Mirrors in Space for Low-Cost Terrestrial Solar Electric Power at Night

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***ABSTRACT* — A constellation of 18 mirror satellites is proposed in a polar sun synchronous dawn to dusk orbit at an altitude of approximately 1000 km above the earth. Each mirror satellite contains a multitude of 2 axis tracking mirror segments that collectively direct a sun beam down at a target solar electric field site delivering a solar intensity to that terrestrial site equivalent to the normal daylight sun intensity extending the sunlight hours at that site at dawn and at dusk each day. Each mirror satellite in the constellation consists of a linear string of mirror elements and each terrestrial solar electric field site has a 10 km diameter and can produce approximately 5 GW per terrestrial site. Assuming that in 10 years, there will be approximately 40 terrestrial solar electric field sites evenly distributed in sunny locations near cities around the world, this system can produce more affordable solar electric power during the day and further into the morning and evening hours. The typical operating hours or power plant capacity factor for a terrestrial solar electric power site can thus be extended by about 30%. Assuming a launch cost of $400/kg as was assumed in a recent NASA Space Power Satellite study for future launch costs, the mirror constellation pay back time will be less than 1 year. A logical continuation of this space mirror satellite concept can potentially lead to solar electric power at a cost under 6 ¢ per kWh.**

***Index Terms* — photovoltaics, satellite, solar power system, space power.**

I. BACKGROUND

The idea of using mirrors in space to beam sunlight down to earth for terrestrial solar electric power generation is not new. Dr. Krafft Ehricke first proposed this idea in 1978 [1, 2] as shown in figure 1 under the title Power Soletta. Because of the simplicity of mirrors compared to the complexity of the Space Power Satellite concept, his idea was brilliant particularly for the time in which it was first proposed.

Specifically, Ehricke proposed a constellation of satellites in an orbit 4200 km in altitude beaming power down to a 1200 sq km site in Western Europe. Deflecting sunlight down to earth where it is then converted to electricity is conceptually much simpler than converting it to electricity in space and then microwave beaming it down to earth and then converting it to electricity as per the Solar Power Satellite concept.

The key physical limitation for this concept relates to the size of the sun's disc as viewed from earth. The sun's disc subtends an angle, φ, of 10 mrads. This means that the minimum size of a sun spot produced on the earth's surface from a mirror in space at an altitude, A, is:

$$2A \tan(\varphi/2) \qquad (1)$$

Applying this formula for a mirror in orbit at an altitude of 4200 km gives a sun spot diameter on earth of 42 km with a corresponding area of 1385 sq km. This explains the 1200 sq km solar field size for the Power Soletta concept. This also means that in order to produce an intensity of sunlight on earth equivalent to the normal daylight sun intensity, the area of the 3 mirrors shown beaming power down in figure 1 would have to be 1385 sq km and the area of the 10 mirror satellites in the constellation in figure 1 would have to be 4617 sq km. Unfortunately, the enormous task of placing this mirror area in orbit was somewhat discouraging in 1978.

In addition, there are two other problems with this concept as Ehricke proposed it. One problem is that this orbit falls in the Van Allen radiation belt. A second problem will reside with the size of the earth solar electric power field and the resulting problem of then distributing the power produced throughout Europe. Ehricke assumed that the 1200 sq km solar field would produce electricity at 15% efficiency implying a 180 GW central power station which then implies enormous distribution problems.

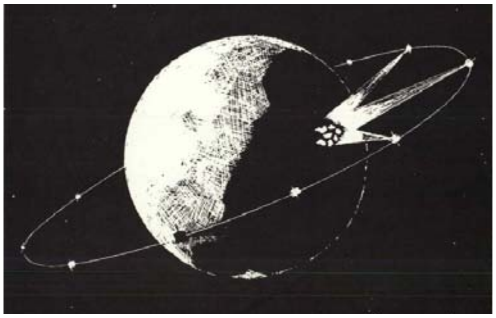


Fig. 1: Power Soletta proposed by Dr. Krafft Ehricke.

While this Power Soletta concept was intriguing, given the problems just described, NASA has focused much more attention over the subsequent years on the Space Power Satellite (SPS) concept [3, 4]. A recent version (2003) of this SPS concept is shown in figure 2. This Integrated Symmetrical Concentrator (ISC SPS) concept is of interest here because it also utilizes mirrors [3, 4]. As shown in figure 2, in this concept, two sets of 36 mirrors with each mirror approximately 0.5 km in diameter are used to beam sunlight to a central PV converter platform that then generates electricity and beams microwave energy to an earth generating station. This satellite is assumed to be located in Geosynchronous Orbit at an altitude of approximately 36,000 km. The special 8 km diameter earth receiver / generator station is assumed to generate 1.2 GW of electricity.

There are also problems with this ISC SPS concept. One problem is its complexity. More than just mirrors are now required and it now no longer uses a potentially existing terrestrial solar electric power station.

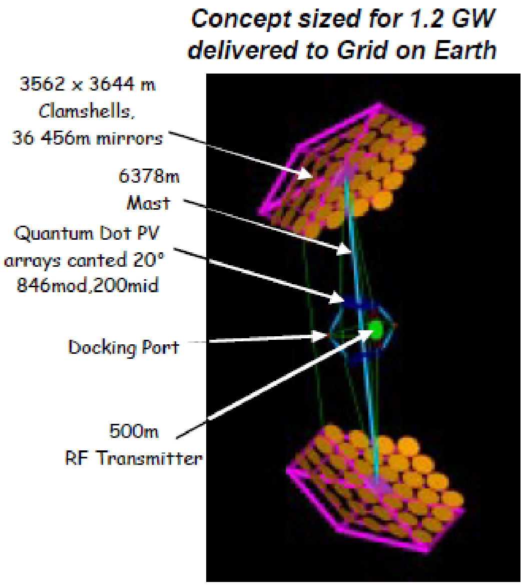


Fig. 2: Integrated Symmetrical Concentrator Solar Power Satellite by NASA. Dimensions: 5 km x 15 km.

Within the context of mirrors in space, one promising feature associated with the ISC SPS design is the assumed use of 0.5 km diameter mirrors (figure 2). There are also other recent developments related to mirrors in space. A Japanese Ikaros Solar Sail satellite is now en route to Venus and L'Garde and NASA [5] are now developing a 10,000 m^2 lightweight reflector (figure 3) for a Sunjammer solar sail flight scheduled for launch in 2014.

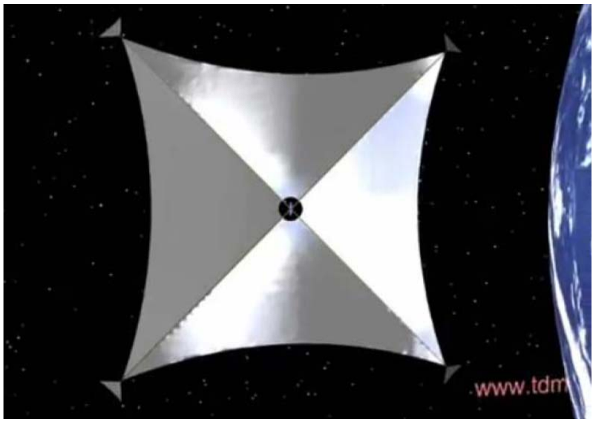


Fig. 3: L'Garde's 10,000 m^2 Sunjammer solar sail scheduled for launch in 2014 [5].

Another promising recent development is the large and growing use of solar cells in terrestrial fields to generate electricity. As of 2011, the total world wide solar electricity generation reached 65 GW and this is growing at a rate of 30% per year. At this rate, in 10 years, there should be 65 x $(1.3)^{10}$ = 900 GW of PV in fields world wide. Furthermore, 5 GW terrestrial electric power stations are now already being built [6].

One problem for solar generated electricity is that the solar energy available to a 1-axis tracking solar power station on earth on average is only about 7 kW hours per m^2 per day. With mirrors in space, sunlight can be potentially provided during night time hours. However, a challenge is to invent a method whereby mirrors are provided in space for night time solar electric power simply and affordably. Ehriche chose the mirror orbit at 4200 km because he wanted to provide solar electric power all night. Herein, we propose that a better orbit choice will be a dawn to dusk sun synchronous orbit. For this orbit while no one ground station will be available for 24 hours per day, the space mirrors will be available for 24 hours per day and as the world turns in 10 years from now, they will provide extra hours for an array of ground stations distributed around the world. This high mirror utilization will pay for the cost of the space mirrors especially as they are light weight and in LEO rather than in GEO orbit.

II. Concept: Mirrors In Dawn / Dusk LEO Sun Synchronous Orbit

Now imagine 18 mirror satellites in a sun synchronous orbit at an altitude of approximately 1000 km as shown in figure 4. There are several immediate benefits that result from this MiraSolar satellite constellation configuration.

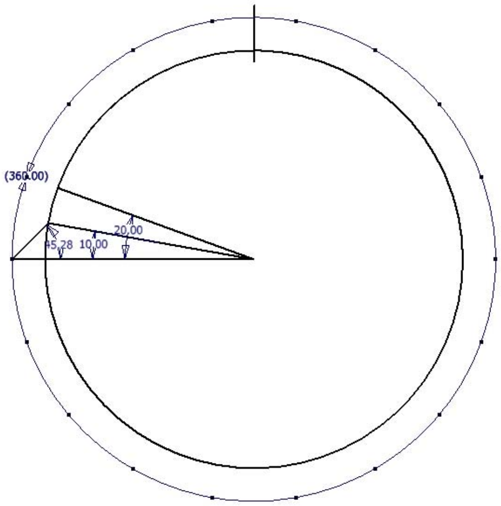


Fig. 4: An 18 mirror satellite constellation 1000 km high is in a dawn/dusk sun synchronous orbit around earth. North is up. The mirror satellites are evenly spaced in latitude at the equator by 20 degrees.

First, applying (1), the illuminated sunlight spot size on the earth is now only 10 km in diameter instead of the 42 km spot size associated with the Power Soletta configuration. Furthermore, the size of each mirror satellite now required to produce a solar intensity equivalent to daylight sunlight is now smaller as well. A 10 km mirror satellite would be comparable in size to the 5 km x 15 km ISC NASA SPS satellite size. As we will show in a later section, the size of this earth based electric power station is now approximately 5 GW instead of the Power Soletta sized 180 GW station.

In this paper, we shall assume this 18 satellite constellation will be available to an array of ground solar electric stations distributed around the world. As already noted, 10 years from now, there will be 900 GW of solar in the world. All of this will not be in central power fields but if we assume that 1/3 of the 900 GW is or could be, then there will be 300/5 = 60 available solar ground stations. These stations will be located in sunny parts of the world near population centers. Table I presents a partial list of potential sites. Here, we shall assume that over the course of 24 hours as the world turns, 40 of the potential 60 future sites depending on the weather for that day will be selected to receive additional sun beam energy in the early morning and early evening hours. Our goal is then to calculate the additional energy this collection of sites can produce and to compare that revenue stream with the potential mirror constellation cost in order to calculate a pay back time for this mirror constellation.

TABLE I
TENTATIVE SOLAR ELECTRIC POWER GROUND SITES

1.) LA, San Diego, S. Ca.
2.) Hawaii
3,) Albuquerque
4.) Phoenix
5.) Las Vegas
6.) El Paso
7.) Alaska
8.)Calgary
9.) Denver
10.) Kansas City, St. Louse
11.) Miami
12.) Boston, N.Y., N.J.
13.) Mexico City
14.) Panama
15.) Rio de Janeiro
16.) Brasilia
17.) Lima Peru
18.) Buenos Aires
19.) Madrid
20.) Rome
21.) Berlin
22.) Istanbul
23.) Moscow
24.) South Africa
25.) Saudi Arabia
26.) Bombay
27.) Calcutta
28.) Bangkok
29.) Manila
30.) Taiwan
31.) Sydney
32.) Tokyo
33.) Beijing
34.) Tibet Plateau
35.) Inner Mongolia
36.) Cairo
37.) Delhi
38.) Perth.

III. SLANT RANGE AND 1-SUN EQUIVALENT HOURS

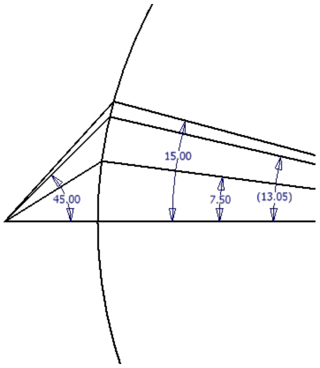
In addition to the sun's disc size which determines the satellite and earth station sizes as per (1), there is another important equation that relates the solar intensity at the ground site to the slant range to the satellite in view at the earth station. The sun beam intensity will decrease with the slant angle, θ, and slant range, R, as per (2).

$$I=I_o \cos(\theta)/R^2 \qquad (2)$$

Referring to figure 5, $\theta = 0$ and R = A when a mirror satellite is vertically over head.

This slant range equation is important for calculating the effective one-sun beam energy available per day to each ground site. One-sun beam energy will be calculated in kWh per m^2.

Figure 5: N is up here. The circle represents the earth's surface at a 35^o latitude. As the world turns, the target ground station moves up and the slant angle and slant range increase. 15^o represents 1 hour. When the slant angle is 45^o, the earth has turned 13^o or 60x13/15 = 52 minutes.



In order to estimate the available sun beam energy per day, we first look at the north-south (NS) dimension and then the EW dimension.

Figure 4 allows an examination of the sun beam energy in the NS time dimension. Figure 4 is a view looking in the direction of the sun with the earth's NS axis up and with the satellite sizes and altitude in real proportion relative to the earth's size. All 18 satellites are continuously circling the earth with a period of 105 minutes. So, at a given earth ground site, the time interval for one satellite overhead to be replaced by the next will be 5.8 minutes. When a satellite is directly overhead, by design, the power at the ground site will be 1-sun or 1 kW/m^2. However when a satellite is not overhead as for example with a view angle of 45^o, applying equation 2, the cosine loss will be 0.7 and the range loss will be down by a factor of 2. However, because there will be 2 satellites available for beaming power, this factor of 2 loss can be avoided. So, the power available at the ground site will continuously oscillate on a 5.8 minute period between 1 and 0.7 kW/m^2.

Next turning to the power variation at a ground site as the earth slowly turns. Figure 5 gives a representative case. Three different latitude slant ranges are shown in this figure. When a satellite is directly overhead, the power is again 1 kW/m^2. However, when the earth has turned 30 minutes (7.5^o), the slant range has increased to 1,230 km which means that the power at the site falls to 0.67 kW/m^2. Here, we shall assume that the solar ground stations, be they silicon PV or trough CSP, are using 1-axis EW tracking so that there is no cosine loss in the EW direction. One can continue this process of estimating power vs time out to 1 hour or 15^o. The average is approximately 0.7 kW/m^2 over the 1 hour period so that the sun beam energy is then 1 hour x 0.7 kW/m^2. Given that satellites are in view at a given ground site both before and after the peak times and both in the early morning and the early evening, the daily available sun beam energy is about 2 hours x 0.7 kW/m^2 per solar ground station.

IV. ECONOMICS

The primary reason why this MiraSolar concept is interesting is its very attractive economics. In table II, first the revenues are calculated and then the costs are calculated.

TABLE II
REVENUE AND COSTS PROJECTIONS FOR MIRASOLAR SATELLITE CONSTELLATIONS

Revenue - Assumptions

1.) 18 satellites in dawn/dusk orbit 1000 km above earth.
2.) The sun's disc diameter viewed from earth is 10 mrad. This implies solar spot size on earth from a mirror up 1000 km equal 1000xtan(10 mrad) = 10 km.
3.) Assume each mirror satellites has area = ground site.
4.) Solar intensity = 1.37 kW/sq m = 1.37 GW per sq km. If mirrors are at 45 degrees deflecting sunlight 90 degrees toward earth, the beam intensity directed at earth will be 0.95 GW/sq km. The area of each satellite is π x 25 sq km = 78.5 sq km. The energy in the sunlight beamed down toward earth = 75 GW. Assuming slant range losses, the average intensity on earth will be 0.7 GW/sq km.
5.) Assuming that an already installed PV array on earth uses 20% efficient modules and has a ground coverage ratio of 50% and occupies an area with a diameter of 10 km equal to the sun beam size, then that ground station will produce 0.7 GW/sq km x 0.1 x 78.5 sq km = 5.5 GW.
6.) Now assume that in the year 2022 there are 40 ground stations distributed around the world that the 18 satellite constellation will serve and that the constellation gives 1 hr x 0.7 kW/m^2 of sunlight to each station in the morning and 1 hr x 0.7 kW/m^2 to each station in the afternoon for a total of 2 hrs x 0.7 kW/m^2 of sunlight per day per station.
7.) Combined, the 40 earth stations will produce 5.5 x 40 = 220 GW. The total energy produced from the sun beamed satellite constellation = 220 GW x 2 x 365 hrs per year = 160,000 GWh /yr = 1.6 x 10^11 kWh/yr.
8.) Assume that the price for electricity is $0.1 / kWh, annual revenue $1.6x10^10 / yr = **$16 billion per yr**.

Mirror Satellite Mass – Inputs

1.) The mirror weight on the Ikaros solar sail (7.5 micron thick plastic) is 6g / sq m = 6 metric tons (MT) per sq km.
2.) The Echo I satellite used 12.5 micron mylar with 0.2 micron Al as a mirror weighing 10 MT per sq km [2].
3.) Mass of mirror element**,** L'Garde estimate [5]: Estimate for 250 m x 250 m solar sail of 10 g per m2. This translates to 10 MT per sq km.
4.) Assume goal 20 MT per sq km for each MiraSolar satellite. Then each weighs about 1600 MT or 6x10^6 kg.

Mirror Satellite Cost

1.) It all depends on launch cost for LEO orbit (Not GEO).
2.) The ISC SPS study [4] assumed $400 per kg.
3.) SpaceX Falcon Heavy [7] = $1,100 per kg.
4.) Air Force Lab revolutionary approach [8] = $250 / kg
5.) MiraSolar sat [4] cost $0.6 B; constellation **[4] $11 B.**
6.) MiraSolar sat [7] cost $1.8B; constellation **[7] $32 B.**
7.) MiraSolar sat [8] cost $0.4 B, constellation **[8] $7 B.**

Payback time range: [4] 0.7 y; [7] 2 y, [8] 0.5 years.

Referring to the calculation of revenues first, there are two key assumptions. First note that while the assumed overhead ground power density is 1 kW/m^2 or 1 GW/km^2, the average power density is assumed to be 0.7 kW/m^2 or 0.7 GW/km^2 (Item 4 in revenue assumptions in table II). The power produced per ground station of 5.5 GW follows from this assumption.

The second key assumption is that the daily energy available at each ground station is 2 hours x 0.7 kW/m^2. (Item 6 in revenue assumptions in table II) This is as just calculated for the figure 5 example.

From these two key assumptions and assuming $0.1 per kWh, the annual revenues work out to be $16 billion.

Next referring to the satellite mass calculation, fortunately, there is a detailed L'Garde study [5].

The major uncertainty lies with launch cost. There are 3 different LEO launch cost references. There is the near term Falcon Heavy [7] or an estimate used in the NASA SPS study [4] assuming more frequent launches or a revolutionary system proposed in an Air Force Research Lab study [8]. Given that launch costs should be less with reusable launch vehicles and frequent standard launch procedures, the NASA estimate of $400 per kg will be used here. With this assumption, the payback time is 0.7 years.

V. MIRASOLAR SATELLITE DESCRIPTION

Given that the economics looks very promising, we now turn to a preliminary description of a MiraSolar satellite.

Figure 6 shows a view of the earth with several MiraSolar satellites shown conceptually in a dawn / dusk sun synchronous orbit.

Fig. 6: The mirror satellites can be gravity beam stabilized as illustrated. Here, the mirror satellites are very simplified and exaggerated in size simply to illustrate a concept.

This constellation is potentially viable now because of the rapid growth in solar installations around the world. However, it is assumed here that a political decision will be required to implement this MiraSolar constellation concept and its actual implementation will then take approximately 10 years. By that time, we assume that there will be approximately forty 5 GW ground solar electric generating locations distributed around the world with approximately 7 available in each continent. If in fact there are 40 x 5.5 GW = 220 GW of solar ground stations available 10 years from now, that will still be only 220/900 = 24% of the projected solar electric power production in 2022.

Although no bigger in area than the figure 2 ISC Space Power Satellite, a MiraSolar satellite is still very big. What might a MiraSolar satellite look like and how can it be assembled in space? Figure 7 shows a gravity beam stabilized mirror satellite element. This mirror element can serve as a building block for a linear MiraSolar satellite as shown in figure 8.

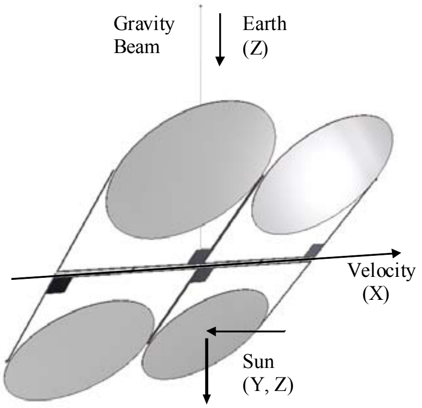


Fig. 7: MiraSolar satellite element can serve as initial test article as well as a repetitive building element.

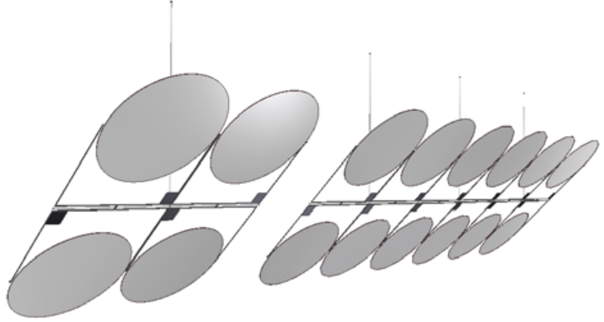


Fig. 8: Each MiraSolar satellite can be built up from multiple mirror segments. Four hundred segments in a linear sequence will produce a 10 km diameter 1 kW/m^2 sun beam.

How might a large mirror satellite be built? As noted in figure 8 in a preferred embodiment, there will be a large number of mirror elements held relative to each other along a backbone. In an example case where the satellite is in an orbit at 1000 km, the mirror satellite will be approximately 0.6 km wide and 200 km long. These dimensions are approximate. For example the altitude of the orbit may be chosen in the range from approximately 500 to 2000 km with the satellite size then varying as per (1). The size of the mirror elements can also be varied. One possible mirror element might be 250 m in diameter. This dimension is similar to L'Garde's largest modeled solar sail.

In one embodiment, each mirror element will be independently rotatable in 2 axes. Figure 9 shows one potential mirror element configuration, a detailed view of one of the mirrors in figure 7.

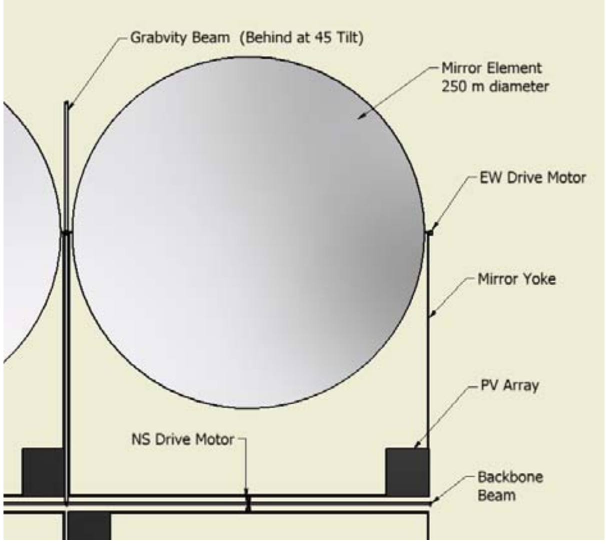


Fig. 9: Detailed view of one of the mirrors from figure 7 showing 2-axis drive motors powered by small PV panel. Motors provide EW and NS mirror movement to acquire ground target site.

In this example, there are NS motors attached to the main backbone. Each of these NS motors attaches to a mirror yoke that secures each mirror element at the N and S edges of each mirror element. There is also an EW motor attached to the yoke and the mirror frame as shown for each mirror element. Near each of these motors, there are relatively small solar cell arrays that supply power to these motors so that the mirror can be rotated around both the EW and NS axes as directed by a beam direction controller not shown.

The fabrication of the mirror elements must also be considered. They will need to be very light weight. Fortunately, this problem has been addressed first in the original Ehricke NASA study and most recently in the Ikaros and L'Garde projects. One possible way a mirror element might be fabricated would be to use a stretched mirror membrane with a rigid inflatable rim [3].

VI. FUTURE ROADMAP

How does one begin? One could start with the controlled pointing mirror segment in figure 7 in orbit to demonstrate the mirror and pointing technology. It could also provide a light beam passing over the various Disney amusement parks around the world for entertainment every evening. It would be 1/400th the intensity of sunlight but 100 times more intense than moonlight.

Then one could proceed to build the first 18 MiraSolar satellite constellation as per figures 4 and 8. Once this is successful, one can then continue to add 2 more MiraSolar constellations staggered in longitude as shown in figure 10. These three constellations could then provide 3 additional sunlight hours in the morning and 3 additional sunlight hours in the evening.

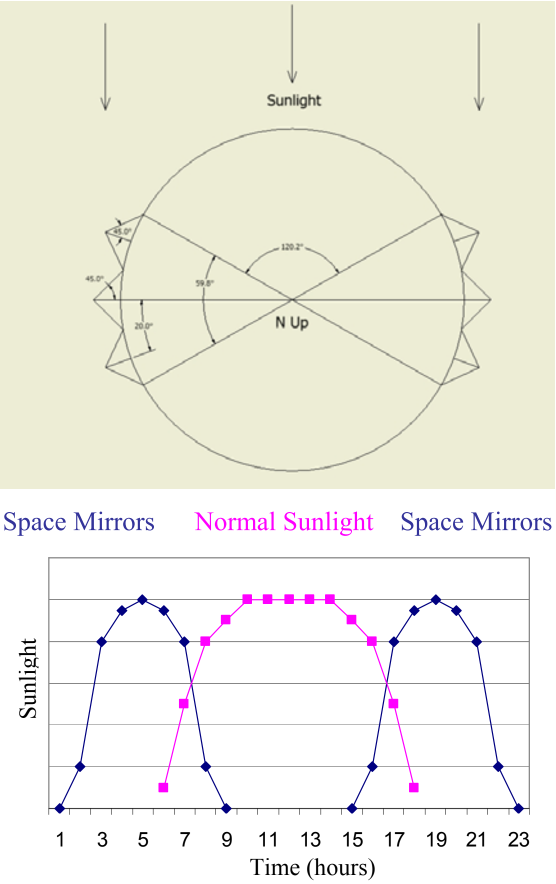


Fig. 10: Deflected sun beams from mirrors in sun synchronous dawn to dust low earth orbit can provide 3 hours additional solar energy in early morning and 3 more hours in evenings to ground solar electric power stations reducing the cost of solar electricity to < 6 cents per kWh.

VII. CONCLUSIONS

Table III provides a summary comparison of key parameters contrasting the MiraSolar system with the ISC SPS concepts. In this table, the cost comparisons are done using the ISC SPS assumed launch cost of $400 per kg so that the 2 systems can be compared on an equal cost basis.

Table III highlights the Advantage of the MiraSolar concept over the ISC SPS concept. Simply note what is not needed for the mirror concept. The elements no longer needed are the solar converter, the special ground station, the microwave power beaming, and the complex heat management.

Referring to table III, note that the cost of the MiraSolar in $ per W is 10 times less than the SPS. However, also note that in both cases, this cost per W is for a system based on 24 hours of power per day. While for the SPS this power is at one ground site, for the MiraSolar case, the ground sites are to be built anyway and the 24 hours is from the point of view of the space mirror system.

The advantages of the MiraSolar constellation can be summarized as follows:

1.) The economics works because the mirrors in space are always available 24 hours per day.
2.) For the terrestrial power producing sites, capacity factor is increased by 9/7 = 1.28 (18 satellites) or 13/7 = 1.8 (54 satellites) for high latitudes at almost no additional cost.
3.) Ultimate simplicity.
4.) Each mirror sat in LEO is no bigger in area than the 5 km x 15 km NASA ISC in GEO.
5.) While expensive, its cost is spread over 10 years.
6.) Combines the national space exploration program with the world wide energy future.

TABLE III: SPACE POWER SYSTEM COMPARISONS

Parameter	MiraSolar	ISC SPS
Orbit	1,000 km	36,000 km
# Satellites	18	1
Mirror Area per Sat	78 sq km	12.8 sq km
Total Mirror Area	1404 sq km	12.8 sq km
24 hr/day Earth Power	220x2/24 = 18.3 GW	1.2 GW
Cost ($400/kg)	$11 B	$14 B
$ per 24 h GW	$0.6 B/GW	$11.7 B/GW
Earth Station Size	5.5 GW	1.2 GW

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