right on.

A 120 degree -3.0 dB beam width is not uncommon among the types of antennae that talk directly to your computer.

Let's expand the diagram above and plot the changes in reception power within the half power beam width below. Consider the following diagram:



Solar Array Power Roll Off Pattern

Offset Degrees From Normal	Roll off in power	Roll off in decibels
0	1.00	0.00
18	0.95	-0.22
26	0.90	-0.46
37	0.80	-0.98
46	0.69	-1.58
53	0.60	-2.21
60	0.50	-3.01
70	0.34	-4.66

It looks like the -0.22 dB beam width is 36 degrees. This is a huge beam width on this axis. If the sun is within this beam width of plus or minus 18 degrees the array will receive 95% of the sun's available power on this axis. If the second axis is considered and they both are kept within their respective 36 degree windows for the day the worst the array can do is lose about 0.45 dB of the sun's power throughout the day due to bad sun angles upon the collecting surface. The reason of course is that if the sun offset angle on both axes is kept at 18 degrees all day long, each axis will lose 0.22 dB of the sun's power. Adding these power losses together, one for each axis, results in the array as a whole losing about 0.45 dB of the sun's power.

Since the array exhibits all the plotted characteristics of a directional antenna, a design that moves the array to maximize the received signal from the sun is possible. Accuracy in sun tracking technology is proportional to its cost and complexity. Tracking the sun to one degree of accuracy requires automated electronics and actuator technologies working on both axes. These types of technologies are expensive and because they are electro-mechanical in nature they are subject to environmentally caused breakdown, and of top of that, they have a mean time between failure (MTBF) like all other electro-mechanical devices. The analysis above suggests that one can relax the tracking requirements from two degrees (+/- 1 degree) on each axis to 36 degrees (+/- 18 degrees) on each axis and only give away 0.45 dB in power collection ability over the course of a day.

We at The Ravina Project view the design implied by our analysis as, “Good Enough”. “Good Enough” design philosophy gives away a little in performance but makes up for it by greatly increasing the performance of some other characteristic.

In this case the relaxed constraints on tracking allow: for simplified designs that may in fact be implemented using manpower to move the array and, in addition, for lowering costs by dramatically reducing the cost to build and operate such a structure.

Note that if the sun’s altitude in the sky is at 65 degrees and the collecting array is horizontal, it is collecting the sun’s energy at a rate of over 90% or it is losing only about 0.45 dB of the sun’s power, worst case.

If one axis can be kept within 15 degrees of Normal, the other can expand to 20 degrees offset from Normal and still be within the 0.45 dB loss constraint (-0.42 dB). The rectangle in which the sun must be kept can be 30 degrees (+/- 15 degrees from Normal, -0.15 dB maximum) on one side and 40 degrees (+/- 20 degrees from Normal, -0.27 dB maximum) on the other.

Since the power from the sun is minimal less than 5 degrees from the horizon and since the sun’s power is within -0.45 dB when it is at 65 degrees of altitude, the angular distance to be covered by a tracking array on its vertical axis anywhere on the surface of the earth is 60 degrees. This suggests that the 30 degree side of the rectangle should in a design, be devoted to array elevation. **Position one** will be at **70** degrees of elevation covering the sun from sun rise to an altitude of 35 degrees in the sky. **Position two** at **40** degrees will cover the sun’s motion from 35 degrees until it reaches 65 degrees. **Position three** would be **flat**. At that point the array becomes horizontal and does not have to be moved until the sun retreats from 65 degrees altitude in the sky. The setting on the azimuth when flat is irrelevant.

We cover the sky, from 5 degrees to the Zenith with 3 positions on the vertical axis.

The other side of the rectangle is 40 degrees in length. Using the same design logic as the discussion above regarding aiming constraints and the sun’s altitude in the sky, we can construct an aiming program, if you like, to ameliorate the power moderation due to the sun’s movement on its azimuth. Nine movements then are required to cover sun azimuths between 0 and 360 degrees and keep the power roll off on this axis within minus 0.27 dB. The positions could be as follows: **20, 60, 100, 140, 180, 220**, **260, 300, and 340** degrees. These azimuth positions are not exact. Only the angular distance between positions must be exact. The actual orientation could be site dependent.

This regimen of movement seems to be simple enough to be designed into a manual tracking system.

We are not mechanical Engineers. We hope that people will read this paper and design accordingly.

Conclusions

We had a clue that the receiving lobes of a solar array were rather broad before we took this data. We had been watching and logging the angles of the sun and the hour by hour power as registered on our Outback MX-60 ™ solar charge controller for more than a year. We did not know what to make of it at the time but now we do. The power lobes are huge!

We believe that a low tech powered sun tracker design is possible using generated power to make the small number of movements each day. The sun angles could be reduced to a lookup table which would be valid for decades. A high current DC interface would drive the motors moving the array surface on two axes with feedback signals from the joints indicating their angles. The controller is a black box with an accurate clock and externally programmable for its latitude, longitude, elevation, date and time of day. The trick in this simple design would be to make it ‘bullet proof’ for all kinds of climate conditions and for the operators who have an assumed educational/training level.

Furthermore, an even lower tech solution is possible if manpower is used to change the array angles during the day. We envision a table driven chart that will allow Third World workers to change the angle of the array just by knowing the local date and time. They can set their *Timexes* ™ by listening to WWV or to some other time standard on the radio. Since manpower is in excess in the Third World, a manually operated tracker can be conceived and built from local materials. This would be perfect for a community owned and operated power station.

There have been quite significant advances in lighting technology. Soon we will have lighting that will make today’s florescent illuminated low power light bubs, power hogs for the same amount of illumination.

We are on the verge of a revolution in solar efficiency. Whether that revolution comes from MEG technology or other nanotechnologies yet unknown, is yet to be seen. However, and this is the important thing, power, literally thrown away because of poor sun angles, will be in great demand. A fixed array generating 8 aperture-hours a day is one thing. A simple, “Good Enough” tracker generating half again more is quite another. When we in the future get 5000 watts from 12 square meters of array surface that extra 50% becomes a huge amount of power over the course of a year.

We envision a table driven manual tracker set up with colour codes on the tracker. The operator turns the array each day using the tables and time of day. A 2000 watt collector would be enough to electrify several buildings in a village and make many modern technologies available.

In the rural Third World, electrical power is a luxury if it is available at all. We hope it changes.

We at The Ravina Project see as one of the major projects of the 21st century the electrification of the rural Third World if for no other reason that to bring these people into the world community with all the benefits that would fall out of that effort for everyone. However, with rising commodity prices and the cost of wiring, using traditional methods of wired infrastructure are prohibitively expensive. For instance, using tens of thousands of pounds of metal wiring strung through impenetrable terrain, vegetation or both to bring power to small villages is tough to do on many fronts. High material costs mean such transmission lines would be stolen at the first opportunity.

We envision a cheaper and easier solution. We propose creating islands of power using new technologies of power collection / storage and ultra low powered illumination that are being developed now and that can be deployed over the next 5 to 10 years. Once a supply of reliable electrical power is available to a community, huge changes can begin on many fronts too numerous to mention.

This local island electrical infrastructure would accomplish at least two things. It would permit local people to: own, operate, secure and make a living wage from the operation. Secondly, the localized infrastructure would allow the surrounding area to join the rest of their country and the world through use of modern technologies.

"If we knew what we were doing, it would not be called research."
- A. Einstein

Project Directors

Susan Laffier B.SW., M.SW.
Gordon Fraser B.A., MCSE, CCDP

The Ravina Project,
Toronto, Ontario,
Canada M4J3L9

gord@theravinaproject.org

Friends of The Ravina Project

Ben Rodgers B.A., M.A.,
NABCEP Certified Solar PV Installer™
Designer of the Dynamic Array structure

Prof. Fraser Bleasdale Ph.D.
Department of Psychology
Otonabee College
Trent University

